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ASUKA Hydrographic Data Collection

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Abstract

Repeated hydrographic surveys across the Kuroshio and its recirculation south of Japan were carried out by a group called ASUKA (Affiliated Surveys of the Kuroshio off Cape Ashizuri) since 1992. Conductivity-temperature-depth profiler (CTD), expendable CTD (XCTD), expendable bathythermograph (XBT), and digital bathythermograph (DBT) data obtained from 155 cruises were collected for a period of 16 years, from November 1992 to May 2008. A uniform data processing was applied to raw data from the XBT and XCTD. Salinity profiles for the XBT and DBT measurements were estimated by using mean temperature–salinity relations. Biases of the salinity profiles for the XCTD measurements were estimated by using the tight relationships between temperature and salinity at temperature of 14.1 and 2.5°C, and the estimated biases were then subtracted from the salinity profiles. For the XBT and XCTD data, pressure was estimated from the inferred depth for the combined use with the CTD data. By using the integrated hydrographic dataset, temporal mean volume transport of the Kuroshio and its recirculation was estimated with an assumption of zero-velocity surface at 1800 dbar.

Key words : *ASUKA, Hydrographic data, Kuroshio, Kuroshio recirculation*

1. Introduction

In 1990s, an effort was made to estimate the volume and heat transports of the Kuroshio and its recirculation south of Shikoku, Japan. During 1993–1995, a group called ASUKA (Affiliated Surveys of the Kuroshio off Cape Ashizuri), composed of scientists or representatives from various universities and Japanese agencies (see the Appendix for detail), carried out oceanographic surveys along a line across the Kuroshio[1–6]. The line was chosen to coincide with a sub-satellite track of the TOPEX/POSEIDON altimeter and the altimeter data combined with the field observation data give a long continuous record about the Kuroshio transport[7,8]. This effort was intended to be the western boundary current mooring array PCM5[9–11] of the World Ocean Circulation Experiment (WOCE), which was designed to be combined with trans-Pacific hydrographic data along 30°N[12] [WOCE Hydrographic Programme (WHP) line P2] to estimate the meridional heat transport of the mid-latitude North Pacific[13,14].

Subsequent to the two-year intensive ASUKA observation period, pressure sensor-equipped inverted echo sounder (PIES) observations were maintained until 2004 at both the coastal and offshore sites of the Kuroshio on the ASUKA line to obtain a time series of geostrophic transport of the Kuroshio[15]. In addition to the above two sites, PIES and current meter moorings were deployed around the Nankai Trough on the ASUKA line during 2000–2001. Hydrographic surveys were carried out on the mooring deployment and recovery cruises.

During 2004–2006, PIES and current meter array observations were carried out for north of 30°N along the ASUKA line and along 30°N from the ASUKA line to 142°E by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC). Hydrographic surveys were also carried out on the mooring deployment and recovery cruises[16].

In 2004, reoccupation of trans-Pacific hydrographic stations along the WHP P2 line was conducted in support of Climate Variability and Predictability (CLIVAR) and CO_2 programs[17,18].

Repeated towed acoustic Doppler current profiler (ADCP) observations[4] were carried out with hydrographic surveys for north of 30°N along the

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ASUKA line by the Fishery Agency of Japan after the two-year intensive ASUKA observation period until 2002.

The Japan Meteorological Agency (JMA) conducted hydrographic observations along the ASUKA line as a member of the ASUKA Group during the two-year intensive ASUKA observation period (1993–1995). The JMA have continued hydrographic observations along the ASUKA line after the two-year period; in particular, it have carried out hydrographic surveys for north of 25°N four times a year since 2001[19]. These hydrographic data are distributed by Data Report of Oceanographic and Marine Meteorological Observation (CD-ROM) or available through the JMA web site[20]. Long-term hydrographic observations across the Kuroshio were also carried out by the JMA near the ASUKA line (north of 29°30'N along 135°15'E) four times a year from 1956 to 2000[21,22]. Time series of the Kuroshio transport can be estimated for more than 50 years by combining the long-term hydrographic data and the hydrographic data along the ASUKA line.

Hydrographic data obtained from those repeated hydrographic surveys during and after the intensive ASUKA observation period were collected and uniformly processed with some hydrographic survey data before the intensive ASUKA observation[23] as an integrated dataset, which is called ASUKA Hydrographic Data Collection. The dataset is available through the Research Institute for Applied Mechanics (RIAM), Kyushu University web site (http://www.riam.kyushu-u.ac.jp/oed/asuka/ahdc/) and details of the dataset are presented.

