ISBN 0-9698420-2-3
ISSN 1198-273X

PICES SCIENTIFIC REPORT No. 2 1995

The Okhotsk Sea and Oyashio Region

NORTH PACIFIC MARINE SCIENCE ORGANIZATION

PICES

PICES Scientific Report No. 2
1995

THE OKHOTSK SEA AND OYASHIO REGION
(Report of Working Group 1)

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April 1995
Secretariat / Publisher
North Pacific Marine Science Organization (PICES)
c/o Institute of Ocean Sciences, P.O. Box 6000, Sidney, B.C., Canada. V8L 4B2

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FOREWORD

This is a final report (1993) of PICES Working Group 1. The objective of the report was to present a review of the importance of the Okhotsk Sea and Oyashio Region on the ventilation of the North Pacific Ocean, such as the formation of the North Pacific intermediate water.

This report was written through the efforts of the Working Group 1 members. The Chairman would like to thank all members and others (see Appendix A) for their efforts in developing a good report that provides the Physical Oceanography and Climate Committee (POC) with a comprehensive review of the oceanography of the region. I would particularly like to thank Prof. Yutaka Nagata (as co-editor), for his diligent efforts in helping me put together the report.

Lynne D. Talley
Chairman

Part 1. GENERAL INTRODUCTION AND RECOMMENDATIONS

The northwestern North Pacific is the site of the densest ventilation of the North Pacific Ocean. Ventilation of the oceans is the primary means by which the ocean transports heat, fresh water and surface properties such as dissolved carbon dioxide into the interior of the ocean where it is then carried far from its source. The North Pacific is the one ocean basin in which very deep ventilation does not occur; its deep waters originate in the northern North Atlantic and around Antarctica and are very old relative to the deep waters of other oceans. However, the North Pacific is ventilated to a depth of 1,000 to 2,000 m, mainly as a result of dense shelf water formation in the northern Okhotsk Sea. Deeper and denser ventilation occurs in the Sea of Japan, but this marginal sea is nearly completely isolated from the North Pacific, so its ventilation does not have a great effect on the North Pacific. The ventilated water from the Okhotsk Sea flows out into the North Pacific; while much remains in the subarctic North Pacific, a portion flows southward into the subtropical region, where the top of this water is characterized by a salinity minimum. Thus the northwestern North Pacific is connected to a much larger scale ocean circulation.

About two-thirds of the Okhotsk Sea is covered with sea ice in winter: ice formation in the Okhotsk Sea is at a very low latitude for the world ocean. Ice formation in the northwest shelf region results in deep ventilation and dense water production. The dense water is believed to be important in formation of the North Pacific Intermediate Water and is the only mechanism for ventilation of the North Pacific for a considerable density range.

The northern North Pacific is also a region of great biological abundance. Fisheries in the Bering Sea, Oyashio region and the Okhotsk Sea are among the most productive in the world. The biomass of the Okhotsk Sea rivals that of the Bering Sea. The "Oyashio" takes its name from its high productivity: parents (oya) current (shio) in Japanese. The Oyashio waters originate in the Okhotsk Sea and East Kamchatka Current, which is also the source of water for the Okhotsk Sea. However, the high oxygen and nutrient content of Oyashio and Okhotsk Water is not apparent in the East Kamchatka Current whose water is strongly modified in the Okhotsk Sea before it returns to the Oyashio.

In this report, we confine our attention to the physical oceanographic aspects of the Okhotsk Sea and Oyashio area. The biological and chemical aspects of the region should be discussed at some point, but will not be reviewed by this PICES Working Group.

Since two countries border the Okhotsk Sea and several other countries are also involved in observations, data availability is a central issue for this important region of the North Pacific. We devote a section to physical oceanographic observations including as much information as we could gather on what data have been collected, and what should be available and from whom. A very large amount of work remains to be done to bring all of the unclassified data to a stage where it is of the greatest use.

Because of the new political conditions which have made at least a certain level of international work in the Okhotsk Sea feasible and because of the importance of this region to fisheries and climate, a section on recommended observational programs is included.

A major deficiency in this report and the discussion of this working group is extensive input from Russian scientists, including a comprehensive bibliography and general acquaintance with their large amount of knowledge on the Okhotsk Sea and Kuril region. Therefore we recommend that PICES sponsor an international meeting in Vladivostok so that Russian scientists engaged in work in this region may have a chance to communicate their knowledge and so that communication and planning for projects which require international cooperation and/or support may be facilitated.

Principal recommendations of Working Group 1 are:

(a) PICES should encourage organization of a meeting on the Okhotsk Sea and Kuril region in Vladivostok sometime in the near future, with discussions of physical oceanography, fisheries and data exchange. Continued communication between scientists interested in this region is vital for the success of the types of projects recommended below.

(b) Data exchange and archiving:
- Full efforts should be made to facilitate incorporation of unclassified Russian hydrographic, sea level and sea ice measurements into the appropriate international databases, and to identify datasets which are not archived in WDCB which should be part of the international archive.
- Efforts should be made to ensure that all special (non-routine) Japanese hydrographic and current (ADCP and current meter) data sets in the Okhotsk Sea are archived in the appropriate international databases.
- CTD data collected in the Okhotsk Sea, Kuril region and along major routine network lines in the Mixed Water Region should be archived in high density form (1-2 decibars or meters) as well as at standard depths.

(c) International cooperation should be sought for observations relating to ventilation of the North Pacific and the exchange of Okhotsk Sea waters with the North Pacific. The greatest deficiencies are in quantitative estimates of all processes: rates, transports, variability and budgets. Recommended projects and studies for the Okhotsk Sea are:
- sea ice formation, dense shelf water formation in the northwestern Okhotsk Sea, and the polynya over Kashevarov Bank.
- Kuril straits exchanges and mixing.
- Soya Current volume, fresh water and heat transports; how the Soya Current leaves the shelf.
- influence of mesoscale eddies in the southern Okhotsk Sea on water struc-ture and dynamics, including mixing of saline Soya Current water.

(d) Recommended projects and studies for water mass transformation in the Oyashio region are:
- Oyashio transport monitoring.
- transformation of waters in the Oyashio/ East Kamchatka Current region, including the role of large anticyclonic eddies in NPIW formation, water exchange and branching of the Oyashio current.
- NPIW formation in the Mixed Water Region, including investigation of the role of Kuroshio warm core rings in NPIW formation, water exchange and branching of the Oyashio.

(e) International cooperation should be sought for the following logistical items which are deemed of great importance to the success of physical oceanographic work in the Okhotsk Sea and Kuril region:
- linkage of Japanese and Russian geodetic networks (tide gauge leveling).
- permission be sought and precedents set to allow Russian research vessels to enter Japanese ports and vice versa, to avoid excessive deadheads when working in the Okhotsk Sea.
- exchange of SST and sea ice observations and for technical improvements for Russian data collection and staff training.

1.0 RECOMMENDATIONS FOR INTERNATIONAL COOPERATION IN THE OKHOTSK SEA AND KURIL REGION

The two areas of suggested cooperation for physical oceanography are in observations and data exchange. Section 2 below describes the data which are available, as best we can determine, and the current state of progress in archiving them.

The greatest lack of information is in quantitative estimates of transformation rates, transports, time scales, and budgets of heat and salt. Observational programs of the greatest importance, because they are central to understanding water mass transformation, and for which there is a lack of enough information to make quantitative estimates at present, are:

(a) water mass modification in the Okhotsk Sea including formation of the intermediate water mass
(b) exchange of Okhotsk Water with the Oyashio/East Kamchatka Current, including transports through the Kuril Island straits, the role of large eddies in mixing the waters along the Kurils, and the formation of NPIW in the Mixed Water Region where Oyashio Water meets Kuroshio Water
(c) improvement in sea ice analysis and forecasting.

1.1 Okhotsk Sea water mass modification

As described in Moroshkin (1962) and reviewed in Section 2.3 below, the Okhotsk Sea Water is considerably different from the East Kamchatka Water which is its source. The dichothermal layer (temperature minimum) of the Okhotsk Sea is deeper and colder, high levels of oxygen are found at depth, and the intermediate waters are considerably fresher and colder at the same density. These taken together imply that the Okhotsk Sea is a major region of ventilation for the intermediate depth layer in the North Pacific (Moroshkin, 1962; Reid, 1965; Kitani, 1973; Wakatsuchi and Martin, 1990; Talley, 1991). Important factors in understanding this modification are dense shelf water formation in the northern Okhotsk Sea, the inflow and fate of saline Soya Current water, dilution from the Amur River outflow, mixing in the Kuril Island straits, and transport into the Okhotsk Sea through the deeper Kuril Island straits. Overall salinity and heat balances for the Okhotsk Sea are an important part of this study.

