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14. ABSTRACT

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Deep flow and transport through the Ulleung Interplain Gap in the Southwestern East/Japan Sea

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ABSTRACT

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1. Introduction

The East/Japan Sea (East Sea hereafter) is divided into three deep basins by a submarine plateau and bank (Fig. 1). Deep water formation takes place in the Japan Basin (JB) in the northern East Sea (Seung and Yoon, 1995; Kim et al., 2002) and leads to a thermohaline circulation that transports deep, cold water southward towards the Ulleung Basin (UB) and Yamato Basin, located in the southwestern and southeastern East Sea, respectively. Reports have been given of the dominant cyclonic abyssal circulation within each of the three basins as well as for the entire East Sea (Hogan and Hurlburt, 2000; Senjyu et al., 2005). The abyssal circulation in the UB also contains cyclonic and anticyclonic cells on sub-basin scales (Teague et al., 2005). Warming of these deep waters has been reported (Kim et al., 2004), which is attributed to changes in the overturning circulation (Kang et al., 2003). For the climate of the East Sea, interbasin water exchanges are of fundamental importance due to associated fluxes of heat and salt that then determine the density of seawater, and hence act as driving forces for the overturning circulation.

Water masses below about 300 m in the JB consist of the East Sea Central Water (ESCW), East Sea Deep Water (ESDW), and the East Sea Bottom Water (ESBW) (Kim et al., 1996). The ESDW, with a potential temperature

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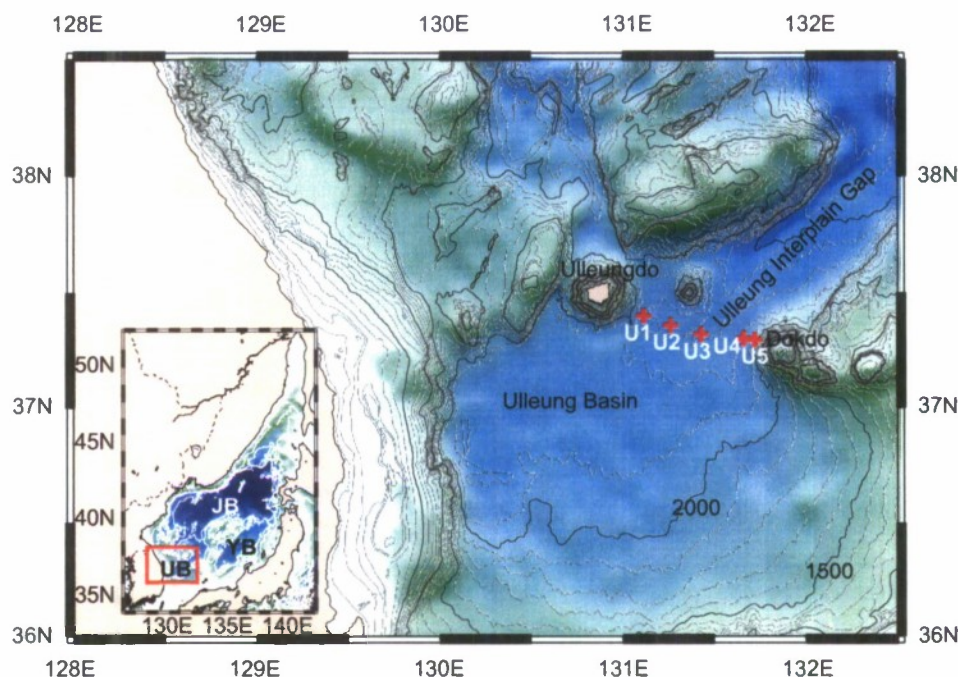E-mail address: kichang@snu.ac.kr (K.-I. Chang).

Fig. 1. A topographic map of the Ulleung Basin in the southwestern East Sea, and locations of current moorings in the southwestern Ulleung Interplain Gap, which channels the deep water exchange between the northern Japan Basin and the southwestern Ulleung Basin. An array of five current meter moorings U1–U5 were deployed from November 2002 to April 2004. JB, UB, and YB denote the Japan Basin, Ulleung Basin, and Yamato Basin, respectively.

lower than 0.1 °C (Kim et al., 1999), occupies a layer from 1800 to 2500 m, between the ESCW and vertically homogeneous ESBW in the JB. The ESDW is also found in the UB below about 1500 m (Chang et al., 2002b) and must originate from the JB since no source of deep cold water exists in the UB. The UB's only connection with the JB below 1500 m depth is through the Ulleung Interplain Gap (UIG), a deep (ca. 2500 m deep and 75 km wide) passage. The bottom temperature distribution indicates that the deep water below 0.1° in the interior UB (referred to as DW hereafter including the ESDW and the ESBW) connects with the JB only through the UIG (Chang et al., 2004).

Quasi-persistent deep southwestward flows have been evidenced by a single current meter mooring in the middle of the southwestern UIG between Ulleungdo and Dokdo ("do" means an island.) (Chang et al., 2002a) (We refer to this section of the UIG between the two islands as the UIG henceforth in this paper.). This inflow must be balanced by a combination of outflow and upward mass flux into the thermocline. Assuming a unidirectional DW inflow of 0.5 Sv through the entire UIG based on data from the single mooring, Chang et al. (2002a) conjectured a high vertical diffusion rate of $67 \times 10^{-4}\,\mathrm{m^2\,s^{-1}}$ across the 0.1 °C isothermal surface in the interior UB. Teague et al. (2005) suggest that the deep outflow could take place over the Korea Plateau or through the eastern UIG. The former would imply substantial vertical motion because the Korea Plateau is about 500 m shallower than the UB, and is unlikely. Numerical model results also indicate deep flow leaving the UB in the eastern UIG near Dokdo (Hogan and Hurlburt, 2000). A schematic abyssal circulation pattern by Senjyu et al. (2005) also suggests that the

in- and outflows through the UIG are a part of the basin-wide cyclonic circulation. However, current data have been unavailable in the eastern UIG to confirm the outflows. This paper presents results from the deployment of an array of five current meter moorings in the UIG for about 16.5 months, with a central goal to quantify the mean and temporal variability of deep flows through the entire UIG, and to especially examine any net deep water flux through the gap.