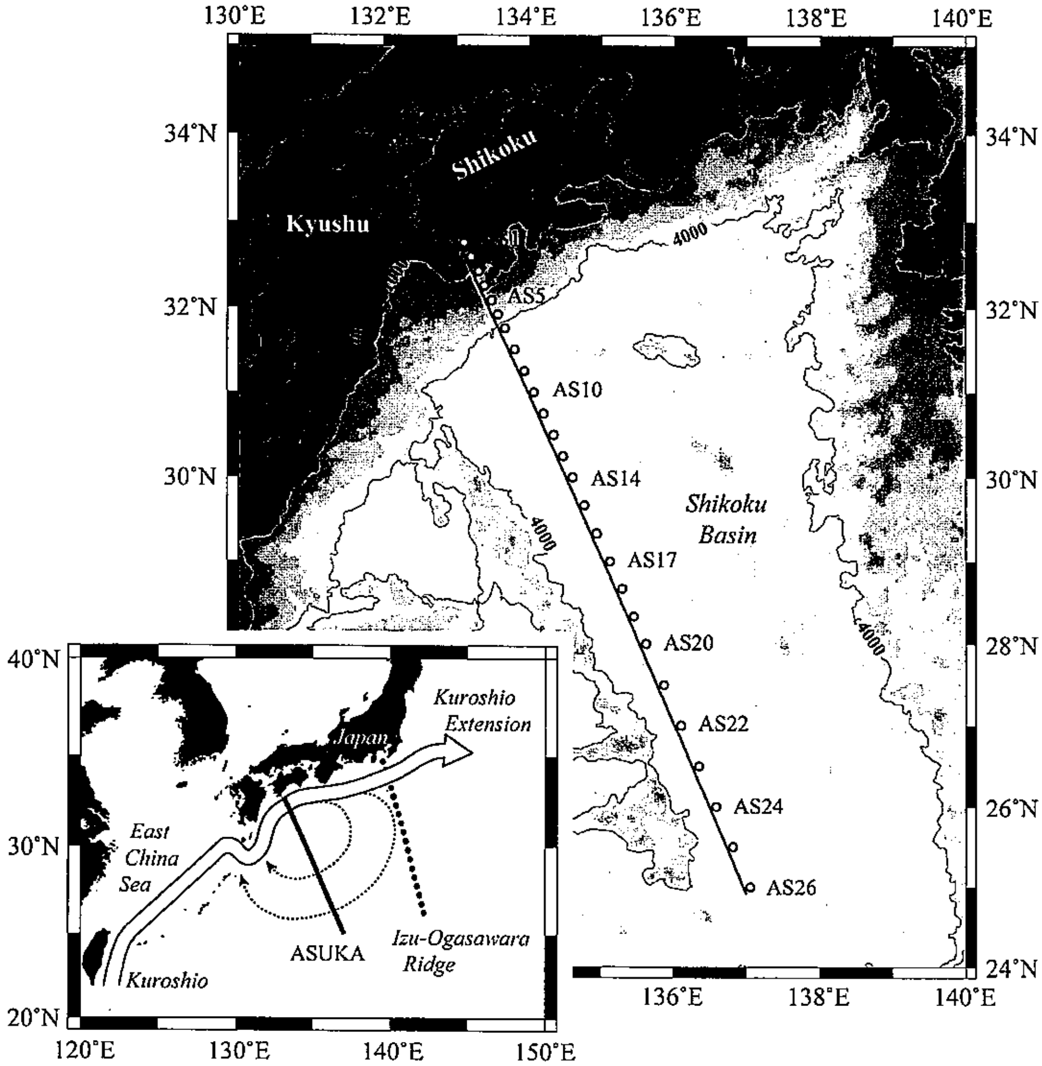

Fig. 1 Standard locations of hydrographic stations (open circles) along the ASUKA observation line southeast of Shikoku, Japan. The sub-satellite track of the TOPEX/POSEIDON satellite altimeter is shown (solid line). Schematic of surface flow patterns is shown in the inset. Selected bottom topography contours (m) are also shown.

Table 1 List of repeated hydrographic surveys conducted along the ASUKA line. Abbreviations for the data source are listed in the Appendix.

ID	Cruise	Date (UTC)		Vessel	Observation	Data Source
1	YY199211	1992	Nov. 28 - Nov. 30	Shoyo	CTD	H. Yoritaka (HD-MSA)
2	SH199305	1993	May 30 - May 31	Shumpu-maru	CTD/XBT	N. Yoshioka (KMO-JMA)
3	XK199307		July 2 - July 5	Kaiyo	CTD	A. Misumi (OORD-JAMSTEC)
4	YY199307		July 6 - July 7	Shoyo	CTD	H. Yoritaka (HD-MSA)
5	SH199307		July 31	Shumpu-maru	CTD*/XBT	N. Yoshioka (KMO-JMA)
6	SH199309		Sep. 25 - Sep. 26	Shumpu-maru	CTD/DBT	N. Yoshioka (KMO-JMA)
7	KE199310		Oct. 17 - Oct. 27	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
8	TE199311		Nov. 17 - Nov. 28	Tenyo-maru	CTD/XBT	K. Mimoto (NNFRIK-FA)
9	IY199401	1994	Jan. 8 - Jan. 10	Kaiyo-maru	CTD	K. Okuda (NRIFS-FA)
10	YY199401		Jan. 18 - Jan. 22	Shoyo	CTD	H. Yoritaka (HD-MSA)
11	TN199401		Jan. 30 - Jan. 31	Tansei-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
12	SH199402		Feb. 25	Shumpu-maru	CTD	N. Yoshioka (KMO-JMA)
13	HK199402		Feb. 26 - Feb. 28	Hakuho-maru	CTD*/XBT	H. Ichikawa (FF-Kagoshima Univ.)
14	BO199405		May 2 - May 6	Bosei-maru	CTD/XBT	M. Fukasawa (SMST-Tokai Univ.)
15	YY199405		May 10 - May 14	Shoyo	CTD	H. Yoritaka (HD-MSA)
16	SH199405		May 12	Shumpu-maru	CTD/XBT	N. Yoshioka (KMO-JMA)
17	TY199405		May 31 - June 1	Toyoshio-maru	CTD	A. Kaneko (FE-Hiroshima Univ.)
18	SE199407		July 6 - July 8	Seisui-maru	CTD/XBT	Y. Sekine (FB-Mie Univ.)
19	YY199407		July 8 - July 10	Shoyo	CTD	H. Yoritaka (HD-MSA)
20	SH199407		July 28	Shumpu-maru	CTD/XBT	N. Yoshioka (KMO-JMA)
21	SF199407		July 29 - July 30	Shirafuji-maru	CTD/XBT	K. Mimoto (NNFRIK-FA)