1.1.1 Dense shelf water formation in the northwestern Okhotsk Sea

In the northwestern Okhotsk Sea, there are shallow shelves and the shallow Kashevarov Bank. It has been demonstrated that sea ice formation in winter produces dense bottom water in this region (Kitani, 1973; Alfultis and Martin, 1987). This dense water is an important source of the intermediate water mass of the Okhotsk Sea (Moroshkin, 1962; Kitani, 1973). Since this intermediate water mass is the primary source of surface properties for the intermediate layer of the North Pacific, it is important to study its formation, production rate, properties and variability.

The polynya which is located over Kashevarov Bank in winter (Kovshov and Sinyurin, 1982) is a site of intense heat loss which may lead to dense water formation (Alfultis and Martin, 1987). The polynya is due to strong upwelling and vertical mixing, which may be related to large tidal amplitudes. The very limited hydrographic observations, all from summer, have not shown dense bottom water, rather greatly enhanced vertical mixing, but the surface heat flux through the wintertime polynya is very large and dense water production is suggested. A special project to study this polynya should be undertaken from a ship with ice-breaking capability during January-March. A detailed CTD/tracer survey and moored measurements under the ice, including currents, temperature and salinity is recommended. Deployment of newly-developed moored instruments which measure sea ice thickness and concentration, drifters deployed in and below the ice, and continuing AVHRR and SSM/I satellite-based studies are recommended.

Very limited data from the northwestern shelf of the Okhotsk Sea, close to the Kashevarov Bank, revealed saline bottom water on the shelf at a density of 27.05 σ_θ (Kitani, 1973). Based on property scatter, Talley (1991) suggested that shelf water production could be even higher, perhaps to 27.2 σ_θ. Measuring the properties and production rate in winter could be carried out by deploying a number of moorings on the shelf and slope, in the downstream direction from the formation region, by using current meters and temperature and conductivity recorders, in high concentration near the bottom. In addition, a CTD/tracer survey should be carried out during deployment and recovery. If done in conjunction with the Kashevarov polynya study, an icebreaker could look at properties in winter. Tracers should include CFC's and delta O^{18}. AVHRR and SSM/I measurements and information from JMA and Russian SST and sea ice bulletins to provide surface boundary conditions. An attempt at calculating surface heat flux, ice growth rates and brine rejection rates should be undertaken.

Good quality standard meteorological observations are also required. The first step should be to check and calibrate the Russian instruments at the permanent sites around the Okhotsk Sea. A tower might be constructed to collect meteorological data on one of the uninhabited islands which are located in the northwestern Okhotsk Sea close to the region of interest.

1.1.2 Soya Current study

The Soya Warm Current is important in the overall salinity balance of the Okhotsk Sea. Its relatively saline waters originate far to the south in the Tsushima Current and it is suspected that it is its high salinity which sets the maximum density of ventilation in the Okhotsk Sea. The reason for the difference in density of ventilation between the Okhotsk Sea and Bering Sea, which lies at a much higher latitude, might well be the saline waters of the Soya Current. Not all of the inflow from the Sea of Japan is saline however; there is also very cold and fresher water which originates near Tartar Strait (west of Sakhalin and north of Soya Strait) in the northern portion of Soya Strait. There are two issues regarding the Soya Current: its transports and how its waters leave the shelf.

To obtain the volume transport of the Soya Warm Current, direct current measurements in the strait on both the Russian and Japanese sides are desirable. However, it is unlikely that such measurements can be carried out in the near future. Therefore, to estimate the volume transport of the Soya Warm Current, the relationship between the sea level difference between Wakkanai (Hokkaido) and Korsakov (Sakhalin) and current velocities in the southern part of Soya Strait can be investigated. The two tidal stations will need to be leveled. Currents in Soya Strait could be measured by ADCP from a ferry between Wakkanai and Korsakov if regular service resumes. There is probably an old undersea telephone cable between Hokkaido and Sakhalin which can be used to monitor transport. Properties of the Soya Warm Current Water will continue to be monitored along the standard seven lines north of Hokkaido.

1.1.3 East Sakhalin Current and anticyclonic Kuril Basin flow

The East Sakhalin Current appears to be strong in winter based on pack-ice drift and very weak in summer, based on dynamic topography. Data sufficient for calculating transports of the current are somewhat limited. Deep flow southward along Sakhalin is the main route for dense water flowing southward from the northwestern shelf region and it can be traced by the presence of high oxygen (Wakatsuchi and Martin, 1990; Talley, 1991). Almost nothing is known quantitatively about the transport and seasonal variability of this flow. Tidal variability in this region may be large. Upwelling eddies along the coast have also been observed (Sapozhnikov, personal communication). Ana-lysis of existing data, followed by good CTD transects with tracers perpendicular to the coast of Sakhalin are suggested.

The Kuril Basin includes a large number of anticyclonic eddies of 50-150 km scale based on satellite imagery of sea ice and SST data (Kuzmina and Sklyarov, 1984; Hatakeyama et al., 1985; Wakatsuchi and Martin, 1990; Mitnik and Kalmykov, 1992), and the Basin may also have some permanent anticyclonic circulation (Wakatsuchi and Martin, 1990; various Kawasaki et al. depictions in Section 5.3.2). The eddies or circulation are the vehicle for mixing saline Soya Current water into the Okhotsk Sea, and the northern side of an anticyclonic gyre is the route by which newer water from the East Sakhalin Current flows towards Bussol' Strait. Additional analysis of satellite images, pack-ice drift, historical data, and extension of the present JFA surveys of the Kuril Islands farther into the Kuril Basin is suggested.

1.1.4 West Kamchatka Current

The West Kamchatka Current is assumed to be the region of primary northward flow into the Okhotsk Sea from Kruzenshtern Strait. Although the region is apparently fairly well sampled by hydrographic observations (Figs. 1.1.1, 1.1.2, 1.1.3), there appear to be no good syntheses of the observations. Not much has been published regarding the transport or variability of the West Kamchatka Current. It might be that the northward flow is intermittent, offshore of the Kamchatka coast, or severely dominated by tides. A primary question regarding the water mass structure of the West Kamchatka region is how far the Pacific water entering at Kruzenshtern Strait extends into the Okhotsk Sea and where the main modification of this water occurs. It is suggested that an analysis of the historical data in collaboration with Russian scientists be done.

1.1.5 Tides and sea level in the Okhotsk Sea

Tidal amplitudes and currents are very large in some parts of the Okhotsk Sea, due to the relatively weak vertical stability, and severe tidal mixing takes place in passages and straits, over shelf breaks and over banks. Tidal currents are up to 5 knots in some of the straits. As reviewed below, tidal mixing is an important part of the overall water mass modification in the Okhotsk Sea and any study of exchange and mixing through the Kuril straits must include study of tidal processes. Also, it has been suggested by Russian scientists that the internal tide is sufficiently large to overwhelm the baroclinic shear signature of geostrophic currents in regions such as the East Sakhalin Current and West Kamchatka Current as well as in the Kuril straits, so it might be necessary to consider the tides when estimating geostrophic currents within the Okhotsk Sea. Present knowledge of the circulation has been deduced primarily from water mass analysis rather than geostrophic calculations.

There are several tidal stations around the Okhotsk Sea: three along Hokkaido, at least one on Sakhalin, several along the Siberian coast, one on the west coast of Kamchatka, and some in the Kuril Islands. Diurnal components of the tide are important in the Okhotsk Sea. Recent Japanese moored current meter observations in the central Okhotsk Sea suggest that inertial components are significant. With the various sea level stations around the periphery, it should be possible to make tidal corrections accurately with a relatively simple numerical model. However, in the Kuril straits where tidal mixing is an important process, a special tidal observation program matched with water mass analysis should be designed.

An additional important potential use of sea level measurements is to estimate geostrophic current transports across straits such as Soya Strait, important Kuril Straits (Bussol' and Kruzenshtern Straits in particular), and Kamchatka Strait (east of Kamchatka). In order to do this, the sea level stations need to be leveled periodically. In particular the stations across Soya Strait should be leveled relative to each other. Japanese stations are leveled relative to Tokyo every few years; it is not known to us how often the Russian stations are leveled.

1.2 Influence of Okhotsk Sea waters on the subarctic Pacific and Oyashio

The waters that flow out of the Okhotsk Sea are fresher and more oxygenated than those which flow in. The Okhotsk Sea Water is mixed with East Kamchatka Current Water which does not flow into the Okhotsk Sea. Tidal mixing along the Kuril Islands results in a mixed water which may be the principal type of water which flows out of the Okhotsk Sea. The resulting Oyashio water may also contain recognizably different components of Okhotsk Sea and subarctic waters. The Oyashio flows southwestward past Hokkaido and into the Mixed Water Region where it meanders and its water mass front turns northeastward. Some Oyashio water intrudes southward in the Mixed Water Region where it interacts with Kuroshio Water to form NPIW. An important aspect of the mixing of Okhotsk Sea and subarctic waters throughout this region is the large warm core rings which are spawned by the Kuroshio, move slowly northeastward following the deep trench, and may be found far north along the Kurils (Section 2.5). Mixing within the Kuril Island straits may also be important in modifying Okhotsk Sea Water prior to exchange with the North Pacific.