2. Moored current meter observations

An array of five moorings that span the entire gap between the 2000-m isobaths was placed across the UIG from November 2002 to April 2004 (Fig. 1), and is referred to as Leg IX. Mooring locations and velocity statistics are given in Table 1. The moorings from west to east are U1, U2, U3, U4, and U5. Mooring U3 corresponds to a long-term mooring EC1, which has been placed since 1996 as described in previous papers (Chang et al., 2002a, 2004). Mooring U1 was placed at about 2110 m to avoid possible damage due to crab net activity. The mooring separation was about 5–20 km. The moorings were instrumented at two depth levels, one between 1690 and 1830 m and the other one at 20 m above the bottom with Aanderaa recording current meter (RCM)-7 or RCM-8 current meters that recorded current speed and direction, and temperature every 30 min. Mooring U3 carried additional current meters above 1500 m, which are not included in the present study because our focus is on the deep currents and deep water transport below 1800 m. Of the 10 RCM current meters deployed below 1600 m,

Table 1

Basic statistics for low-pass filtered currents subsampled at 12 h intervals at five moorings in the Ulleung Interplain Gap

Station	Mooring/total depth (m)	Number of days used	Velocity component	Mean (cm s⁻¹)	SD (cm s⁻¹)	IT (day)	Standard error (cm s⁻¹)	Max. (cm s⁻¹)	Min. (cm s⁻¹)	Vector mean Speed (cm s⁻¹)	Dir. (°)	Max. speed (cm s⁻¹)	MKE (cm² s⁻²)	EKE (cm² s⁻²)	EKE/ MKE	Principal axis (°)	Direction stability
U1 37°23.876' 131°06.732'	1760/2110	494	Ur	−0.15	1.81	3.0	0.20	5.39	−10.28	0.19	230.2	12.61	0.02	5.28	307.3	81.80	0.08
			Vr	0.11	2.70	2.9	0.29	9.76	−12.01								
	2090/2110	494	Ur	−0.19	1.75	3.4	0.20	6.89	−9.44	0.29	144.5	12.47	0.04	4.65	114.3	82.04	0.15
			Vr	−0.21	2.50	2.7	0.26	10.289	−12.39								
U2 37°21.394' 131°15.649'	1830/2270	493	Ur	−0.96	2.01	4.5	0.27	5.80	−8.02	1.17	227.3	12.01	0.69	5.33	7.7	73.77	0.43
			Vr	0.68	2.58	3.9	0.32	9.03	−7.40								
	2250/2270	494	Ur	−0.87	2.17	4.3	0.29	6.19	−10.31	0.93	212.3	12.00	0.43	5.69	13.2	73.18	0.39
			Vr	0.32	2.59	3.5	0.31	9.72	−8.98								
U3 37°19.136' 131°25.625'	1685/2255	494	Ur	−0.89	2.52	5.2	0.36	6.00	−9.64	1.05	224.2	9.73	0.55	5.42	9.8	44.25	0.38
			Vr	0.56	2.12	4.3	0.28	6.24	−5.84								
	2235/2255	187	Ur	−0.85	2.74	6.0	0.70	6.21	−8.88	0.85	197.4	9.13	0.37	4.57	12.5	24.60	0.37
			Vr	0.08	1.28	2.5	0.21	3.86	−5.31								
U4 37°17.932' 131°39.486'	1750/2150	495	Ur	2.28	4.55	13.9	1.08	12.64	−9.73	2.31	2.2	15.23	2.67	13.16	4.9	3.56	0.50
			Vr	0.40	2.37	2.2	0.22	12.72	−10.13								
	2130/2150	325	Ur	0.92	3.10	7.3	0.66	10.27	−7.32	0.92	13.9	10.38	0.43	5.74	13.5	9.04	0.32
			Vr	−0.03	1.38	2.4	0.17	5.27	−5.97								
U5 37°17.681' 131°43.229'	2040/2060	495	Ur	4.44	6.02	4.6	0.82	28.31	−14.11	4.47	5.1	28.47	10.01	19.69	2.0	6.91	0.74
			Vr	0.54	1.78	1.8	0.15	6.34	−5.80								

The statistics are based on Leg IX time series. SD and IT denote the standard deviation and integral timescale. All directions are measured clockwise from north. The integral timescale is defined as the discrete integral of the time-lagged autocorrelation function from zero lag to the first zero crossing after demeaning and detrending the time series. Standard errors in the mean velocity components are calculated using the number of degrees of freedom obtained by dividing the record length in days by twice the integral timescale. Direction stability is defined as the ratio between the vector mean and scalar mean speed.

7 returned complete records of data for about 16.5 months (495 days). Data were not recorded for the entire measurement period at 1800 m on U5 because of a data storage unit failure. Two current meters at 20 m above the bottom on moorings U3 and U4 yielded only 187 and 325 days of data from the start of the recording, respectively, because of a power shortage. After recovery of the moorings in April 2004, new moorings were re-deployed at U3 immediately after the recovery and at U5 in July 2004 about 3 months after its recovery in April 2004. Both moorings at U3 and U5 (referred to as Leg X) were successfully recovered in February 2005.

The RCM registers a minimum current speed of $1.1 \, \text{cm s}^{-1}$, which is treated as a current stall. Data processing consists of treatment of a number of stalls in the same manner as in Teague et al. (2005); decomposition of velocity time series into along-channel (Ur, 12° from the north in a clockwise direction) and cross-channel (Vr) components, removal of major tidal constituents by a harmonic analysis, and application of spline fits to the Ur and Vr time series for stall periods no longer than 5 h and setting to zero values for longer periods. Ur and Vr are then low-pass filtered utilizing a 40-h Hanning cosine filter and then subsampled every 12 h.

3. Results

3.1. CTD sections

Conductivity–temperature–depth (CTD) sections across the UIG accompanied the deployment and recovery of the moorings in November 2002 and April 2004, with an additional CTD survey conducted in June 2003. Fig. 2 shows sections of the potential temperature with the placements of current meters.

This paper is concerned with the deep flow that is associated with the structure of the potential temperature

in deep waters. However, it is necessary to examine the upper structure as well, since the upper and lower layers are closely linked because the permanent thermocline is relatively shallow in the East Sea (e.g., Chang et al., 2004). A permanent thermocline with a range of potential temperature between 2 and 10 °C was observed between 100 and 200 db in November 2002 and June 2003. Its bottom deepened to about 300 db in April 2004. Above the permanent thermocline a very strong seasonal thermocline was notable in June 2003, but a thermostad, which was slightly warmer than 10 °C, was clearly developed in April 2004. This thermostad is likely the extension of what have been often observed in the interior of the UB and in the UIG below the seasonal thermocline during the warm seasons (Chang et al., 2002b, 2004; Gordon et al., 2002; Shin et al., 2005). The thermostad was not observed either in November 2002 or June 2003.