22	KE199408		Aug. 22 - Aug. 23	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
23	HK199409		Sep. 9 - Sep. 17	Hakuho-maru	CTD	S. Imawaki (RIAM-Kyushu Univ.) K. Taira (ORI-Univ. of Tokyo)
24	XK199409		Sep. 10 - Sep. 13	Kaiyo	CTD	A. Misumi (OORD-JAMSTEC)
25	SH199409		Sep. 17 - Sep. 18	Shumpu-maru	CTD/XBT	T. Utsunomiya (KMO-JMA)
26	BO199410		Oct. 20 - Oct. 21	Bosei-maru	CTD/XBT	M. Fukasawa (SMST-Tokai Univ.)
27	YY199411		Nov. 1 - Nov. 3	Shoyo	CTD	Y. Iwanaga (HD-MSA)
28	KE199412		Dec. 3 - Dec. 6	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
29	YY199501	1995	Jan. 11 - Jan. 12	Shoyo	CTD	A. Ogawa (HD-MSA)
30	TN199501		Jan. 24 - Jan. 26	Tansei-maru	CTD/XBT	S. Imawaki (RIAM-Kyushu Univ.)
31	KE199503		Mar. 5 - Mar. 8	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
32	XK199504		Apr. 16 - Apr. 19	Kaiyo	CTD/XBT	I. Nakano (OORD-JAMSTEC)
33	SH199505		May 5 - May 7	Shumpu-maru	CTD/DBT	T. Hinata (KMO-JMA)
34	HK199505		May 13 - May 20	Hakuho-maru	CTD/XBT	S. Imawaki (RIAM-Kyushu Univ.) M. Kawabe (ORI-Univ. of Tokyo)
35	TY199506		June 6 - June 7	Toyoshio-maru	CTD	A. Kaneko (FE-Hiroshima Univ.)
36	BO199506		June 14 - June 16	Bosei-maru	CTD/XBT	K. Kutsuwada (SMST-Tokai Univ.)
37	SE199507		July 8 - July 10	Seisui-maru	CTD/XBT	Y. Sekine (FB-Mie Univ.)
38	SH199507		July 11 - July 12	Shumpu-maru	CTD/XBT/DBT	T. Hinata (KMO-JMA)
39	YY199507		July 14 - July 16	Shoyo	CTD	Y. Shimohira (HD-MSA)
40	SF199507		July 29 - Aug. 2	Shirafuji-maru	XBT	K. Mimoto (NNFRIK-FA)
41	XK199507		July 30 - Aug. 1	Kaiyo	XBT	I. Nakano (OORD-JAMSTEC)
42	KE199508		Aug. 21 - Aug. 23	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
43	SH199509		Sep. 1 - Sep. 2	Shumpu-maru	XBT/DBT	K. Hayashi (KMO-JMA)
44	SF199509		Sep. 8 - Sep. 9	Shirafuji-maru	XBT	K. Mimoto (NNFRIK-FA)
45	IY199510		Oct. 2 - Oct. 3	Kaiyo-maru	CTD	Y. Hiroe (NRIFS-FA)
46	SH199510		Oct. 25 - Oct. 26	Shumpu-maru	XBT	T. Shiga (KMO-JMA)
47	TE199511		Nov. 9 - Nov. 16	Tenyo-maru	CTD/XBT	K. Mimoto (NNFRIK-FA)
48	KE199511		Nov. 18 - Nov. 22	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
49	NC199512		Dec. 6	Chofu-maru	CTD/XBT	T. Hinata (KMO-JMA)