1.2.1 Kuril Island strait transports (Bussol', Kruzenshtern and shallower straits)

Connection between the Okhotsk Sea and the North Pacific takes place through a number of different straits. The most important are Bussol' and Kruzenshtern Straits. The latter is slightly shallower than Bussol' and is the northernmost deep passage through the Kuril Islands. It is believed that most flow into the Okhotsk Sea occurs through this strait. Bussol' Strait is located in the central Kuril Islands and is the deepest passage. It is the main location of flow out of the Okhotsk Sea although it is believed that there is also some inflow there particularly of the deepest waters. Outward flow of the shallowest waters may also occur through the southernmost Kuril passages. Clear priorities for new observational programs are Bussol' Strait, Kruzenshtern Strait and Etorohu (Friza) Strait, in that order.

Within the straits, tidal flows are extremely strong (up to 5 knots) and dominate the mean flow. Vertical mixing has been demonstrated to be of great importance to the waters flowing in and out. Tidal fronts along the islands are also very strong. It is possible that the net Eulerian transport through a strait is zero whereas the Lagrangian transport water mass exchange might not be. Russian observations suggest that there is usually inflow into the Okhotsk Sea on the north side of a strait and outflow on the south side (see the Luchin reports in Appendix B). Quantifying the net Eulerian flow and the net water property exchange will require a mix of coastal and large-scale oceanographic observations.

Russian scientists have conducted surveys of the passage periodically since 1948 (e.g., Bogdanov, 1968). Between 1948 and 1953, seven surveys of the passages were carried out on R/V Vityaz. Recent POI programs consisted of closely spaced CTD stations across the strait (2-5 nm), repeated CTD profiles (every half hour for about 36 hours) to account for the tides, and sea level measurements at a coastal area close to the strait (Gladyshev, 1993). Direct current measurements of several days duration have been made several times within these years, but maintenance of surface moorings and interpretation of the measurements is difficult because of the very swift currents.

Future work in Kuril passages must rely heavily on cooperation with Russian scientists. The first priority is to encourage publication of scientific papers analyzing existing data. A suitable framework for collaborative field observations must be found and pilot observations made. This type of observational program is a mix of coastal and large-scale oceanography. Measurements of the straits' transports would consist of:

(1) repeated sections across the strait by ship-borne ADCP with closely-spaced CTD casts, to estimate the Eulerian through-flow transport,
(2) use of surface and subsurface floats to estimate the Lagrangian transport,
(3) tracer measurements,
(4) use of any existing cables to monitor through-flow transport,
(5) repeated transects along the axis of flow by ship-borne ADCP with CTD casts, to analyze Lagrangian transport and tidal exchange,
(6) moored arrays of pressure gauges, inverted Doppler profilers and current meters,
(7) monitoring of tidal fronts by satellite observations, and
(8) assessment of strait transport driven by differences in atmospheric pressure.

1.2.2 Kuril region currents: the East Kamchatka Current, the Oyashio and large eddies

The structure of the Oyashio is strongly influenced by the mesoscale eddies found east of the Kuril Islands. These rings, with a diameter of 150 - 200 km, provide an effective offshore transport and branching of the Oyashio. They also control northward advection of warm water by streamers along the eddy chain. Eddies in the southern region have warm, saline cores and that they originate as Kuroshio warm core rings. In contrast, the eddies in the northern area have cold, fresh cores and their origin is not clear, although it is thought that winter convection, entrainment of fresher East Kamchatka Current and Okhotsk Sea water, and deepening at the eddy center may result in a transformation of the anticyclonic Kuroshio ring's warm core into the anticyclonic Kuril cold core ring.

Special investigation of the Kuril eddies with international collaboration may be proposed. Three key problems to study are:

(1) climatological study of the rings (statistical parameters of their distribution and movement, size, number etc.),
(2) kinematics and dynamics of the eddies,
(3) transformation of the physical structure of the eddies in the central Kuril area.

The first study would employ historical data (satellite IR images, hydrographic data, temperature maps), based on cooperation and data exchange between Russia and Japan. The second project requires a large number of satellite-tracked drifters and could be done through international cooperation. The third requires synoptic surveys of the eddies during the period from fall to spring when surface cooling transforms the core.

1.2.3 NPIW transport and formation rate in the Mixed Water Region

The Oyashio flows southward along Hokkaido and usually forms two "intrusions" or meanders around a warm core feature which originally comes from the Kuroshio (Kawai, 1972). Part of the Oyashio waters break off and intrude even farther south into the Mixed Water Region, whose northern boundary is usually defined as the Oyashio front. The bulk of the Oyashio waters flow northeastward and back around the subarctic gyre, forming the northern boundary of the Mixed Water Region. Thus waters from the Okhotsk Sea which are modified by mixing with North Pacific waters and by local air-sea interaction come into contact with waters from the Kuroshio. The salinity minimum which characterizes NPIW is formed when the Oyashio waters intrude beneath the more saline Kuroshio waters (Hasunuma, 1978).

Many questions remain about exactly how the Oyashio and Kuroshio waters meet in the mixed water region. There are few estimates of the amount of transport of Oyashio water into the Mixed Water Region and hence into redesignation as NPIW in the subtropical gyre of the North Pacific. Knowledge of this transport is important for study of subarctic/ subtropical gyre exchange.

Direct measurements of Oyashio transport are a basic; the Oyashio may have a large barotropic component, but estimates of its transport have been based mainly on calculations relative to zero at 1,000 to 1,500 m. Continuing support for the two sets of measurements now being conducted southeast of Hokkaido is essential.

Estimates of how much Oyashio Water enters the Mixed Water Region and hence the subtropical gyre should be improved. Meridional hydrographic (preferably CTD) sections located somewhere between 150°E and 160°E (152°E or 155°E have been used before) yield basic transport estimates of NPIW eastward out of the Mixed Water Region and continuation of measurements in this region is needed. Independent estimates of NPIW formation rate rely on measuring the amount of Oyashio and Kuroshio water which enter the Mixed Water Region and understanding the role of Tsugaru Warm Water. This clearly becomes the question of where the Oyashio water preferentially meets the Kuroshio water, where mixing occurs between them, and what the mixing mechanism is. Concerted efforts to analyze the high-resolution CTD data set from the Mixed Water Region as part of routine surveys is needed, and special larger-scale synoptic programs such as recently reported by Yasuda et al. (1993 Nemuro Workshop) are required.

1.3 Sea ice analysis and forecasting

The JMA forecasts sea ice in the Okhotsk Sea based on a model which used a fixed pattern of currents. The results of their forecast are fairly impressive; improvements could be made by using better realizations of the currents and possibly mixing patterns. Russian aircraft observations could be included profitably in overall analyses of sea ice. Improvements to Russian analysis and forecasting will require technological improvements.

2.0 PHYSICAL OCEANOGRAPHIC OBSERVATIONS

Observations listed here include research vessel hydrographic observations (temperature, salinity, oxygen and nutrients), direct current observations using current meters, IES's, and drifters, sea level measurements, sea ice observations using aircraft, ships, and radar, and satellite observations. As indicated below, coverage of the Okhotsk Sea by hydrographic observations is excellent in the Soya Warm Current Region, reasonable along the Kuril Islands and the West Kamchatka Current region, and very poor in the important northern shelf region. Direct current measurements are exceedingly sparse and any improvement to this situation would be welcome. No availability or international cooperative use of Russian data in the Okhotsk Sea has been reported, although present observational programs are changing this situation very slightly.

2.1. Hydrographic observations (bottle and CTD)

Favorite et al. (1976) showed the distribution of all oceanographic stations available to him north of 30°N between 1960 and 1971. These are updated here (Fig. 1.1.1), based on the holdings of WDCA. The total WDCA holdings for the North Pacific are 339,370 bottle stations where temperature was measured. Figure 1.1.1 (a-c) outlines which data are available in WDCA north of 40°N. It is apparent from looking at station distribution in the Okhotsk Sea that the Soya Current region along the north coast of Hokkaido is sampled the best. The West Kamchatka Current region is also relatively well sampled, although there do not appear to be extensive analyses of these data in the literature (see Section 2.3). Prior to 1976 there were regular Japanese cruises to the central Okhotsk Sea. When the 200 nm EEZ was established in 1976, there were disagreements between Japan and Russia over interpretation of the zones which effectively eliminated Japanese observations in the central Okhotsk. WDCA observations in the important northern shelf regions are extremely limited.