Below the permanent thermocline in Fig. 2, there are several features that should be noticed in relation with currents in deep waters. First of all, isotherms are almost level at about 1000 db in all three sections. Above this particular depth isotherms slope upward towards Dokdo in June 2003 and April 2004. This implies a southward flow in the upper layer, as observed frequently in the UIG associated with the meandering of the East Korean Warm Current or the development of the anticyclonic Ulleung Warm Eddy (Chang et al., 2002b). Because of fewer stations, the structure below 1500 db is poorly resolved in June 2003. However, eight or six stations in November 2002 and April 2004 are dense enough to resolve clearly structures in deep waters, indicating some differences between the two sections. In November 2002 isotherms below 1000 db slope upward from U3 to U4 and downward from U4 toward Dokdo, suggesting a geostrophic current flowing southward at U4 and U5 if one assumes a level of no motion at 1000 db. The observed current at U5 at the time of the CTD survey was southward for about 2 days from the beginning of the mooring followed by alternating
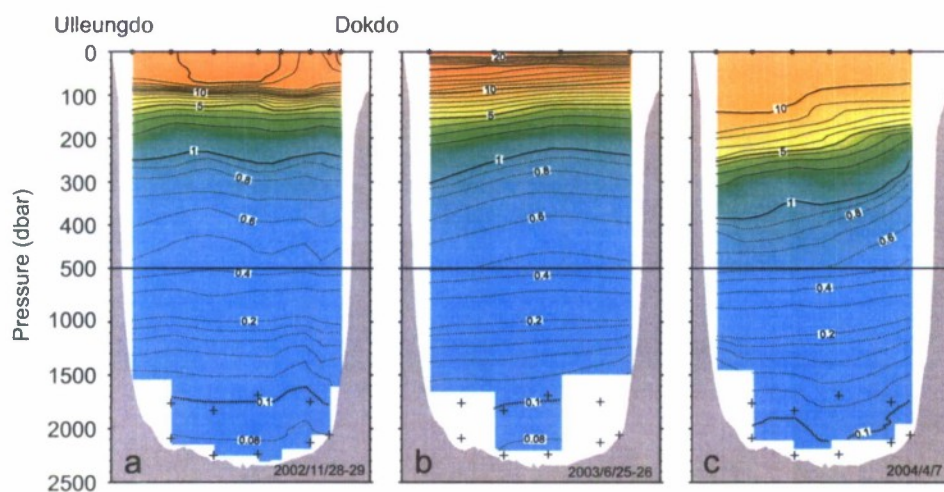

Fig. 2. Potential temperature sections across the Ulleung Interplain Gap taken three times during Leg IX moored current observation. Bold lines are used for every 5 °C, and dotted ones for every 0.1 °C from 0.9 to 0.2 °C and every 0.02 °C below 0.2 °C. The 1 and 0.1 °C isotherms are also denoted by bold lines. Note the different depth scales above and below 500 dbar. CTD stations are shown with dots, and crosses indicate the placement of moored instruments from U1 (left) to U5 (right). The bathymetry is based on the composite of ship's echo sounding data at intervals of every one mile during the hydrographic surveys.

northward and southward flows, each of which persisted for 12 days. The current at U4 was persistently southward during this period. The excitation of the 12-day fluctuations of current at U5 together with southward current at U4 was also observed between August and October 2004. It is conjectured that the current at U5 before the mooring would have been southward for about several days, and the CTD section in November 2002 represents those southward currents at both U4 and U5. On the other hand, the same isotherms slope upward toward Dokdo in April 2004, and this time a northward current is suggested near Dokdo. The geostrophically inferred deep currents also agree with the observed flows at U4 and U5 near the end of the mooring (Fig. 3). Slopes of deep isotherms change their sign around middle of the UIG in April 2004, indicating the reversal in the current direction, which is also consistent with opposite currents at U3 (southward) and U4 (northward) (see Fig. 3).

Mean depth of the 0.1 °C isotherm across the section has changed from about 1700 m in November 2002 to about 2000 m in April 2004. Analysis of the long-term CTD data indicates a lowering of the section-averaged depth of the 0.1 °C isotherm by about 270 m from 1630 to 1900 m during the period from 1995 to 2004 (not shown in the UIG, but see Fig. 8 for interior of the UB). The change of the depth of the 0.1 °C isotherm observed from November 2002 to April 2004 would include a short-term variation in addition to the long-term trend over 40 years. Further details of the warming of the deep water in the UIG are beyond the scope of this study.

3.2. Velocity field

Time series of 40-h low-passed vector currents and record-length mean current vectors with their respective principle-axis ellipses are shown in Figs. 3 and 4, respectively. Basic statistics of the currents are also provided in Table 1. Standard errors for each velocity component are smaller than the mean values except for

the weak mean flow at mooring U1, suggesting that the mean flows based on annual timescales are stable.

The most striking aspect of Figs. 3 and 4 is the remarkable speed and the persistence of northward flow at U5 located at the base of the steep continental slope in the eastern UIG near Dokdo. The current at U5 is northward except for a few reversals over time periods of 10 days or less. The mean current speed at U5 during Leg IX, 4.5 cm s^{-1}, is the largest observed among all the moorings. Accordingly, the mean kinetic energy (MKE) is the highest, and the ratio between the eddy kinetic energy (EKE) and the MKE shows the lowest value (Table 1). The maximum speed at U5 reaches 28.5 cm s^{-1} for the low-passed currents and 33.4 cm s^{-1} for the unfiltered currents. The direction stability at U5 is also the highest and indicates that the deep flow at U5 is directionally stable. Deep
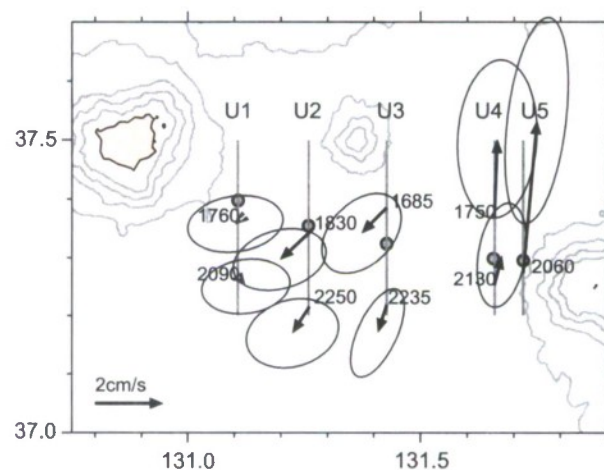