* Salinity data is not available

2. Hydrographic Observations

The ASUKA observation line was purposely located along the sub-satellite track of the TOPEX/POSEIDON satellite altimeter (Fig. 1). The TOPEX/POSEIDON (1992–2002), Jason-1 (2002–2008) and Jason-2 (2008–present) have been measuring the sea surface height since September 1992. Actual hydrographic standard stations were shifted about 10 km to the east in order to avoid entering in the US Navy Maneuver Area "Lima" located near the hydrographic station AS5.

Ship-based hydrographic surveys along the ASUKA line were carried out on 155 cruises during November 1992 to May 2008 (Table 1), by using four types of instrument: Conductivity-temperature-depth profiler (CTD), expendable CTD (XCTD), expendable bathythermograph (XBT), and digital bathythermograph

Table 1 (*Continued*).

ID	Cruise	Date (UTC)		Vessel	Observation	Data Source
50	YY199601	1996	Jan. 11 - Jan. 12	Shoyo	CTD	S. Ikeda (HD-MSA)
901	SH199602		Feb. 14	Shumpu-maru	CTD	T. Utsunomiya (KMO-JMA)
51	KF199602		Feb. 14 - Feb. 15	Keifu-maru	CTD	T. Maehira (MD-JMA)
52	XK199603		Mar. 25 - Mar. 26	Kaiyo	XBT	N. Yoshioka (OORD-JAMSTEC)
53	SH199605		May 6 - May 7	Shumpu-maru	CTD	K. Kadono (KMO-JMA)
54	IY199605		May 11 - May 12	Kaiyo-maru	CTD	Y. Hirota (NRIFS-FA)
55	BO199605		May 19 - May 21	Bosei-maru	XBT	M. Fukasawa (SMST-Tokai Univ.)
56	SH199607		July 11 - July 12	Shumpu-maru	CTD	K. Kadono (KMO-JMA)
57	SF199607		July 21 - July 22	Shirafuji-maru	XBT	K. Tamai (NNFRIK-FA)
58	SH199608		Aug. 27 - Aug. 28	Shumpu-maru	CTD	K. Hayashi (KMO-JMA)
59	SF199610		Oct. 5 - Oct. 6	Shirafuji-maru	XBT	K. Tamai (NNFRIK-FA)
60	SH199610		Oct. 15 - Oct. 16	Shumpu-maru	XBT	T. Shiga (KMO-JMA)
61	HK199610		Oct. 18 - Oct. 31	Hakuho-maru	CTD/XBT	S. Imawaki (RIAM-Kyushu Univ.) M. Kawabe (ORI-Univ. of Tokyo)
62	TE199611		Nov. 20 - Nov. 21	Tenyo-maru	XBT	K. Tamai (NNFRIK-FA)
63	NC199612		Dec. 2	Chofu-maru	XBT	T. Hinata (KMO-JMA)
64	YY199701	1997	Jan. 9 - Jan. 10	Shoyo	CTD	K. Oka (HD-MSA)
65	SH199702		Feb. 13 - Feb. 14	Shumpu-maru	XBT	T. Hinata (KMO-JMA)
66	SF199705		May 2 - May 8	Shirafuji-maru	XBT	K. Tamai (NNFRIK-FA)
67	SH199705		May 6 - May 7	Shumpu-maru	CTD/XBT	T. Nakamura (KMO-JMA)
68	YY199706		June 6 - June 7	Shoyo	CTD	S. Ikeda (HD-MSA)
69	SH199707		July 9 - July 10	Shumpu-maru	CTD	S. Naito (KMO-JMA)
70	KE199708		Aug. 21 - Aug. 23	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
71	SH199709		Sep. 3 - Sep. 4	Shumpu-maru	XBT/DBT	T. Hinata (KMO-JMA)
72	SH199710		Oct. 17 - Oct. 18	Shumpu-maru	CTD	K. Kadono (KMO-JMA)
73	TE199711		Nov. 10 - Nov. 13	Tenyo-maru	XBT	K. Tamai (NNFRIK-FA)
74	KE199711		Nov. 18 - Nov. 19	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
75	YY199711		Nov. 26 - Nov. 28	Shoyo	CTD	H. Kinoshita (HD-MSA)
76	SH199801	1998	Jan. 27 - Feb. 7	Shumpu-maru	CTD	T. Shiga (KMO-JMA)
77	SH199805		May 5 - May 6	Shumpu-maru	CTD/XBT	T. Hinata (KMO-JMA)
78	SF199805		May 14 - May 15	Shirafuji-maru	XBT	K. Tamai (NNFRIK-FA)
79	YY199807		July 20 - July 22	Shoyo	CTD**	S. Ikeda (HD-MSA)
80	SH199807		July 21 - July 22	Shumpu-maru	CTD	S. Naito (KMO-JMA)
81	SF199808		Aug. 19 - Aug. 20	Shirafuji-maru	XBT	K. Tamai (NNFRIK-FA)
82	KE199808		Aug. 22 - Aug. 25	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
83	SH199808		Aug. 31 - Sep. 1	Shumpu-maru	CTD/XBT	T. Nakamura (KMO-JMA)
84	SH199810		Oct. 19 - Oct. 20	Shumpu-maru	CTD/XBT	K. Hayashi (KMO-JMA)
85	TE199811		Nov. 11 - Nov. 19	Tenyo-maru	XBT	K. Tamai (NRIFS-FA)
86	SH199901	1999	Jan. 23 - Jan. 25	Shumpu-maru	CTD/XBT	K. Kadono (KMO-JMA)
87	KE199903		Mar. 17 - Mar. 20	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
88	SH199905		May 10 - May 12	Shumpu-maru	CTD	T. Nakamura (KMO-JMA)
89	RF199906		June 25 - June 26	Ryofu-maru	CTD	T. Yano (MD-JMA)
90	SH199907		July 22 - July 24	Shumpu-maru	CTD	S. Naito (KMO-JMA)
91	KE199908		Aug. 19 - Aug. 21	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
92	SY199909		Sep. 3 - Sep. 7	Soyo-maru	XBT	T. Saito (NRIFS-FA)
93	SH199909		Sep. 10 - Sep. 12	Shumpu-maru	CTD/XBT	S. Tsubaki (KMO-JMA)
94	SH199910		Oct. 18 - Oct. 19	Shumpu-maru	CTD/XBT	H. Daimon (KMO-JMA)
95	TE199911		Nov. 16 - Nov. 17	Tenyo-maru	XBT	T. Saito (NRIFS-FA)
902	TN199912		Dec. 9 - Dec. 10	Tansei-maru	CTD	T. Sugimoto (ORI-Univ. of Tokyo)
96	SH200001	2000	Jan. 23 - Jan. 24	Shumpu-maru	CTD/XBT	H. Nagai (KMO-JMA)
97	SY200003		Mar. 9 - Mar. 10	Soyo-maru	XBT	T. Saito (NRIFS-FA)
98	KE200003		Mar. 18 - Mar. 22	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
99	SH200005		May 20 - May 21	Shumpu-maru	CTD	T. Nakamura (KMO-JMA)
100	SH200007		July 10 - July 12	Shumpu-maru	CTD	K. Kimura (KMO-JMA)
101	KE200008		Aug. 20	Keiten-maru	XBT	H. Ichikawa (FF-Kagoshima Univ.)
102	HK200009		Sep. 14 - Sep. 15	Hakuho-maru	CTD/XBT	S. Imawaki (RIAM-Kyushu Univ.) M. Kawabe (ORI-Univ. of Tokyo)
103	SH200010		Oct. 23 - Oct. 25	Shumpu-maru	CTD	H. Daimon (KMO-JMA)
104	TE200011		Nov. 16 - Nov. 17	Tenyo-maru	XBT	T. Saito (NRIFS-FA)