The WDCA data set is deficient in both Japanese and especially Russian observations. No Russian observations for the Okhotsk Sea are included in this archive. Current efforts by the WDCA should vastly increase the holdings of Japanese and Russian data, with a promised increase of approximately 300,000 stations, mostly in coastal Japanese waters, and an unknown increase in Russian stations (Levitus, personal communication). WDCB in Moscow apparently contains many more Russian stations including large numbers in the Okhotsk Sea and Kuril region.

Japanese observations in the Okhotsk Sea are made regularly by the MSA along the northern Hokkaido coast in the Soya Warm Current. There are seven lines occupied 1 - 3 times per year. Examples are shown in Fig. 2.3.3. Routine data collection consisted of bottle stations prior to 1992 and only CTD observations since then. CTD standard depth values are reported relatively quickly to the JODC, and it is expected that high resolution data (1 - 2 dbar) will be collected in the future. Since 1989, a regular set of stations along the Kuril Islands has been sampled by the JFA/Hokkaido in September of each year, under a special fisheries treaty with Russia, in which data are exchanged and Russian observers participate in the cruises. Fig. 2.3.16 shows the station pattern, which is repeated each year; in 1993 the pattern was extended north to Kamchatka. Standard depth values are archived at JODC.

Routine Japanese hydrographic observations southeast and south of Hokkaido are made by the JFA, JMA and Hydrographic Department (examples in Fig. 2.3.4). Standard depth data are archived at JODC. Special measurement programs are also carried out in this region, but these data are not always archived at JODC.

Russian data are collected by the Academy of Sciences, the Committee on Hydrometeorology, the Committee on Fisheries, and the Navy Hydrographical Service. The Russian Academy of Sciences (POI and P.P. Shirshov Institute of Oceanology) conducts hydrographic, direct current, and non-standard measurements. Hydrographic data collection is not necessarily regular and data are not always archived at a national data center. Significant amounts of data were collected in the Okhotsk Sea region by the R/V Vityaz during 1949-1957, on 25 special cruises (e.g., Moroshkin, 1962, 1966). Since the mid-1970's POI has been conducting special programs in this region. The hydrographic data set amassed at POI for the Okhotsk Sea is very large and none of it is at WDCA at present; it is a subset of the data in Fig. 1.1.2.

The Russian Pacific Navy Hydrographical Service makes irregular hydrographic measurements, analyzes satellite imagery (NOAA, Meteor), and produces regular SST bulletins.

The Russian Committee on Fisheries started intensive observational programs during the 1950's through TINRO and the Sakhalin, Kamchatka and Magadan TINRO branches. These observations include local hydrographic surveys (BT's), bottle salinities since the 1970's, and CTD's since the mid-1980's. Measurements made by TINRO local branches cover coastal areas off Sakhalin, western Kamchatka, and the northern shelf of the Okhotsk Sea. Since 1988 TINRO's special programs have covered all of the Okhotsk Sea each year with a regular grid of CTD and chemical measurements. A large part of the data is archived at TINRO on magnetic disks (16,000 stations) while most data from the local branches are archived only locally.

The most regular observations along fixed sections and by standard methods have been conducted by the Committee on Hydrometeorology through FERHRI and the Sakhalin, Kolyma, Kamchatka and Primorsky Regional Hydrometeorological Administrations (RHA's). Besides shipboard hydrographic measurements, satellite imagery (NOAA IR, Meteor, Ocean), aircraft reconnaissance of sea ice and sea-surface temperature, regular SST bulletins (5 - 10 days), and standard meteorological measurements and sea level at permanent coastal stations (Fig. 1.1.2) are also collected and analyzed by the RHA's.

The large research vessels of FERHRI make regular observations of hydrography and meteorology in the North Pacific, Japan Sea and Kuroshio region. The "Sections" program from 1981-1991 made 44 surveys of the Kuroshio region, covering each season. Within the Okhotsk Sea, the Sakhalin RHA at Yuzhno-Sakhalinsk has conducted most of the regular observations. These began in the mid-1950's and continues to the present, although coverage has not been complete every year. The Sakhalin coastal area has been the most intensively covered. There are about 30 standard sections of more than 300 fixed stations in the Sea (Fig. 1.1.2).

As of 1987, more than 38,000 hydrographic stations had been collected by (Pishchalnik and Klimov, 1991):

Sakhalin RHA	48%
TINRO	32%
FERHRI	8%
Other Russian	4%
Foreign data	5%
Data prior to 1948	3%

Thus most of the data are archived at the Sakhalin RHA.

Russian data are collected by three national data centers: WDCB (Moscow), ODC (Obninsk), and the ROC (St. Petersburg). These are intended to be in parallel and have the same holdings, but in practice the data holdings differ. Local data sets which might not be archived in these three centers are held by POI, FERHRI, IAPC, RHAs and TINRO local branches. A large hydrographic data base for the Okhotsk Sea has been collected by FERHRI, consisting of 876 cruises with 51,607 stations (Fig. 1.1.2) as listed below (Luchin and Motorykina, 1993). We note that the total Japanese and U.S. holdings in WDCA are larger than in this database, but that no Russian Okhotsk Sea stations are in WDCA.

Country	# cruises	# stations	Period
USSR/ Russia	767	49237	1930-1988
Japan	105	2342	1932-1948, 1954, 1957-1976
U.S.A.	4	28	1962-1963

Much Russian data is in manuscript form, so conversion to digital format is required. The data archeology project of the WDCA and WDCB is working on rectifying this situation. The Russian contact for data from the northwestern Pacific is Igor D. Rostov of POI; he recently spent several months at WDCA. The WDCA contact is Sydney Levitus.

SST analyses for the Okhotsk Sea include:

(a) JMA (Japan): monthly ocean report including the ten-day marine report, available from the JMA in Tokyo
(b) JFA (Japan): Quick Bulletin (every 5 days)
(c) MSA (Japan): Quick Bulletin (2/month)
(d) Sakhalin RHA: 5-day bulletin based on ship of opportunity reports (Yuzhno-Sakhalinsk)
(e) Kolyma RHA: 10-day SST based on airborne radiometer measurements (Magadan)

2.2 Direct current observations in the Okhotsk and Kuril region

Moored current observations have been made by the Japanese in the central Okhotsk (August 1990 - August 1991; 52° - 54°N, 150°E), off Abashiri at the site of Kitaude-Yamato bank (1989-1990), and in the Soya Current at various locations in the 1970's. Results are reviewed in Section 2.4 below. At this time we do not know the data source for the earlier Soya Current observations. The central Okhotsk and Abashiri measurements are still being analyzed by the MSA.

Long-term moored current meter observations are being conducted by the Japanese in the Oyashio southeast of Hokkaido. There are at least four mooring sites along the continental slope; deeper moorings include both shallow and deep current meters. JFA/Hokkaido sites are at 42°05'N, 145°21'E and 42°35'N, 144°56'E (Kawasaki et al., 1990). The two Hokkaido University moorings are located at 41°30'N, 144°0'E and 144°30'E (Miyake et al., 1991).

WOCE current meter observations of deep flow along the western boundary off Hokkaido are being conducted by the U.S.A.'s Woods Hole Oceanographic Institution. (B. Warren and B. Owens are the contacts.)

It was reported that direct current measurements were made in the Kuril Island straits by Russia in the late 1970's, but because surface buoys were used, they were not very successful because of the strong currents and measurements were not made for long periods. Hydrographic and sea level measurements have been used much more successfully by Russian scientists to look at exchange through the straits. No report was presented on other direct current measurements in the Okhotsk Sea, and there might be a problem of confidentiality in making data available. Gladyshev and Bogdanov of POI are the principal contacts for the extensive Russian work in the Kuril straits.

Two surface drifters released in the Bering Sea by NOAA/PMEL in 1990 followed the East Kamchatka Current and entered the Okhotsk Sea through Chetvertyy Strait, close to Kamchatka, near the end of their lifetimes. They showed very large tidal currents in the strait. One drifter went northward presumably in the West Kamchatka Current. P. Stabeno is the contact at PMEL.

Large numbers of drift bottles were released in the Kuril region by Japanese oceanographers from 1893 - 1913 and we are collecting the references for these observations.

2.3 Sea level measurements

Japanese sea level stations are located at Wakkanai, Mombetsu, Abashiri, and Hanasaki. Sea level stations are leveled every few years relative to Tokyo. Data are available from the JODC.

Russian sea level stations are located at the permanent hydrometeorological stations operated by the Sakhalin, Kolyma and Kamchatka RHA's and shown in Fig. 1.1.2. Additional short records of sea level (2 - 3 days) have also been made at numerous locations. Station pairs which span straits should be leveled relative to each other (e.g., Soya Strait: Wakkanai and Korsakov). Data availability for international exchange is still under consideration by the government.