Fig. 4. Record-length mean current vectors with their respective principal-axis ellipses based on data obtained during Leg IX. The principal-axis ellipses, plotted at the tips of the mean vectors, specify the standard deviations of the fluctuating components in the direction of principal major and minor axes.
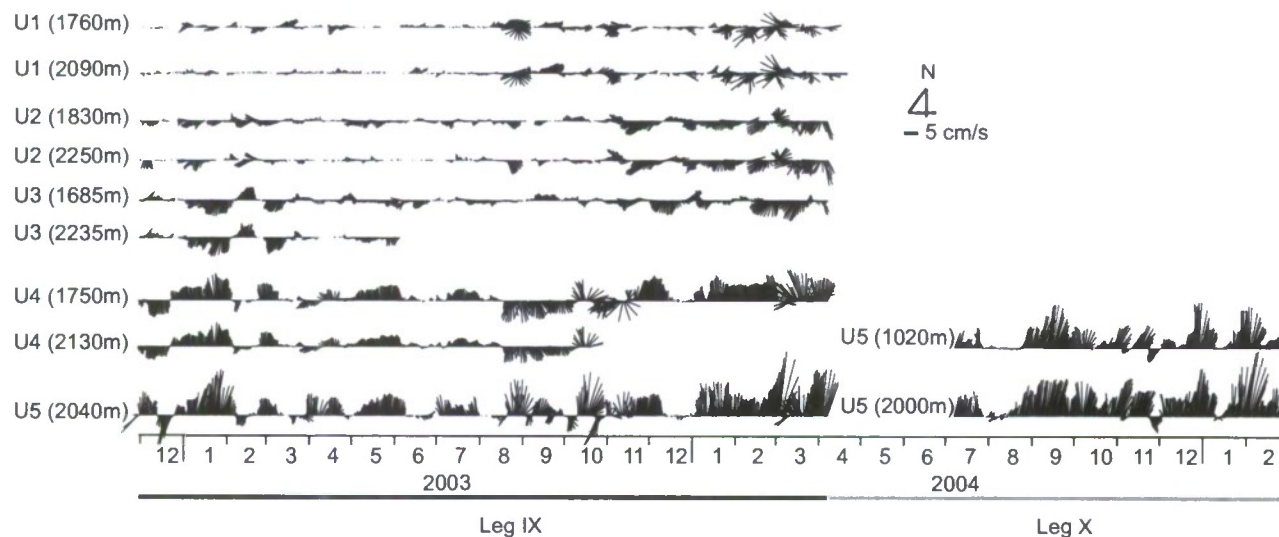

Fig. 3. Vector time series of low-pass filtered 12-hourly currents at five moorings, U1–U5 during Leg IX, and at mooring U5 during Leg X.

currents at U4 located within about 5 km of U5 are also predominantly northward and their fluctuations are almost concurrent with the currents at U5 except for two events we will address shortly. The mean current speed at U4, as compared to that at U5, decreases by almost 80% near the bottom and by about 48% at 1800 m depth (Table 1).

The northward outflow near Dokdo has never been observed, not even in a recent circulation map based on a relatively high-resolution array of current meter and inverted-echo-sounder moorings (Teague et al., 2005). A numerical model, however, predicted a mean abyssal outflow near Dokdo similar to this observation (Hogan and Hurlburt, 2000), although the model-generated mean speed was about half of the observed northward speed. Considering its persistency and strength, the northward flow in the eastern UIG deserves a name and we label this current as the Dokdo Abyssal Current (DAC). The DAC extends from mooring U5 to mooring U4, and probably farther to the west between moorings U3 and U4. The linear interpolation of the mean flows between moorings U3 and U4 approximates the DAC to be about 20 km wide below 1800 m depth.

The reversal of the mean flow occurs between U3 and U4, which are about 20 km apart, and southwestward flows (inflows) are dominant at three western moorings U1, U2, and U3, with almost vanishing mean flow at U1 near Ulleungdo (Fig. 4). The inflow is weaker than the outflow; hence, the mean flow pattern across the UIG is characterized by a strong and narrow outflow in the eastern UIG strengthening towards the east near Dokdo, and a broad inflow in the western UIG, which is relatively strong in the mid-UIG, and becomes weaker towards the west near Ulleungdo.

Deep currents at 1685 and 2235 m at U3 show mainly southwestward flow with occasional reversals on short timescales, and their temporal fluctuations are generally out of phase with those at U5. When the DAC intensified, the southward flow at U3 became stronger (Fig. 5a). Southwestward currents are also dominant at U2. Deep currents at U1, near Ulleungdo, are relatively weak, and the current direction is highly variable. Currents at moorings U1 and U2 in the western UIG became stronger in the second half of the observation period (Fig. 3).
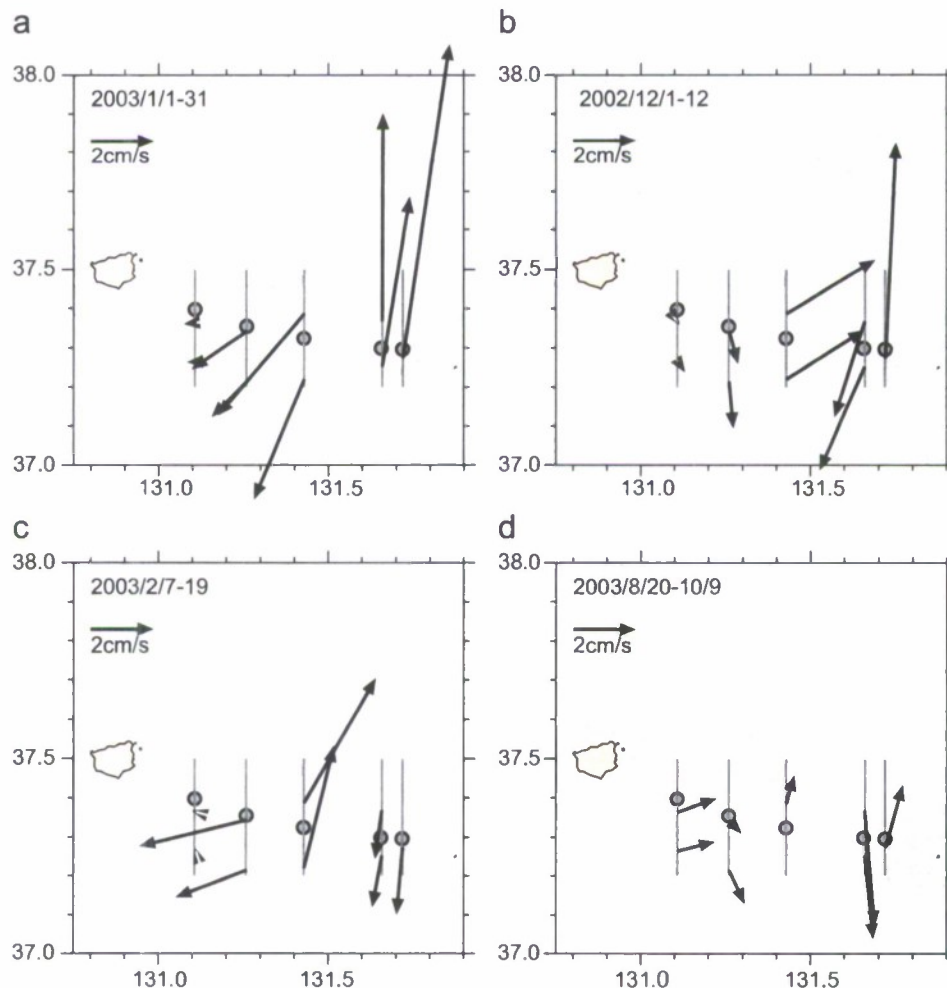