** Data is not yet processed

(DBT). In 1990s, hydrographic surveys were mainly carried out in the Kuroshio region (north of 30°N), except for the intensive ASUKA observation period. Since 2001, hydrographic surveys were constantly carried out in the Kuroshio and its recirculation regions by the JMA (Fig. 2). A total of eight full-depth entire hydrographic sections were obtained (Fig. 3).

Although locations of the hydrographic data obtained on cruises SH199602 and TN199912 (identification number 901 and 902 in Table 1) were different from the ASUKA line, the data from the two cruises were included in the dataset. For the cruise

Table 1 (*Continued*).

ID	Cruise	Date (UTC)		Vessel	Observation	Data Source
105	KE200103	2001	Mar. 18 - Mar. 21	Keiten-maru	CTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
106	YS200105		May 15 - May 16	Shoyo-maru	XCTD/XBT	T. Saito (NRIFS-FRA)
107	KF200106		June 13 - June 15	Keifu-maru	CTD	S. Kawae (KMO-JMA)
108	KF200108		Aug. 4 - Aug. 7	Keifu-maru	CTD/XBT	S. Tsubaki (KMO-JMA)
109	KE200111		Nov. 15 - Nov. 17	Keiten-maru	XCTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
110	KF200112		Dec. 4 - Dec. 7	Keifu-maru	CTD	K. Hayashi (KMO-JMA)
111	SY200203	2002	Mar. 16 - Mar. 17	Soyo-maru	XCTD	T. Saito (NRIFS-FRA)
112	KE200203		Mar. 19 - Mar. 24	Keiten-maru	XCTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
113	SU200205		May 10 - May 11	Shunyo-maru	XCTD	T. Saito (NRIFS-FRA)
114	KF200205		May 25 - May 29	Keifu-maru	CTD	S. Kawae (KMO-JMA)
115	KF200206		June 25 - June 28	Keifu-maru	CTD	S. Kawae (KMO-JMA)
116	SY200206		June 28 - June 29	Soyo-maru	XCTD	T. Saito (NRIFS-FRA)
117	KE200207		July 12	Keiten-maru	XCTD/XBT	H. Ichikawa (FF-Kagoshima Univ.)
118	HK200209		Sep. 15 - Sep. 21	Hakuho-maru	CTD/XCTD	S. Imawaki (RIAM-Kyushu Univ.) M. Kawabe (ORI-Univ. of Tokyo)
119	KF200211		Nov. 2 - Nov. 4	Keifu-maru	CTD/XBT	S. Kawae (KMO-JMA)
120	KF200302	2003	Feb. 27 - Mar. 5	Keifu-maru	CTD/XBT	M. Fujimura (KMO-JMA)
121	NC200305		May 7 - May 13	Chofu-maru	CTD	S. Kawae (NMO-JMA)
122	NC200307		July 22 - July 25	Chofu-maru	CTD	S. Kawae (NMO-JMA)
123	NC200311		Nov. 2 - Nov. 5	Chofu-maru	CTD	S. Kawae (NMO-JMA)
124	NC200402	2004	Feb. 14 - Feb. 16	Chofu-maru	CTD	S. Kawae (NMO-JMA)
125	KF200402		Feb. 22 - Feb. 26	Keifu-maru	CTD	M. Fujimura (KMO-JMA)
126	NC200405		May 5 - May 12	Chofu-maru	CTD	S. Kawae (NMO-JMA)
127	8M200406		June 16 - June 23	Melville	CTD	J. Swift (SIO-Univ. of California)
128	TN200407		July 5 - July 11	Tansei-maru	CTD	H. Ichikawa (IORGC-JAMSTEC)
129	NC200407		July 26 - July 29	Chofu-maru	CTD	S. Kawae (NMO-JMA)
130	XK200410		Oct. 10 - Oct. 22	Kaiyo	CTD/XCTD	H. Ichikawa (IORGC-JAMSTEC)
131	KF200411		Nov. 1 - Nov. 3	Keifu-maru	CTD	M. Fujimura (KMO-JMA)
132	KF200502	2005	Feb. 21 - Feb. 25	Keifu-maru	CTD	M. Fujimura (KMO-JMA)
133	NC200505		May 3 - May 8	Chofu-maru	CTD	S. Kawae (NMO-JMA)
134	NC200507		July 29 - Aug. 1	Chofu-maru	CTD	S. Kawae (NMO-JMA)
135	XK200509		Sep. 12 - Sep. 16	Kaiyo	CTD/XCTD**	H. Ichikawa (IORGC-JAMSTEC)
136	TN200509		Sep. 19 - Sep. 22	Tansei-maru	CTD/XCTD**	K. Ichikawa (RIAM-Kyushu Univ.)
137	NC200510		Oct. 30 - Nov. 2	Chofu-maru	CTD	S. Kawae (NMO-JMA)
138	KF200511		Nov. 2 - Nov. 8	Keifu-maru	CTD	M. Fujimura (KMO-JMA)
139	XK200511		Nov. 20 - Nov. 24	Kaiyo	CTD/XCTD**	H. Ichikawa (IORGC-JAMSTEC)
140	KF200602	2006	Feb. 21 - Feb. 27	Keifu-maru	CTD	C. Nagai (KMO-JMA)
141	NC200605		May 15 - May 21	Chofu-maru	CTD	S. Kawae (NMO-JMA)
142	NC200608		Aug. 4 - Aug. 10	Chofu-maru	CTD	S. Kawae (NMO-JMA)
143	TN200609		Sep. 19 - Sep. 22	Tansei-maru	CTD/XCTD**	K. Ichikawa (RIAM-Kyushu Univ.)
144	XK200609		Sep. 20 - Sep. 21	Kaiyo	CTD/XCTD/XBT**	H. Ichikawa (IORGC-JAMSTEC)
145	KF200610		Oct. 14 - Oct. 19	Keifu-maru	CTD	C. Nagai (KMO-JMA)
146	NC200610		Oct. 18 - Oct. 20	Chofu-maru	CTD	S. Kawae (NMO-JMA)
147	NC200702	2007	Feb. 9 - Feb. 12	Chofu-maru	CTD	S. Kawae (NMO-JMA)
148	KF200702		Feb. 19 - Feb. 23	Keifu-maru	CTD	C. Nagai (KMO-JMA)
149	NC200705		May 7 - May 13	Chofu-maru	CTD	S. Kawae (NMO-JMA)
150	KF200707		July 25 - July 28	Keifu-maru	CTD	T. Shiga (KMO-JMA)
151	NC200710		Oct. 15 - Oct. 17	Chofu-maru	CTD	S. Kawae (NMO-JMA)
152	RF200710		Oct. 20 - Oct. 23	Ryofu-maru	CTD	S. Minato (GEMD-JMA)
153	NC200802	2008	Feb. 8 - Feb. 11	Chofu-maru	CTD	S. Kawae (NMO-JMA)
154	KF200803		Mar. 6 - Mar. 8	Keifu-maru	CTD	T. Shiga (KMO-JMA)
155	NC200805		May 26 - May 30	Chofu-maru	CTD	J. Nakagawa (NMO-JMA)

** Data is not yet processed

SH199602, the hydrographic survey was carried out in cooperation with cruise KF199602 and the hydrographic section was occupied about 20 km east of the ASUKA line. A part of the hydrographic station for the cruise TN199912 was close to the coastal site of the PIES mooring location[15].

3. Data Processing

A method of data processing for the ASUKA Hydrographic Data Collection was described in the previous paper[24] and repeatedly mentioned below with additional information.

The CTD data were reported at 1- or 2-dbar intervals and the data reported at 2-dbar intervals were linearly interpolated at 1-dbar intervals. More than half of the CTD profiles were obtained by using SBE9*plus* or SBE25 CTD system (57%; Sea-Bird Electronics Inc., Washington, USA), and the rest of the profiles were obtained by using Neil Brown Mark III or IIIB (41%; Neil Brown Instrument Systems Inc., Massachusetts, USA) and other CTD systems [2%; ICTD (Falmouth Scientific Inc., Massachusetts, USA) and AST5016-DK (Alec Electronics Co. Ltd., Kobe Japan)].

The XCTD, XBT and DBT data were carefully processed to 1-dbar intervals as follows.

Raw data from the XBT (20 samples s^{-1}) and the latest fall-rate equations for the T-7 and T-6 probes[25], and T-5 probe[26] were used to infer depth. Although another fall-rate equation was proposed for Sparton XBT-7 probe[27] (Sparton of Canada Ltd., Ontario, Canada), the specification is the same as that for Sippican (Sippican Inc., Massachusetts, USA) or TSK (Tsurumi-Seiki Co. Ltd., Kanagawa, Japan) T-7 probe and the fall-rate equation for Sippican or TSK T-7 probe[25] is applicable to Sparton XBT-7 probe[28]. Pressure (p in dbar) was estimated from the inferred