2.4 Sea ice observations

Japanese observations of sea ice in the Okhotsk Sea are reviewed extensively in Part 2. Sixteen coastal observation stations (JMA - 7; MSA - 9), and regular aircraft observations (3/week) are carried out. Sea ice radar observations at Esashi, Mombetsu and Abashiri (Figs. 2.2.3, 4) have been made since 1966 by the Sea Ice Research Laboratory of Hokkaido University. Results are published annually in the Data Report of Low Temperature Science. Visible and infrared satellite measurements have also been used (Aota et al., 1985) to look at sea ice concentration. Satellite microwave radiometer (ESMR, SMMR) and visible and infrared images are also used together, including measurements from the U.S. Nimbus satellites and the Japanese GMS (Cavalieri and Parkinson, 1998; Alfultis and Martin, 1987; Wakatsuchi and Martin, 1990).

Russian sea ice observations are carried out by the Sakhalin, Kolyma and Kamchatka RHA's. Observations are made from aircraft and cover Tartar Strait, the Okhotsk Sea and the western part of the Bering Sea. Meteor and NOAA satellite images are also used. All coastal stations (Fig. 1.1.2) report ice observations. SLR from the Russian Ocean satellites has been used recently in sea ice analysis (Mitnik and Kalmykov, 1992).

2.5 Satellite observations

A number of different satellite data sets have been used to study sea ice, SST and circulation in the Okhotsk Sea, as mentioned in the preceding sections. The first satellite information became available in the 1970's: visible and infrared images of the northwestern Pacific, Okhotsk and Japan Sea from the NOAA and Meteor operational satellites, and later from the geostationary satellite GMS. These data are received by the Russian Hydrometeorological Service (Far Eastern Regional Receiving Center, Khabarovsk [FERRC] and local hydrometeorological observatories, on a regular basis (NOAA AVHRR - 4 times per day, Meteor and GMS - 2 times per day). In spite of their low resolution (1 - 3 km for Meteor and 4 km for NOAA) these images provided the first findings of important mesoscale features in the region (Isatullin and Nazirov, 1972; Bulatov, 1978) and because of their regularity they remain an important data set. Recently high resolution NOAA AVHRR data (HRPT) have become available in Russia, and are collected on an occasional basis. They are received for the southern Okhotsk Sea on a regular basis by the JMA.

Satellite observations of sea ice using the Multichannel Scanning System of Medium Resolution from the Meteor and Okean satellites have provided resolution of 200 to 600 m since the early 1980's. This permitted detailed study of sea ice structure and small scale water dynamics (Kazmina and Sklyarov, 1984; Fedorov and Ginsburg, 1988). MSS-M images are collected at the head receiving center (Moscow) and some data are at FERRC.

Much satellite imagery is useful only in cloud-free conditions and when SST contrasts are large. Sea ice structure and water dynamics may be studied successfully in March - April when the most cloudfree conditions obtain. SST analyses have been restricted mostly to the period from July to October. Sea ice data which are independent of cloudiness are obtained from the Side Looking Radar systems of the Kosmos and Okean satellites from 1983 to 1991 (Mitnik and Viktorov, 1990). These images have a resolution of about 2 km with a swath of 460 km width. All data in the form of films are available from the HRC archives.

Prospective Russian programs are connected with the multisystem space station Priroda and the synthetic aperture radar system Almax, which are to be launched in 1995 and 1996, respectively.

Data from GMS, MOS-1, NOAA and LANDSAT satellites are received and collected by the JMA and NASA. Radar altimeter data from GEOS-3, SEASAT and GEOSAT are also available from some Japanese and U.S. sources and have been exploited for Okhotsk Sea studies (e.g., Wakatsuchi and Martin, 1990).

Sea ice bulletins are published by:

(a) MSA: local bulletins
(b) JMA: entire area
(c) Kolyma RHA (Magadan): operational and annual reports

Part 2. REVIEW OF OCEANOGRAPHY OF THE OKHOTSK SEA AND OYASHIO REGION

Early comprehensive papers on the physical oceanography of the Okhotsk Sea are those of Leonov (1960), who describes the water mass distributions, and Moroshkin (1968) whose monograph on water masses and circulation is recommended reading for anyone interested in learning about the Okhotsk Sea. Neither includes much in the way of transport estimates, description of the role of sea ice, description of large eddies, or details on exchange through the Kuril Island straits. Discussion of the Kuril Island region in winter (Reid, 1972), discussions of the Okhotsk Sea circulation and water masses in relation to the North Pacific circulation (Dodimead et al., 1963; Reid, 1965; Favorite et al., 1976) and discussion of saline shelf water formation under Okhotsk sea ice (Kitani, 1973) are also highly recommended as basic background material. Other recommended papers are discussed throughout Part 2.

1.0 GEOGRAPHY AND PECULIARITIES OF THE OKHOTSK SEA

The Okhotsk Sea is one of the marginal seas of the North Pacific Ocean, and is bounded by the Kamchatka Peninsula, Siberia, Sakhalin Island, Hokkaido and the Kuril Islands (Chishima Islands in some Japanese documents). Figs. 2.1. 1 and 2.1.2 show the whole of the Okhotsk Sea and the Kuril Islands. Many features have both Russian and Japanese names; Table 1 and Fig. 2.1.2 show these names; "old" indicates that the Russian is clearly preferred. The Okhotsk Sea's area is about 1,528,000 km^2, and its mean depth is about 800 m (Yamaji indicates 838 m and Yoneda 777 m as the averaged depth in Coastal Oceanography of Japanese Islands, 1985). There is a broad continental shelf along the Kamchatka and Siberian coasts, and a relatively deep basin of triangular shape in the central and southern portions. The deepest portion is the Kuril Basin (Chishima Basin in old Japanese documents), located in the southwest, the bottom of which is very flat (3,200 - 3,300 m).

The Okhotsk Sea is connected to the Japan Sea through Soya Strait and Tartar Strait (Mamiya Strait). The latter is north of Sakhalin and is very narrow (8 km in the narrowest portion) with a sill depth of only 12 m; its effects on the oceanography of the Okhotsk Sea apparently are negligible although the region south of the strait in the Japan Sea may be important for deep water formation in the Japan Sea and may affect the properties of water flowing through Soya Strait into the Okhotsk Sea. The mouth of the Amur River is located near the northern part of Tartar strait, and almost all of the discharged fresh water flows into the Okhotsk Sea. The width of Soya Strait is about 42 km and its sill depth is about 55 m. As discussed later, warm and saline water, originating from the Tsushima Warm Current in the Japan Sea, flows into the Okhotsk Sea and forms the Soya Current flowing southeastward along the coast of Hokkaido. This connection with the Japan Sea profoundly affects the water properties of the Okhotsk Sea, ventilation in the Okhotsk Sea, and hence water properties in the Oyashio.

The Okhotsk Sea is separated from the North Pacific Ocean by the Kuril Islands and their associated ridge (Figs. 2.1.1 and 2.1.2: note that geographical names vary with authors and countries). Part of the East Kamchatka Current flows into the Okhotsk Sea through the northern passages of the islands; this water then flows out through the southern passages after considerable modification. This modified Okhotsk Sea Water is important in formation of the Oyashio Water. Among the northern passages, Kruzenshtern Strait (Mushiru Strait) is the deepest, with sill depth of about 1,400 m. Bussol' Strait (Uruppu Strait), located in the center, is the deepest, at about 2,300 m (Yasuoka, 1967).

The surface layer of the Okhotsk Sea contains very fresh water, and winter convection occurs only within a thin surface layer. This peculiar condition allows sea ice formation at a very low latitude in the Okhotsk Sea in comparison with other seas and oceans: new sea ice is formed just off Hokkaido in mid-winter, the latitude of which is only 44°N. Active sea ice formation in the northwestern shelf region generates dense shelf water. This water loses its high salinity character before it flows out to the central part of the Sea. However, this water is believed to be important in the ventilation of intermediate waters of the entire North Pacific.

These features are discussed in the following sections. Most of the review below is based on the substantial Japanese literature and on the few other papers written or translated into English. An extensive review of Russian literature must await more complete involvement in this work by Russian oceanographers. Though the accumulation of recent knowledge on the Okhotsk Sea allows a reasonable qualitative description of the physical nature of the Okhotsk Sea, quantitative discussion and detailed dynamics remain for future research.

2.0 SEA ICE IN THE OKHOTSK SEA

2.1 Sea ice observations in the Okhotsk Sea

Systematic visual observations of sea ice in the Okhotsk Sea were started by Japan in 1892 at six coastal locations: five meteorological observatories at Soya, Esashi, Abashiri, Nemuro, and Sana, and the lighthouse at Cape Ochiishi. The number of the Japanese observation points had increased to 34 by 1935. Observations of offshore sea ice were started in 1930 by vessels of the Japanese Navy, and in 1935 by aircraft of the Japanese Meteorological Agency. The purpose of the latter observations was to forecast abnormal cold weather in northern Japan. these activities were interrupted by the Second World War.