Fig. 5. Mean current vectors for some selected periods during Leg IX. (a) Monthly mean currents in January 2003, which shows strong northward DAC in the eastern Ulleung Interplain Gap at U4 and U5 concomitant with the strong southwestward deep flows in the central Ulleung Interplain Gap at U3 and U2. Other plots show mean current vectors during the periods of three events when southward deep flows occurred at U4. (b) during December 1–12, 2002, (c) during February 7–19, 2003, and (d) during August 20–October 9, 2003.

The mean currents at all moorings are weaker than 4.5 cm s^{-1}, but the flow is dominated by strong mesoscale events (Fig. 3) that occur irregularly and display typical periods ranging from about a half of a month to 2 months. The EKE, ranging from 3 to 20 cm^2 s^{-2}, is higher than the MKE at all moorings with a maximum (minimum) ratio at U1 (U5). The EKE level near the seabed at U3 is almost the same as observed during other mooring periods in earlier studies (Chang et al., 2002a; Teague et al., 2005). After demeaning of the time series, the principal axis determines the major direction of current fluctuations. For deep flows below 1800 m depth, major current fluctuations occur in the north–south direction at moorings U4 and U5, in the northeast–southwest at U3, and mainly in the zonal direction at moorings U2 and U1 in the western UIG. Current fluctuations of the deep observations are mainly barotropic at all moorings. The integral timescale is a measure of the time for which the fluid remembers its previous state. Integral timescales for Ur (3–14 days) are longer than for Vr (2–4 days), suggesting that the scale of the along-channel variability is longer than the cross-channel variability. It is longest at mooring U4 with scales of 14 days at 1750 m depth and 7 days near the seabed. It ranges from 3 to 6 days at the other moorings with the shortest scale at U1.

3.3. Flow reversals in the eastern UIG

The DAC observed at moorings U4 and U5 is characterized by quasi-persistent northward flows with fluctuations occurring in bursts over periods ranging from about 15 days to 2 months and with short periods of flow reversals to the south. There were about 13 events of short-term, less than 10 days, flow reversals at mooring U5 during Leg IX, while the flow reversals were less frequent during Leg X. The flow reversals at U5 during Leg IX were mostly concomitant with reversals at U4 except for two events. A persistent southward flow occurred at U4 for about 50 days between August 20 and October 9, 2003 (Fig. 3). During this period, the flow reversal at U5 was more frequent, resulting in a weak mean northward flow opposite to the flow direction at U4, which was only about 5 km from mooring U5 (Fig. 5d). The deep flows were also weak at western moorings U2 and U3, and the mean flow direction over this period was changed from the predominant southward direction to northward at mooring U3. The directions of deep flows averaged over a period in early December 2002 at U4 and U5 were also opposite, southward at U4 and northward at U5 (Fig. 5b). The northward flow at U5 was strong (6.9 cm s^{-1}), and the most notable feature during this period was the occurrence of strong northeastward flows at U3. A similar strong northeastward flow at U3 also occurred in mid-February 2003, when relatively weak southward flows occurred at U5 (Fig. 5c). Mean flows at U2 during this period became stronger and shifted to more westward directions as compared to the mean flow directions in other periods.

Mean currents during the periods of some events during Leg IX indicate that the flow direction at U3 changed to the northeast or to the north when the flows at both U4 and U5 or either U4 or U5 changed direction to the south. The disrupted flow pattern in the UIG observed during these periods may be associated with small-scale deep eddies and has been seen in a fine resolution numerical model (see Fig. 8 in Teague et al., 2005).

3.4. Deep water transport

The main purpose of the moored current observation was to obtain an accurate measurement of the DW flow entering and leaving the UB through the UIG. Here we calculate the volume transport of the deep water below 1800 m depth based on data from five moorings during Leg IX, which mostly consists of the DW.

Time series of total transport and individual transports at each of the five moorings are calculated. The shallower measurement levels differ by 30–115 m from the 1800 m level. To compute the Ur at the 1800 m depth level at each mooring, the data at the two depth levels are linearly interpolated or extrapolated. It is relatively straightforward to integrate the mean Ur between two depths (at 1800 and 20 m above bottom) in the horizontal and in the vertical to obtain the transport time series. Integration was rectangular in areas associated with the velocities at each of the three instruments at U2, U3, and U4, extending half way to the next instrument horizontally and to the bottom in the vertical. For the peripheral moorings U1 and U5, integration was rectangular between the two nearby instruments, and triangular from the peripheral current meters outwards to the gap's lower slope at 1800 m, assuming the velocities in these areas are about the same as those at the peripheral moorings.

For shorter time series at U3 and U4 at 20 m above bottom, we first estimated mean vertical shears of the along-channel flow during the periods when the current data at two depth levels were available. Then the flows at 20 m above bottom for the gap periods were estimated by applying the same mean shears to the measured flows at the level above. The mean shears with standard deviations between the two depths are 0.26 ± 0.89 and 0.16 ± 0.99 cm s^{-1} at U3 and U4, respectively. The standard deviations of the shear for the along-channel flows are about 3–5 times smaller than those of the along-channel flows at U3 and U4 (Table 1), indicating the current fluctuations at two depths are mainly barotropic and the vertical shear remains relatively stable as compared to the current fluctuations. Because of failure of a data storage unit, the 1800 m data are unavailable at mooring U5 where the strongest bottom flow was observed. The mean shear for the along-channel flow between 1020 and 2000 m (-2.91 ± 2.71 cm s^{-1}) was estimated using data obtained during Leg X (Fig. 3). The negative shear indicates a stronger flow at 2000 m compared to the flow at 1020 m, indicative of the bottom intensification of the deep flow at U5. The mean shear observed during Leg X was used to estimate the along-channel flow at 1800 m based on measured flows at 20 m above bottom during Leg IX.