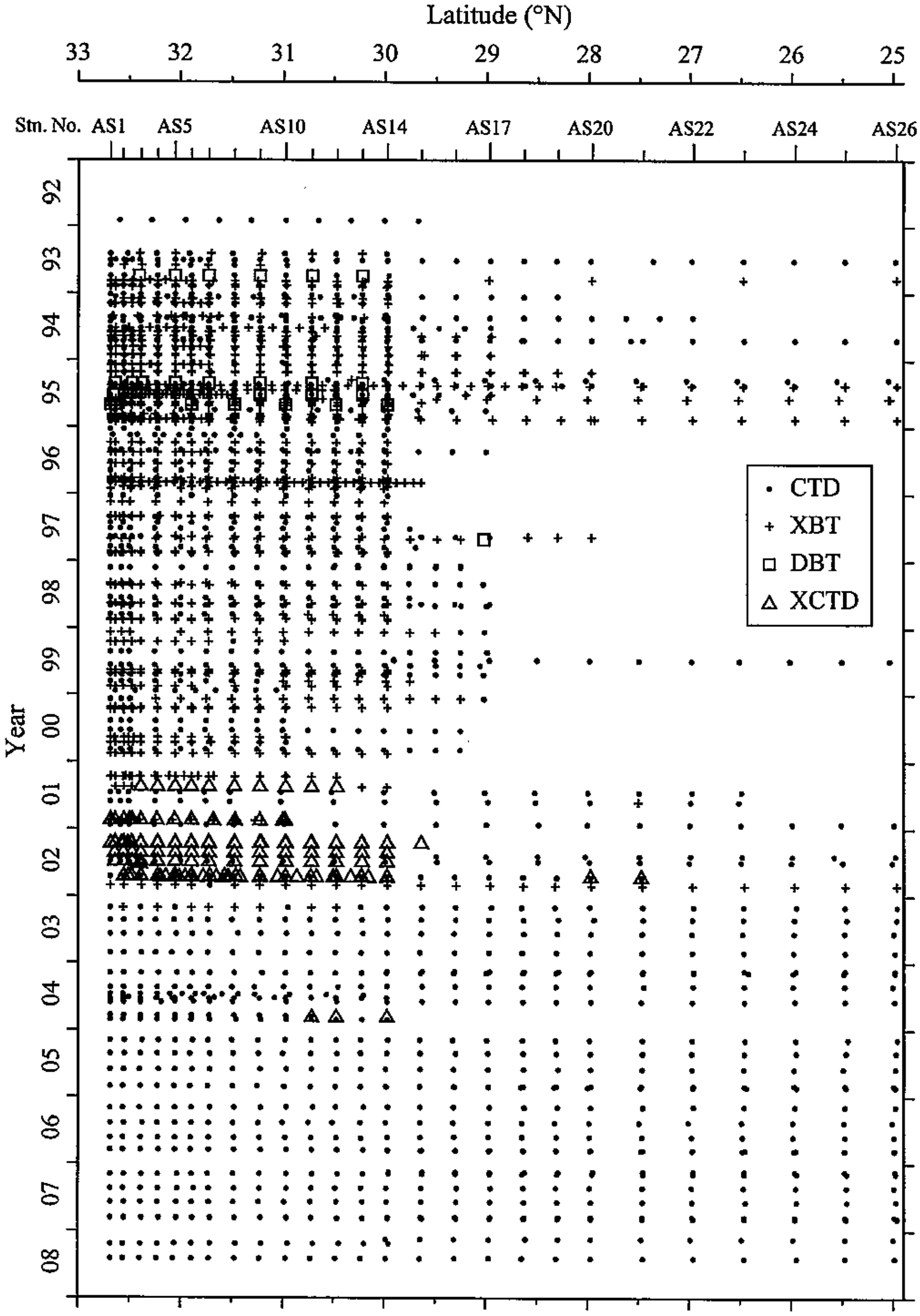

Fig. 2 Hydrographic data distribution along the ASUKA line.

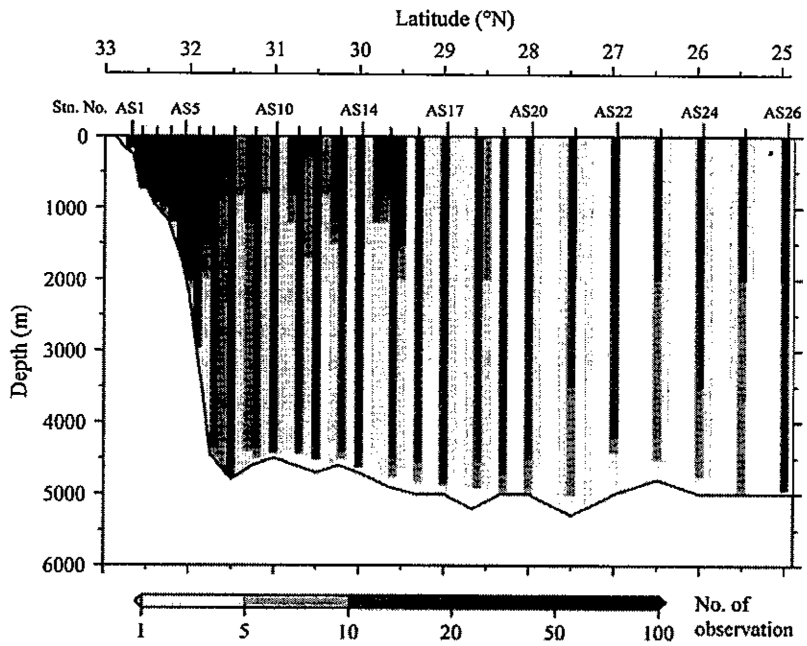

Fig. 3 Section of frequency distribution of the hydrographic data.

depth (z in m) by using the simplified equation[25], $p = z/0.993$. The first eight scans (about 3 dbar) of the XBT data were deleted, and then the data were low-pass-filtered using a median filter with a window of five scans (about 1.3 m). Then, the data were sampled at 1-dbar intervals. About half (52%) of the XBT profiles were obtained by using Sparton XBT-7 probe and the rest of the profiles were obtained by using TSK T-7 (41%), T-6 (4%), and T-5 (3%) probes. To calculate density from the XBT data, it was necessary to determine salinity profiles, because only temperature profiles were obtained from the XBT measurements. Salinity profiles for the XBT measurements were estimated by using mean temperature–salinity relations described in Section 4.

The DBT profiles were obtained by using Micom-BT Type-2 (Tsurumi-Seiki Co. Ltd.). Pressure was calculated from the DBT data, which were reported at 1-m intervals, by using the same method as for the XBT data, since the same conversion equation from measured pressure to depth was used in the DBT system. Then the DBT data were sampled at 1-dbar intervals. Salinity profiles were estimated by using the same method as for the XBT data, because only temperature profiles were obtained from the DBT measurements.