Sixteen Japanese coastal observation stations (7 observatories of the Japan Meteorological Agency and 9 of the Hydrographic Department, MSA) are operating now. Aircraft sea ice observations in the southern Okhotsk Sea are conducted by the Hydrographic Department and by the Japanese Defense Agency 3 times per week in the sea ice season. Locations of Japanese stations are shown in Fig. 2.2.1 (Akagawa, 1969).

Near the coast of Hokkaido a sea-ice radar network was established in 1966 by the Sea Ice Research Laboratory of Hokkaido University (Tabata et al., 1969; Tabata, 1972a and b). The network consists of three radars on the coastal mountains at Esashi, Monbetsu and Abashiri. Results are published annually in the Data Report of Low Temp Science (for example Tabata et al., 1969). Examples of sea ice distribution obtained with the sea-ice radar network are shown in Fig. 2.4.28: detailed structures and movements of the ice field are detectable from this network.

Knowledge of the sea ice extent and its seasonal and interannual variations has been much improved by satellite observations (e.g., Watanabe, 1962d; Campbell et al., 1981; Kimura, 1983; Parkinson and Gratz, 1983; Cavalieri and Parkinson, 1987; Alfultis, 1987; Alfultis and Martin, 1987; Parkinson, 1990; Wakatsuchi and Martin, 1990 and 1991; JMA, 1991).

Infrared and visible images obtained from the U.S. NOAA, Russian Meteor and Japanese GMS satellites have yielded information to study large and small scale features of the Okhotsk Sea ice cover. In the marginal ice zone, mushroom-like structures, coherent vortices and streaks were found using high resolution Meteor-Prioroda MSS-M data (Kuzmina and Sklyarov, 1984; Ginsburg, 1988; Federov and Ginsburg, 1988). These data sets have gaps because of low sun altitude and frequent cloudiness in winter. Remote sensing in the microwave band is independent of weather conditions. Data from the U.S. Nimbus-7 SMMR allow determination of overall ice extent in all conditions, so that its variations can be studied in connection with atmospheric and hydrographic processes. Radar images from the Russian satellites Cosmos and Ocean permit study of the detailed structure of sea ice, its dynamics (Mitnik et al., 1985, 1992; Mitnik and Kalmykov, 1992), and its properties. Acronyms and satellites are listed in Appendix A.

2.2 Ease of ice formation in the Okhotsk Sea

Prior to discussion of sea ice extent and its variability, it is useful to consider why ice formation occurs at the relatively low latitude of the Okhotsk Sea. Vertical profiles of temperature, salinity and sigma-t just off the east coast of Sakhalin (46°56'N, 145°01'E) on November 3, 1978 are shown in Fig. 2.2.2. Water of very low salinity (about 32.5) of thickness 40 - 50m is found at the surface. The layer is separated by a sharp pycnocline from the deeper waters. The temperature of the surface layer decreases due to surface cooling in late autumn to winter, but even when the temperature is lowered to the freezing point, the pycnocline is maintained by the sharp salinity gradient. Thus winter convection reaches only to this pycnocline or halocline. The limitation of winter convection to a thin surface layer is probably the most important reason for such formation of sea ice so far south; a minor contributing factor might also be the increase in freezing point temperature with decrease in salinity.

The circulation which spreads low salinity surface water in the warm season is sketched in Fig. 2.2.3 (Watanabe, 1963b). The distribution of fresh water is very similar to that of the sea ice extent in its expanding stage, as described later, indicating the important effect of the fresh surface water on ice formation. As seen in this figure, the coastal area just off Hokkaido is affected by the saline warm water of the Soya Current. However, the Soya Current weakens in early winter, and ceases to flow or completely submerges under the fresh, cold water of the East Sakhalin Current. Thus new ice formation can be observed along the coast of Hokkaido in mid-winter.

This fresh surface water is thought to originate from fresh water discharge mainly from the Amur River. Aota and Ishikawa (1991) discussed the fresh water budget in the Okhotsk Sea. According to their estimates, the average annual precipitation over the Okhotsk Sea is about 680 mm, and the average evaporation is about 400 mm, but error bars are likely to be large, probably in excess of 50%. This results in a total flux of fresh water through the sea surface of 382 km^3 per year. The mean annual fresh water discharge from the Amur River is 315 km^3 (Discharge of Selected Rivers of the World published by UNESCO, 1974). The discharge from other areas from Siberia to the East Kamchatka Coast is estimated to be 148 km^3, based on the area of watershed and the precipitation/evaporation difference. Thus the total fresh water supply into the Okhotsk Sea is about 845 km^3. This fresh water must be balanced with salt flux through Soya Strait and with relatively fresh water outflow into the North Pacific Ocean. It should be noted that the fresh water supply through river discharge accounts for 55% of the total fresh water supply for the Okhotsk Sea. The discharge from the Amur River alone accounts for 37%. More accurate estimates of the heat and fresh water balances in the Okhotsk Sea are needed, particularly of the portion of the balance due to the Soya Current and exchange with the North Pacific.

Sea ice formation and extent are influenced by air and water temperature, wind conditions and existing ocean currents. Distributions of the mean surface pressure (mb) and mean surface temperature (°C) in January are shown in Fig. 2.2.4 (Watanabe, 1959). Northerly winds prevail in winter since this area is usually located between the Siberian High to the west and the Aleutian Low to the east. The air temperature is lower on the western side; winter temperature at the northwestern Siberian coast is -25°C, at the northern Sakhalin coast -20°C and at the southern Sakhalin coast -10°C. The temperature in the eastern part is warmer since the prevailing winds pass over the Bering Sea and the northern North Pacific. As discussed later, the direction of the prevailing wind significantly affects inter-annual variations of ice extent.

Sea surface temperature in the cooling season from October through December is given by Akagawa (1968, 1972) using Russian maritime meteorological data for 1960 to 1970 (Fig. 2.2.5). Sea surface temperature is determined both by oceanographic processes and by surface cooling. Akagawa pointed out that the mean temperature in the first half of the analyzed period (1960-1965) is lower than that in the second half (1966-1970), and that the average date of pack ice appearance off Hokkaido in the first half is 5 days earlier than in the second half. Together with the resemblance in the patterns between the ice margin in its earlier stages and of surface isotherms, this suggests that sea surface temperature influences the ice formation and growth in the Okhotsk Sea.

As shown schematically in Fig. 2.2.3, the relatively warm saline water which enters the Okhotsk Sea through the northern passages of the

Kuril Islands flows northward off the west coast of the Kamchatka Peninsula and reduces sea ice formation there. The East Sakhalin Current flowing southward just off the east coast of Sakhalin carries sea ice southward and considerably influences the sea ice extent in the Okhotsk Sea. (Recent evidence suggests that the East Sakhalin Current is very weak in the warm seasons, and so the current shown in Fig. 2.2.3 is more representative of the winter situation.)

2.3 Seasonal and inter-annual variations of sea ice extent

2.3.1 Gross features of the seasonal variation in the Okhotsk Sea

All sea ice in the Okhotsk Sea is first year ice. The Japan Meteorological Agency (1991) analyzed 20 years of sea ice data in the Okhotsk Sea, showing the days of mean, maximum and minimum sea ice extent from 1971 to 1990, the probability of sea ice occurrence from 1971 to 1990, and the normal concentration of sea ice from 1978 to 1990. These figures are given for every 10 days starting from December 1, but here we show only the first 10 days of each month for the mean, maximum and minimum sea ice extent (Fig. 2.2.6), the existence probability (Fig. 2.2.7) and normal concentration in the first 10 days of March (Fig. 2.2.8).

Sea ice is formed firstly in northern Shelikof Bay (especially Penzhinskaya Bay), and in the western corner of Shantarsky Bay in late October or early November. Sea ice formation also occurs along the west coast of the Kamchatka Peninsula in early November, but offshore expansion is limited due to the existence of relatively warm and saline water originating from the North Pacific. Ice formation usually starts just off river mouths. The ice-covered area expands gradually offshore in the northwestern part of the sea, and its margin tends to be parallel to depth contours. The ice extent expands rapidly southward along the east coast of Sakhalin and reaches the coast of Hokkaido usually in early February. As discussed before, as surface fresh water exists in this area, this southward expansion is partly due to expansion of the new ice formation area following the temperature decrease in early winter. The expansion is also induced by drifts of pack ice due to the prevailing northerly wind and to the southward East Sakhalin Current.

The maximum sea ice extent occurs usually in March (in late February in some years), and then the sea ice area retreats in just the opposite sequence to its expansion. In June, almost all of the Okhotsk Sea is open water, but some sea ice may persist in the coastal area of Shantarsky Bay into July.

2.3.2 Sea ice thickness

Although satellite information is very useful for sea ice investigation, little information on ice thickness is produced with present technology. Quantitative estimates of the sea ice volume and its variability is required for more complete understanding of sea ice formation and its influence on oceanographic conditions in the Okhotsk Sea. A special project may be required for improvement of these estimates.