Mean transports below 1800 m at each of the five moorings are listed in Table 2. The northward transport

Table 2
Mean transports with standard errors ($Sv = 10^6\,m^3\,s^{-1}$)

Stations	U1	U2	U3	U4	U5
Net transport (Sv)	-0.0079 ± 0.0086 (0.0781)	-0.0612 ± 0.0180 (0.1353)	-0.0781 ± 0.0300 (0.2081)	0.0996 ± 0.0465 (0.1945)	0.0525 ± 0.0097 (0.0702)
Total transport (Sv)			0.0050 ± 0.0249 (0.2056)		

Standard deviations are also shown in parentheses.
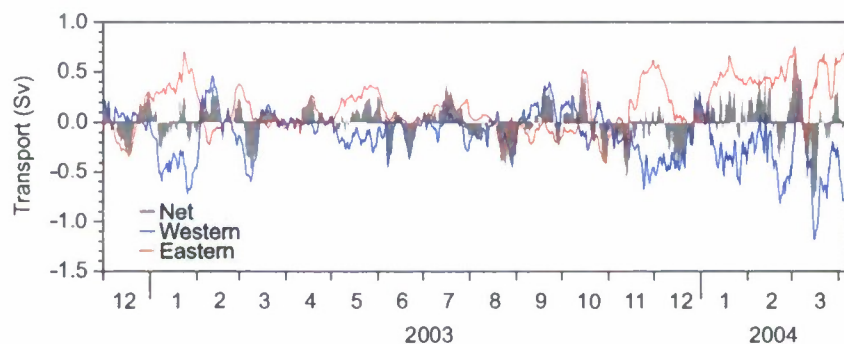
Fig. 6. Transport ($10^6\,m^3\,s^{-1}$) time series. Integrated transports for three western (U1, U2, and U3) and two eastern (U4 andU5) moorings are shown in blue and red colors, respectively. Grey tones denote the time series of net transport.

occurs mainly at U4 and U5 in the DAC, and the southward transport at U3, U2, and U1 in the central and western UIG with the maximum mean southward transport at U3. Although the deep flows at U5 are stronger than those at U4, the transports at U4 are larger than those at U5 because of the smaller width of the current at U5 used in calculating the transport. The transport time series are shown in Fig. 6. Western and eastern transports are summations of transports using moorings U1, U2, and U3 for the western transport and using moorings U4 and U5 for the eastern transport, as they have the preponderance of inflow (southward) and outflow (northward), respectively, in the array. Summing all transport nominally below 1800 m through the UIG yields an estimate for net deep water transport (shaded area in Fig. 6) of 0.005 ± 0.0361 Sv ($1\,Sv \equiv 10^6\,m^3\,s^{-1}$) to the north with a standard deviation of 0.2056 Sv, which is negligibly small and indicates that the inflowing deep water transport is closely balanced with outflows.

The estimated 48-h low-passed net transport deeper than 1800 m (Fig. 6), however, is quite variable with time, and is directed both in and out of the UB. Minimum and maximum net transports are −0.77 Sv in mid-March 2004 and 0.78 Sv in early March 2004. The standard deviation is 0.2 Sv, which is two orders of magnitude larger than the mean transport, and is primarily due to about a 30-day fluctuation. Variability at shorter periods can be seen as well. Negative correlations are visually obvious in transport fluctuations between the western and eastern transports, indicating that the southward and northward transports generally balance. Large fluctuations of the western and eastern transports are apparent in January 2003 and late in the deployment from November 2003 to the end of the deployment.

3.5. Transport and current spectra

Variance-preserving spectra are calculated for the 40-h low-passed time series of transports and deep currents at the five moorings, subsampled at 12 h intervals (Figs. 7a and b). The transport spectra for both the western and eastern moorings peak at 42.7 days. The near 40-day variabilities of inflow and outflow transports are highly coherent but about 180° out of phase (Figs. 7c and d). A secondary peak at 21.3 days occurs for the western transport, but not for the eastern transport. The net transport time series reveals a high energy level, whose energy density is higher than $0.005\,Sv^2$, in the period range between 16 and 64 days (Fig. 7a). The net transport does not peak at 40-day scale because of the highly coherent western (inflow) and eastern (outflow) transports at this period. Instead, the highest energy occurs at 21.3 days for the net transport because of the variability at this scale for the western transport. Spectral peaks for the net transport can also be seen at 10.7 and 7.5 days.

Spectra for deep flows indicate high energy levels at U5 and U4 in the DAC as compared with inflows from U1 to U3 (Fig. 7b). For the outflows, the energy density is higher at U5 near Dokdo than that at U4, while the highest energy density occurs in the middle of the gap at U3 for the inflows. The current spectra show the highest energy densities at 32 days at U1 and U3, and at 42.7 days at other moorings. The 40-day peak is the sharpest at U5 as compared to the 30 and 40-day peaks at the other moorings. A secondary peak occurs at 16 days at U5. Despite the spectral peak at 16 days at U5, the eastern transport does not show the peak at this period since the northward transport occurs mainly at U4 (Table 2) and the
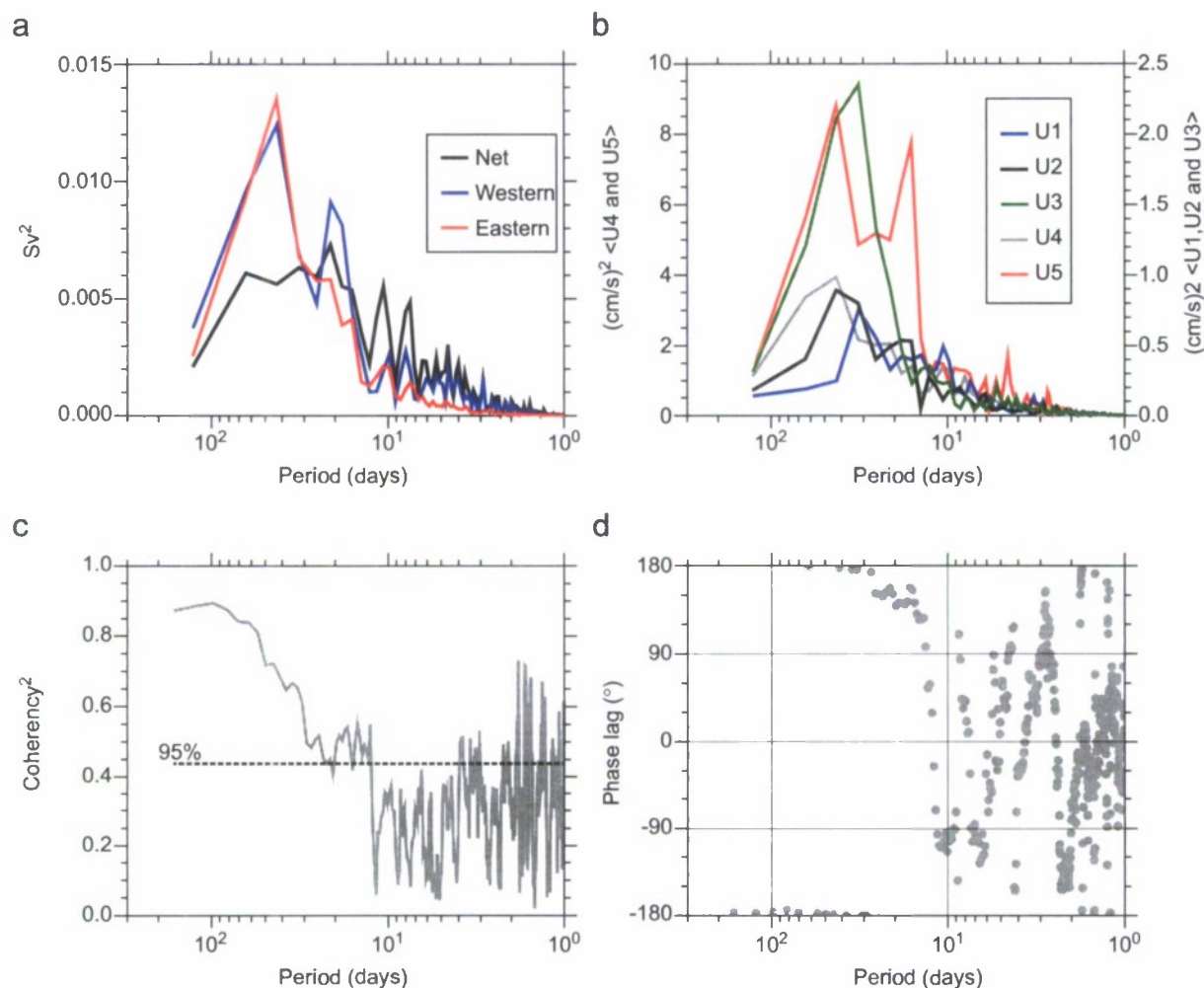
a