Raw temperature and conductivity data from the first nine scans of the XCTD data were deleted, and then the remaining data were low-pass-filtered by using a boxcar filter with a window of 15 scans (about 2 m). The conductivity data were advanced by two scans (about 0.3 m) relative to the temperature data to correct for a mismatch in the response times of the sensors. Pressure was estimated from depth and location (latitude) by calculating backward using a pressure-to-depth conversion equation[29], and salinity was calculated from the pressure, temperature, and conductivity data by using the reference conductivity of 4.2896 S m^{-1} at a salinity of 35, a temperature of 15°C, and a pressure of 0 dbar. Then, the data were sampled at 1-dbar intervals. Biases of the salinity profiles were estimated by using the tight relationships between temperature and salinity at temperatures of 14.1 and 2.5°C (Section 4), and the estimated biases were then subtracted from the salinity profiles. A mean salinity of 34.542 for a temperature of 14.1°C and of 34.535 for a temperature of 2.5°C were used regardless of time and location. Most of the XCTD profiles were obtained by using TSK XCTD-1 probe (94%), and the rest of the profiles were obtained by using TSK XCTD-2 probe (6%).

Salinity profiles for the CTD measurements from cruises SH199307, HK199402 and KE199808 (1 profile) were estimated by using the same method as for the XBT data because of low quality of the reported salinity data. Relatively large biases of the reported salinity profiles for the CTD measurements from cruises BO199410, TN199912 and TN200407 were estimated by using the temperature–salinity relations obtained from the CTD measurements from the cruise before and/or after, and the estimated biases were then

Table 2 Quality flag definitions for the hydrographic data.

Flag value	Definition
1	Not calibrated or unknown.
2	Acceptable measurement.
3	Questionable measurement.
4	Bad measurement.
5	Bias corrected.
6	Interpolated over > 2 dbar interval.
7	Filled with the shallowest value or salinity estimated.
8	Low-pass-filtered.
9	Not sampled.

subtracted from the salinity profiles. Temperature and salinity profiles for the CTD measurements from cruise SH199605 were low-pass-filtered by using a boxcar filter with a window of 11 or 3 dbar in order to remove noise seen in the reported profiles.

Quality flags were set for all the hydrographic data according to the flag definitions for the WHP CTD data[30] with modifications (Table 2). Each hydrographic data has temperature and salinity profiles and some CTD data have dissolved oxygen profiles. Temperature and salinity profiles near the sea surface where the hydrographic measurements could not be made were filled with the shallowest values.

4. Temperature–Salinity Relations

To calculate density from the XBT and DBT measurements, it was necessary to estimate the vertical salinity profiles, because the XBT and DBT measurements provide only vertical temperature profiles. In the Kuroshio region south of Japan, the temperature–salinity relation differs by region: the coastal cold water region north of the Kuroshio axis, the offshore warm water region south of the Kuroshio axis, and the transitional region in between[31]. Mean temperature–salinity relations were similarly calculated by region, and salinity profiles were estimated from the XBT and DBT measurements by using the corresponding mean temperature–salinity relations and XBT and DBT temperature profiles. Along the ASUKA line, the temperature–salinity relation differed by region as follows: (1) the coastal cold water region north of the Kuroshio axis, (2) the region with the local stationary anticyclonic warm eddy[32] south of the Kuroshio axis, and (3) the region south of the warm eddy (Fig. 4). Transition regions between these were not taken into account. Region 1 was defined as north of 32.3°N or the region where the temperature at 400 dbar was colder than 10.5°C; region 3 was defined as south of 27.8°N; and region 2 was defined as the region between regions 1 and 3.

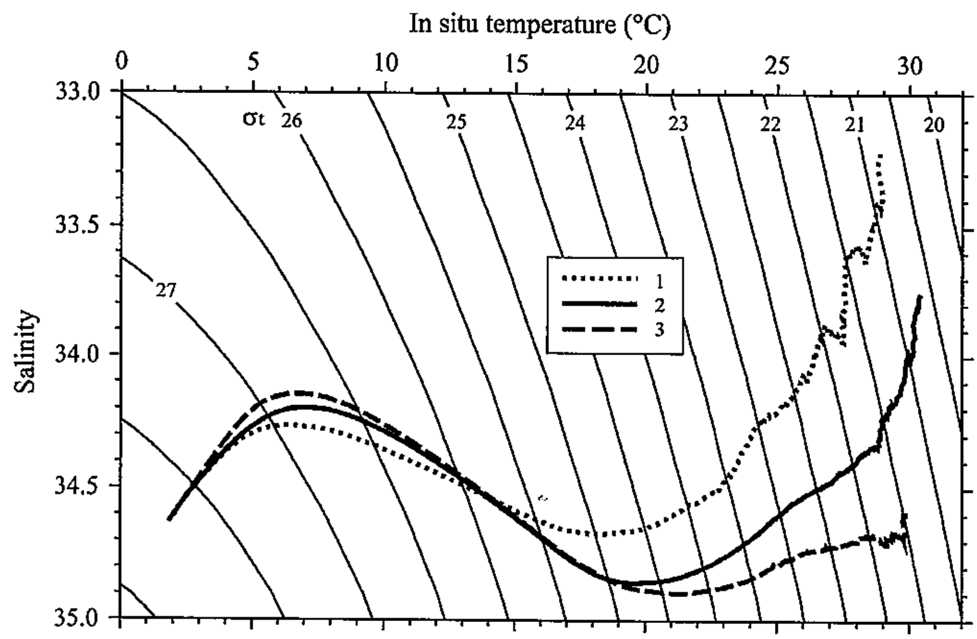

Fig. 4 Mean temperature–salinity relationships calculated from CTD data obtained during November 1992 to February 2007 in the coastal water region north of the Kuroshio axis (1: dotted line), in the region of the stationary local anticyclonic warm eddy south of the Kuroshio axis (2: solid line), and in the region south of the warm eddy (3: broken line). Contour lines indicate the density anomaly (kg m^{-3}) calculated by ignoring compressibility.