From visual observations, the thickness of sea ice reaches about 1.5 m at the northern part of Sakhalin, about 1.0 m at the middle part, and 0.5 m at the southern part (Akagawa, 1969). Tabata et al. (1980) analyzed the USSR hydrographic reports for 1958 to 1965, which include information on sea ice thickness at coastal stations in the northern Okhotsk Sea. As an example, sea ice thickness in the winter of 1969 - 1970 at several stations is shown in Fig. 2.2.9.

2.3.3 Polynyas and open water

Maps of the sea ice extent in March through May (Fig. 2.2.6) and the ice existence probability for March (Fig. 2.2.7) show that a region of open water tends to develop along the northern coast from Shantarsky to Tauyskaya Bay, off Magadan. This coastal polynya is created by strong northerly or northwesterly prevailing winter winds.

Kovshov and Sinyurin (1982) showed recurrent polynyas, including over Kashevarov Bank, for 1977 - 1980, using photographs from NOAA satellites. Mitnik and Kalmykov (1992) used SLR and visible images to depict ice in the Okhotsk Sea: the coastal polynya in the north, the polynya over Kashevarov Bank, and areas of new ice formation along Sakhalin and in Terpeniya Bay are notable, as were the numerous eddies found in the southwestern Okhotsk over the Kuril Basin.

The quantitative analysis of Alfultis and Martin (1987) utilized the SMMR data for the winters of 1978 - 1982, with particular reference to the coastal polynya along the Siberian coast. They referred also to the AVHRR images of the Okhotsk Sea on March 3 and March 10, 1982 (Fig. 2.2.10), which show clearly the existence of the coastal polynya and the thin ice area over Kashevarov Bank. They showed that once the ice cover is established, the northwest continental polynya occurs in all images with low ice concentration variability. They concluded that the coastal polynya is persistent, and the polynya is maintained by the strong northerly or northwesterly winds in winter. Active ice formation occurs in the open water associated with this polynya throughout winter. They estimated the volume of dense shelf water formed in the polynya, obtaining an annual rate of about 0.5 Sv. If the water is mixed with surrounding water with the ratio 1:1 or 1:2, the ratio of the rate of water supply for the density levels of the Okhotsk Sea's intermediate water would be 1 - 2 Sv, which yields a renewal time of 10 - 40 years.

Another polynya is often found in the vicinity of Kashevarov Bank, northeast of the northern tip of Sakhalin. When the bank is completely surrounded by ice, low ice concentration regions overlie the bank. This Kashevarov Polynya is ascribed to forced upwelling or vertical mixing due to the tides. The heat flux needed to maintain the polynya is 50 - 100 W/m^2. This flux can be provided by an upwelling of 6 - 12 km^3 of 2°C water per day, which is equivalent to an upwelling of 0.3 - 0.6 m per day over the entire bank (Alfultis and Martin, 1987).

The coastal polynya and the Kashevarov Polynya will be discussed again with reference to water mass generation and modification.

Wakatsuchi and Martin (1990, 1991) discussed the open water area over the Kuril Basin, and argued that severe winter heat loss there is important in water mass modification just before the Okhotsk Water flows out into the North Pacific.

2.3.4 Interannual variability

Okhotsk Sea ice conditions change on various time scales, as seen in the difference between the minimum and maximum extent for each month (Fig. 2.2.6). Knowledge of the variations has been improved by satellite, aircraft and sea ice radar observations. However, there is a lack of information on sea ice thickness, ocean currents and other hydrographic phenomena.

The efforts of Japanese investigators are mainly focused on the sea ice in the southern Okhotsk Sea off Hokkaido, as information on sea ice is important for navigation and fisheries and as sea ice conditions may be used for forecasting abnormal cold summer weather in northern Japan (e.g., Akagawa, 1980), which brings severe damage to agriculture there.

Parkinson and Gratz (1983) and Parkinson (1990) analyzed ESMR data obtained by NIMBUS-5 for 1973 - 1976. The maximum ice extent differs from year to year as seen in the February sea ice extents, with sea ice covering almost all of the Okhotsk Sea in 1973. The unusually heavy ice in 1973 can be explained by the interannual contrast in the atmospheric pressure fields over the Okhotsk Sea. The prevailing winter winds are influenced by the positions and strengths of the Siberian High and the Aleutian Low. Parkinson (1990) showed that northerly winds from Siberia prevailed in 1973, and that in other years the winds blew around the northern margin of the Aleutian Low. In this usual case, the air mass travels over the Bering Sea instead of the Okhotsk Sea.

Campbell et al. (1981) showed that sea ice in the Bering Sea was light in 1973 when the Okhotsk Sea ice was heavy, and conversely that the heavy Bering Sea ice cover in 1976 corresponded to light ice cover in the Okhotsk Sea. By using zonal Fourier harmonics 1 through 3 of sea level pressure averaged between 45°N and 70°N, Cavalieri and Parkinson (1987) showed that the out-of-phase relation between the two seas is caused by the change in atmospheric systems including the Siberian High and the Aleutian Low. In January and February, 1973, southerly winds prevailed over the eastern Bering Sea and northwesterly winds prevailed over the entire Okhotsk Sea.

Sea ice extent also varies on shorter time scales. Parkinson and Gratz (1983) reported pulsation of the ice margin in the Okhotsk Sea during its developing stage. Cavalieri and Parkinson (1987) reported 10 - 15 day period variations of sea ice extent in both the Okhotsk and the Bering Seas, showing an out-of-phase relation also for these shorter period fluctuations.

For very unusual cases such as the heavy sea ice cover in 1973, the correlation between the sea ice extent and the atmospheric pressure system appears to be clear. However, the smaller variations such as seen in 1974 - 1976 (Parkinson, 1990) are difficult to explain solely by atmospheric pressure. For example, Sato et al. (1989) found a good correlation between the area covered by sea ice in the Okhotsk Sea south of 46°N at the end of February and the surface air temperature averaged for January-February of the same year at Abashiri (Fig. 2.2.11). As discussed in Section 2.3.2, surface air and sea temperatures also should be taken into account.

The interannual variability of the sea ice extent in the southern Okhotsk Sea is different from that of the northern Okhotsk Sea, as discussed separately in the next subsection.

2.4 Sea ice off the coast of Hokkaido

2.4.1 Seasonal variations

Directly adjacent to the coast of Hokkaido is the warm and saline Soya Current Water originating from the Sea of Japan through Soya Strait; colder and fresher water is usually observed to intrude offshore of the Soya Current Water (see Section 2.4). The Soya Current exhibits large seasonal variations as discussed later; the largest volume transport occurs in summer, decreases through autumn to early winter, and is submerged or ceases in mid-winter. In mid- or late November, the surface salinity drops suddenly as the Soya Current Water in the surface layer is replaced with fresh and cold water originating from the East Sakhalin Current. The changes in surface salinity (converted to σ_t at 15°C) at Mombetsu from October to December are shown in Fig. 2.2.12 for 1957 to 1962 (Watanabe, 1963b). The sudden decrease of salinity is indicated with a wide arrow in each figure. New local ice formation usually starts in early January (white arrow) when the air temperature decreases. In mid-January to mid-February, the pack ice usually invades this region from off the East Coast of Sakhalin (black arrow). There are counter-examples, such as in 1974 when the coastal sea surface temperature was abnormally high, and drift ice invaded Lake Saroma before the occurrence of local ice formation (Aota and Uematsu, 1989). In addition, it is difficult to differentiate pack ice from Sakhalin from locally-formed ice, and some ambiguity occurs in the first days of pack ice appearance.

The fresh winter surface water along Hokkaido is so light that the dense Soya Water submerges and continues to flow near the bottom. The invasion of this fresh and light water causes a sea level rise along the coast. The variations of the 5-day mean sea level during October to December at Wakkanai (located on the Japan Sea side of Soya Strait) and Abashiri and the difference between two stations are shown in Fig. 2.2.13 (Akagawa, 1977). The sea level difference drops by 10.5 cm over this period. The atmospheric pressure shifts from autumn to winter conditions during this period, and the air pressure effect on sea level is estimated to be 7.5 cm. The residual difference results from the replacement of heavy (saline, warm) Soya Current Water by light (fresh, cold) East Sakhalin Current Water.

Seasonal variations of the pack ice concentration off Hokkaido are shown in Fig. 2.2.14, as observed by the ice radar network of the Sea Ice Research Laboratory, Hokkaido University (from Aota). Ice concentration is shown in percentage for each radar image (at Esashi, Monbetsu and Abashiri) and for all observation ranges. The concentration is highly variable even in mid-winter mainly due to the change of wind direction as discussed later. The pack ice disappears from the coast of Hokkaido in late March - early May. The date of the first ice appearance is almost identical for all stations, and its variation is small, while the last date tends to be delayed towards the south from Esashi to Abashiri, and the deviation is considerably larger than that of the first date (Aota et al., 1988; Aota and Uematsu, 1989).