b

c

d

Fig. 7. Power spectra for time series of (a) net transport (black), integrated transports in the western (blue, U1–U3 in Fig. 6), and eastern (red, U4 and U5 in Fig. 6) Ulleung Interplain Gap. (b) Power spectra for deep flows. Y scales for U1, U2, and U3 are on the right, and those for U4 and U5 are on the left. (c) Coherency and (d) phase lag between the western and eastern transports.

16-day variability is absent at U4. The excitation of 16-day fluctuations at U5 often accompanies the flow reversals from north to south in the eastern gap at U4 and/or U5. The 16-day fluctuations characterized by alternating northward and southward flows at U5 can be clearly seen in December 2002 and between August and October 2003 (Fig. 3). During these periods the southward deep flows persisted at U4, and the deep flow at U3 changed its direction to northeast or north as previously noted (Fig. 5). The energy level of shorter-term variability, however, is greatly diminished at U4 and U3, suggesting that the 16-day variability is trapped on the sloping topography in the vicinity of Dokdo. Shorter-term variability with periods ranging from about 10.7 to 18 days also occurred in the western gap at U1 and U2 near Ulleungdo.

4. Summary and discussion

An array of five moorings deployed for 16.5 months at abyssal levels in the UIG between Ulleungdo and Dokdo revealed, for the first time, a narrow (~20 km) and strong

quasi-stable northward flow in the eastern UIG, which is named the DAC, with a mean speed of 4.5 cm s⁻¹ and a maximum speed of 28.5 cm s⁻¹ at 2000 m depth. The mooring data indicate a two-way flow in the UIG that consists of relatively weak southward flows directed into the UB over about two-thirds of the western UIG. More intense northward flows (DAC) directed out of the UB and strengthening near Dokdo are found in the eastern UIG. The velocity measurements across the entire UIG also revealed that the net transport is negligible below 1800 m through the gap, suggesting that previous estimates of the deep water transport through the UIG based on a single mooring (Chang et al., 2002a) or on numerical model results (Hogan and Hurlburt, 2000) may be poor. Hence, the previous estimates of diapycnal mixing should be reconsidered.

Although the estimate of mean volume transport is negligibly small, current data and the associated volume transport show sizable temporal fluctuations with time-scales of 20–50 days. Both the inflow and outflow transports have spectral peaks at 42.7 days and they are significantly correlated. Deep currents at each mooring

location also exhibited similar scale fluctuations, with spectral peaks occurring at either 32 or 42.7 days. Secondary peaks at smaller scales at periods ranging from 10 to 20 days also occurred near Ulleungdo, but most notably at U5 near Dokdo. The excitation of deep flow fluctuations at U5 at periods of 10–20 days was often accompanied by flow reversals from north to south at nearby mooring U4.

The observed weak and broad deep flows in the western UIG could be affected by a seamount east of Ulleungdo, called Anyongbok Seamount (National Oceanographic Research Institute, 2007), the shallowest depth of which extends to 450 m below the sea surface (Fig. 1). Other moored current data in the UIG are available at two locations, M1-5 from June 1999 to June 2001 and E3 from March 2005 to May 2006, northeast of our mooring array and the seamount (Fig. 8). It should be noticed that 2-year-long mean near-bottom current at M1-5 showed southwestward flow of a similar magnitude at U3 (Teague et al., 2005). On the other hand, the 14-month long mean current at E3 east of M1-5 showed a northward near-bottom current with its speed comparable to the mean speed at U5, contrasting a weak current in an opposite direction at M1-5. The current measurements upstream of our UIG section suggest strongly that the observed broad inflow in the western UIG might be a continuation of the broad southwestward flow in the upstream region. Dynamics of the asymmetric two-way flow pattern in the UIG is under investigation.

An implication of the net transport variability to conditions downstream of the UIG is the time response of the volume of the deep water or the excursion of deep isotherms interior of the UB. We calculated the possible vertical excursion of the $0.1\,^\circ$C isotherm in the UB using the net transport time series and the area enclosed by the $0.1\,^\circ$C isotherm ($\sim 10^4\,\mathrm{km}^2$, Chang et al., 2002a). The maximum excursion is about 100 m, suggestive of a

Fig. 8. Record-length mean currents from near-bottom current meters in the Ulleung Interplain Gap. Currents at M1-5 and E3 northeast of the array of five moorings from U1 to U5 were measured between June 1999 and June 2001, and between March 2005 and May 2006, respectively. Isobaths are 200, 500, 1000, 1500, 2000, and 2500 m.

short-term variation of deep isotherms that could be detected by CTD observations. We collected historical CTD data taken within 15 km from a point in the central UB (37°N, 130°E), which is about 50 km distant from the central UIG. Temporal variation of the depth of the $0.1\,^\circ$C isotherm clearly shows the deepening of the isotherm, indicative of the warming of deep water (Fig. 9a). The linear trend of the deepening of the 0.1° isotherm is about 31 m/year. The detrended time series, however, also suggests a short-term variation of the isotherm (Fig. 9b), which might arise from the low-frequency variability of the deep water transport through the UIG. Vertical stretching and shrinking of the deep water column implied by the rise and fall of deep isotherm (isopycnal) with a dominant periodicity of 20–50 days would cause a similar scale of temporal variability of observed abyssal currents (Chang et al., 2002a) and circulation interior of the UB.