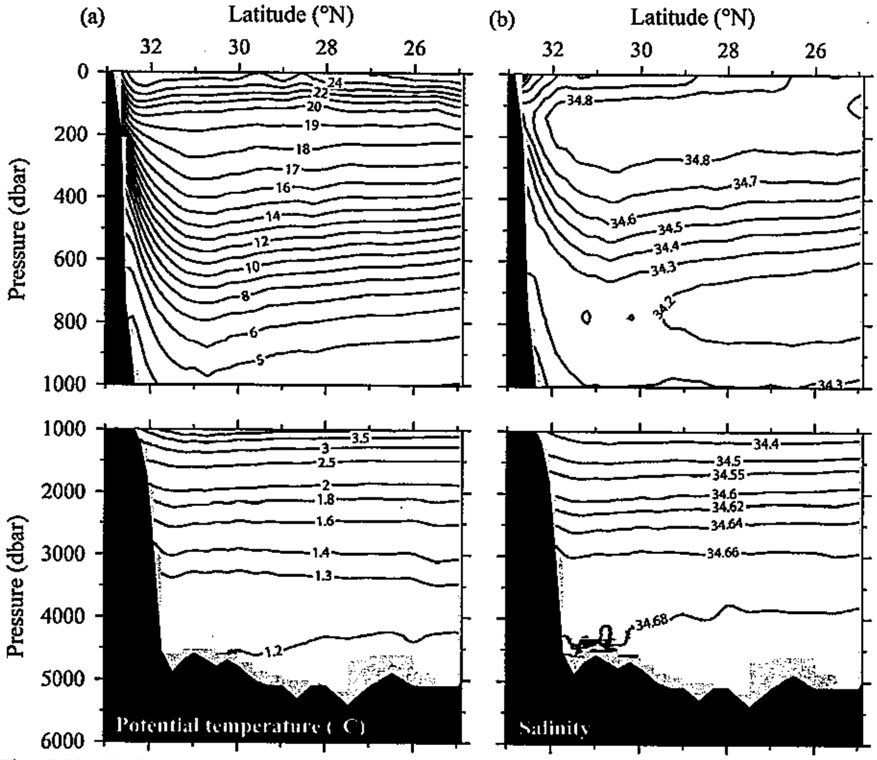

Fig. 5 Vertical sections of the temporal mean potential temperature (a) and salinity (b).

5. Discussion

Temporal mean temperature and salinity profiles at standard stations were calculated from the hydrographic data (Fig. 5). Estimated salinity profiles for the XBT and DBT measurements were not used for the calculation of mean salinity profiles. Temporal mean volume transport of the Kuroshio and its recirculation was estimated from geostrophic velocities relative to 1800 dbar or bottom whichever is shallower calculated from the mean temperature and salinity profiles (Fig. 6). The geostrophic velocities were integrated from the sea surface to 1800 dbar. The reference level of 1800 dbar was selected because vertical profiles of the Kuroshio transport per unit depth normalized by the sea surface transport, calculated from the absolute velocity field[7], showed nearly zero at that level[33]. The Kuroshio flowed east-northeastward with a transport of 56 Sv (1 Sv = 10^6 m^3 s^{-1}) for north of 30.7°N on average. A part of the Kuroshio flow re-circulated (13 Sv) just south of the Kuroshio for north of 29°N corresponding to the local stationary anticyclonic warm eddy[32], and relatively slow recirculation was seen south of the warm eddy.

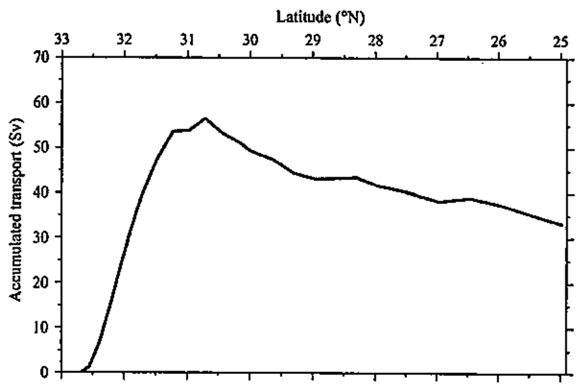

Fig. 6 Horizontal profile of volume transport accumulated from the coast. Geostrophic velocities relative to 1800 dbar or bottom whichever is shallower were integrated for depths upper than 1800 dbar.

The North Pacific Intermediate Water (NPIW), marked by a salinity minimum around 26.8 potential density anomaly (σ_θ; see Fig. 4), varies with interannual and decadal time scales[34]. In the region 2, salinity change of the NPIW was relatively large[24] and a remarkable freshening (about 0.04) of the salinity minimum was found in recent years (2006–2008). Changes in the water properties should be monitored for more detailed discussions.

Appendix

The following are abbreviations for the data source in Table 1, except for Graduate School of Oceanography, University of Rhode Island. Universities and agencies to which members of the ASUKA Group belonged at the hydrographic surveys are expressed with asterisks.

NNFRIK-FA: Nansei National Fisheries Research Institute, Kochi, Fisheries Agency*
NRIFS-FA: National Research Institute of Fisheries Science, Fisheries Agency*
NRIFS-FRA: National Research Institute of Fisheries Science, Fisheries Research Agency*
IORGC-JAMSTEC: Institute of Observational Research for Global Change, Japan Agency for Marine-Earth Science and Technology*
OORD-JAMSTEC: Ocean Observation and Research Department, Japan Marine Science and Technology Center*
CMD-JMA: Climate and Marine Department, Japan Meteorological Agency
GEMD-JMA: Global Environment and Marine Department, Japan Meteorological Agency
KMO-JMA: Kobe Marine Observatory, Japan Meteorological Agency*
MD-JMA: Marine Department, Japan Meteorological Agency
NMO-JMA: Nagasaki Marine Observatory, Japan Meteorological Agency
HD-MSA: Hydrographic Department, Maritime Safety Agency*
FE-Hiroshima Univ.: Faculties of Engineering, Hiroshima University*
FF-Kagoshima Univ.: Faculties of Fisheries, Kagoshima University*
RIAM-Kyushu Univ.: Research Institute for Applied Mechanics, Kyushu University*
FB-Mie Univ.: Faculties of Bioresources, Mie University*
SMST-Tokai Univ.: School of Marine Science and Technology, Tokai University*
SIO-Univ. of California: Scripps Institution of Oceanography, University of California San Diego, U.S.A.
GSO-Univ. of Rhode Island: Graduate School of Oceanography, University of Rhode Island, U.S.A.*
ORI-Univ. of Tokyo: Ocean Research Institute, University of Tokyo*

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