Fluctuations of the volume transport on timescales of 20–50 days in the UIG remain unexplained. Analysis of 3.5-year-long deep current data at mooring U3 also shows that deep currents have dominant fluctuations in a period range of 20–50 days while the seasonal variation is insignificant (Chang et al., 2004). Seasonal variation of deep currents is prominent in the JB with strong flows in winter and almost no flows in summer (Takematsu et al., 1999a), which appears to be associated with the new bottom water formation in winter (Senjyu et al., 2002). Thus, thermohaline forcing may be an important factor in deep flow variability in the JB. Seung (2005) suggested that the spin-up of deep water by wind forcing over the region of deep winter mixing is an important contribution in the generation of abyssal currents in the East Sea. However, there appears no clear evidence for the oscillations at 20–50 days in deep current data obtained in the JB, suggesting that the observed low-frequency variability with periods of 20–50 days in the UIG is not directly coupled to upstream variations in the abyssal circulation and could be forced somewhere within the region south of the subpolar front.

Deep flow variability could be excited locally by energetic upper layer eddy processes (e.g., Johns et al., 1993). Reports have been given of deep flow fluctuations possibly related to mesoscale eddies in the East Sea (Takematsu et al., 1999b; Senjyu et al., 2005). In the UB, a quasi-permanent anticyclonic eddy, the Ulleung Warm Eddy, is often centered at a location south of Ulleungdo (Chang et al., 2004). This eddy generation is associated with the meandering of the East Korean Warm Current (Lie et al., 1995; Kim and Yoon, 1999), and a predominance of southward flow associated with the eddy in the UIG between Ulleungdo and Dokdo has been evidenced (Chang et al., 2002b). The meandering trough of the East Korean Warm Current has a breather-like behavior with a timescale of 60–70 days (Mitchell et al., 2005a), and also sheds a smaller-scale cyclonic eddy, called the Dok Cold Eddy, south of Dokdo (Mitchell et al., 2005b). However, it was shown from a 7-month long time series of upper and deep currents that the deep current fluctuations at mooring U3 are only partly related to energetic upper layer current variations (Chang et al., 2004). Both the local
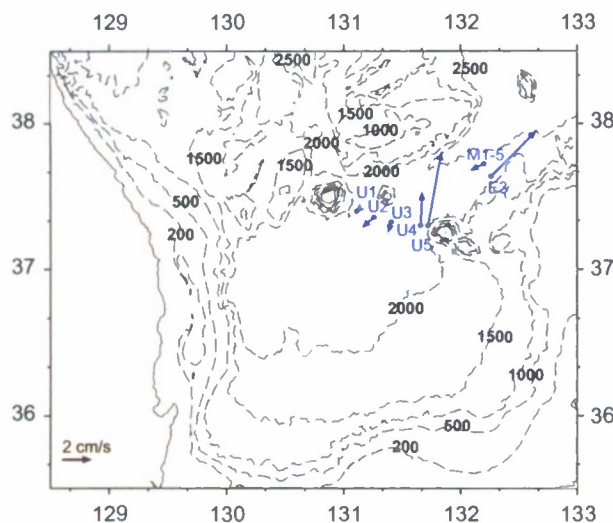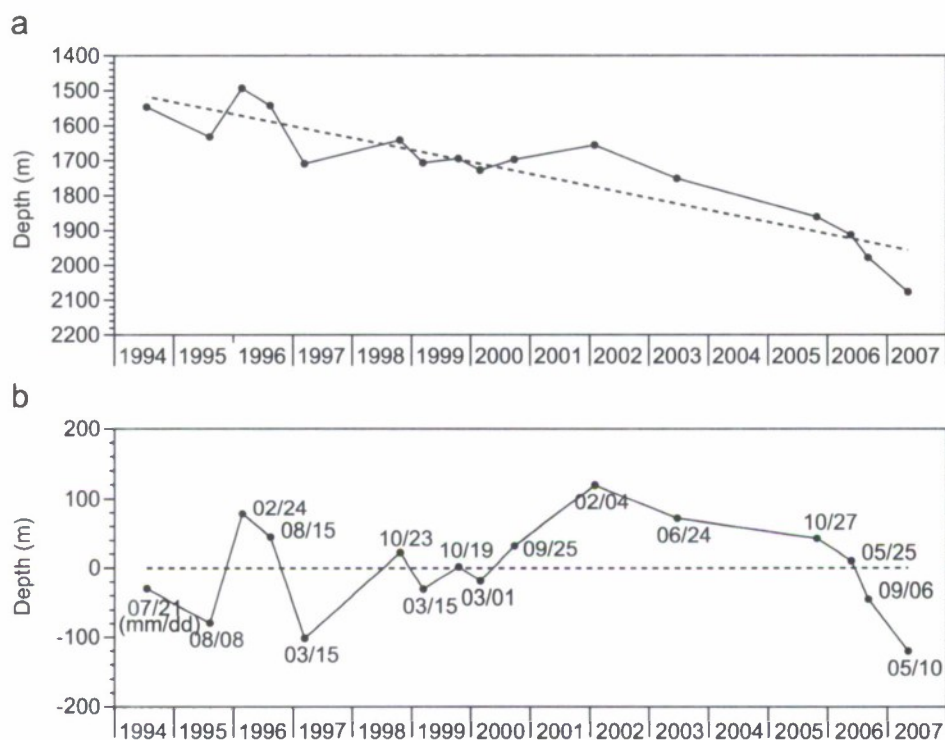
Fig. 9. (a) Time series of the depth of $\theta = 0.1\,^\circ$C isotherm based on CTD data taken in an area within 1S km from a point, 37°N and 131°E, in the central Ulleung Basin. (b) Detrended time series of the depth of 0.1 °C isotherm. Numbers denote the date of CTD casts in each year (month and day).

and remote forcing are factors in the observed low-frequency deep flow variability in the UIG.

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