Pack ice often flows out into the Pacific Ocean through the southern passes of the Kuril Islands. The pack ice and the very cold, fresh water generated by ice melt flowing out through Kunashiri and Nemuro Straits are the origin of the Coastal Oyashio (Ohtani, 1989) and influence ocean conditions off the southeast coast of Hokkaido.

2.4.2 Inter-annual variations

Large inter-annual variability in the seasonal evolution of the pack ice concentration off the coast of Hokkaido was seen in Fig. 2.2.14. In particular, sea ice amounts after 1988 are very small off the coast of Hokkaido; no explanation has been offered. Ogata and Akagawa (1985) obtained long time series (1961 - 1979) for the first and last dates of sea ice appearance, the maximum area of the sea ice (within visual ranges), and the total amount of sea ice (integration of the sea area from the first day of appearance to the last day), by using the visual observation data at Esashi, Ohmu, Monbetsu and Abashiri. For a broader area, Sato et al. (1989) investigated the interannual variation of sea ice area in the Okhotsk Sea south of 46°N. All of these indicate considerable interannual fluctuations of ice extent in the southern Okhotsk Sea.

As discussed in Section 2.3.4, Parkinson and Gratz (1983), Cavalieri and Parkinson (1987), and Parkinson (1990) discussed the unusually large extent of sea ice in the northern Okhotsk Sea in winter 1972-1973, using ESMR data from NIMBUS-5. In contrast, Fig. 2.2.14 and Ogata and Akagawa (1985) and Sato et al. (1989) show that the ice area in winter 1972-1973 in the southern Okhotsk Sea and off the coast of Hokkaido was well below the mean.

Except for the low ice cover in 1973 and the high ice cover in 1978, correlations between the sea ice strengths for the whole Okhotsk Sea and for the area covered by the sea ice radar network is 0.17 (with only 14 data points), and that between for the Okhotsk Sea south of 50°N and for the radar network area is 0.04. Namely, no correlation can be found among them (Aota and Uematsu, 1989).

The pack ice just off the coast of Hokkaido is carried out of the observable radar range of 30 miles when strong winds blow from land to sea. Aota and Uematsu (1989) used the surface pressure difference between Wakkanai and Nemuro as an index of wind strength in the direction orthogonal to the coast, and correlated it with the changing rate of sea ice amount seen in the radar. The good correlation between the two quantities indicates that the sea ice concentration near the coast is strongly influenced by the local winds.

The correlation between sea ice characteristics and meteorological conditions off the coast of Hokkaido have been studied by various investigators (Tabata, 1952a; Eda, 1962; Sasaki, 1963; Schell, 1964; Hata, 1966; Ogata, 1969, 1976a, b; Akagawa, 1973; Yamamoto, 1981 and 1982; Obata and Akagawa, 1985).

Akagawa (1973) analyzed the first and the last ice appearance dates off Hokkaido, at Esashi, Ohmu, Monbetsu and Abashiri, for 1946-1972. In years of abnormally early first appearance of sea ice, the Siberian High was well developed and cyclones passed frequently along the Kuril Islands to the Aleutian Islands; therefore the northerly-northwesterly monsoon with outburst of cold air mass was strong over the Okhotsk Sea. In years of abnormally late first appearance, the Siberian High and the Aleutian Low were weaker, and the North Pacific High shifted northward, so the monsoon was weak. Differences in air temperature accompanied these anomalies. On the other hand, local meteorological conditions appeared to be more important for the date of the last appearance of the sea ice. His results may indicate that the sea ice condition off the coast of Hokkaido might be correlated with the ice condition in the whole Okhotsk Sea, although we cannot find good correlations in discussions cited above. The discrepancy may result from lack of information on ice thickness, as the area of ice extent does not necessarily represent the volume of the sea ice.

2.5 Operational sea ice forecasting

As an operational service the Japan Meteorological Agency publishes Sea Ice Information for the whole Okhotsk Sea and its adjacent seas twice a week (example in Fig. 2.2.15), and Sea Ice Information for the seas adjacent to Japan every day (example in Fig. 2.2.16).

The JMA produces both a one-week and a one-month forecast for the Okhotsk Sea south of about 49°N. For the one-week forecast, a numerical sea ice model is used which includes dynamical processes (drift and deformation of ice field by winds and oceanic currents) and thermodynamic processes (formation and melting of sea ice due to heat exchanges among air, sea water and ice) (Sinohara, 1989 and 1990; Sato et al., 1989). An example of the one-week forecast is shown in Fig. 2.2.17 for the increasing sea ice phase (Kamihira et al., 1991).

For the one-month forecast, a statistical method based on the climatological mean distribution of sea ice is used. The deviation from the climatological mean is assumed to persist to some degree, the coefficient of which is empirically determined for each month. Then, also using empirical relations, a correction is made for meteorological effects derived from the 500 mb surface. An example of the one-month forecast is shown in Fig. 2.2.18 for the increasing sea ice phase (Sato and Kano, 1992).

The accuracy of the JMA's one-week and one-month forecasts is fairly good, given our limited knowledge of sea ice in the Okhotsk Sea as discussed in the previous section. Some of the assumptions used are not very reliable. For example, the one-week forecast model uses a fixed oceanic current field, but it does not include, for instance, the cyclonic eddy over the Kuril Basin discussed by Wakatsuchi and Martin (1990, 1991).

China operates a sea ice forecasting model for the Bohai Gulf area, which is not a part of the Okhotsk Sea, but which has one-year ice at a very southern location. The numerical model in the National Research Center for Marine Environmental Forecasts, Beijing, has been developed in recent years (Wu et al., 1988, 1990). An example of a 3-day forecast from the model is shown in Fig. 2.2.19. The forecast is in good agreement with sea ice observations based on satellite imagery (Fig. 2.2.20), as developed by Huang et al. (1990, 1992, 1993a, 1993b).

No information on Russian sea ice modeling for the Okhotsk Sea was available to us for purposes of this report, but we are aware that there is a significant effort in this area.

Table 1. Geographical locations in the Okhotsk Sea region: (old) indicates that the Russian is preferred.

Label	Russian	Japanese		Note
a	Pervyy Kuril'sky Proliv	Simusyu Kaikyo	(old)	strait
b	Ostrov Shumshu	Simusyu To	(old)	island
c	Ostrov Paramusir	Paramusiru To	(old)	island
d	Chetvertyy Kuril'skiy Proliv	Onekotan Kaikyo	(old)	strait
e	Ostrov Onekotan	Onekotan To	(old)	island
f	Proliv Krenitsyna	Harumukotan Kaikyo	(old)	strait
g	Proliv Cevergina	Syasukotan Kaikyo	(old)	strait
h	Proliv Kruzenshterna	Musiru Kaikyo	(old)	strait
i	Proliv Nadezhdy	Rasyuwa Kaikyo	(old)	strait
j	Proliv Rikorda	Ketoi Kaikyo	(old)	strait
k	Proliv Diany	Simusiru Kaikyo	(old)	strait
l	Ostrov Shimushir	Simusiru To	(old)	island
m	Proliv Bussol'	Kita-Uruppu Suido	(old)	strait
n	Proliv Urup	Minami-Uruppu Suido	(old)	strait
o	Ostrov Urup	Uruppu To	(old)	island
p	Proliv Friza	Etorohu Kaikyo		strait
q	Ostrov Iturup	Etorohu To	(old)	island
r	Proliv Ekaterina	Kunasiri Kaikyo		island
s	Ostrov Kunasir	Kunasiri To		island
t	?	Nemuro Kaikyo		strait
u		Siretoko Misaki		cape
v		Soya Misaki		cape
w	La Perouse (strait)	Soya Kaikyo		strait
x	Mys Kril'on	Nisi-Notoro Misaki	(old)	cape
y	Zaliv Aniva	Aniwa Wan	(old)	bay
z	Mys Aniwa	Naka-Siretoko Misaki	(old)	cape
A	Zaliv Terpeniya	Taraika Wan	(old)	bay
B	Mys Terpeniya	Kita-Siretoko Misaki	(old)	cape
C	Gulf of Tartary			strait
D	Mys Telizavety			cape
E	Sakhalinskiy Zaliv			bay
F	Ostrov Iony			island
G	Kashevarov Bank			rise
H	Deryugin Basin			basin
I	Instituta Okeanologii Rise			rise
J	Akademii Nauk Rise			rise
K	Kuril Basin			basin
L	Penzhinsky Zaliv (Shelikova Zaliv)			bay
M	Tinro Basin			basin

3.0 PHYSICAL OCEANOGRAPHY OF THE OKHOTSK SEA

The Okhotsk Sea is connected to the North Pacific Ocean through the Kuril Islands. Because of the constrictions due to the island chain, in which only two straits are deeper than 1,000 m, the Okhotsk Sea circulation is connected in a complex way with the cyclonic circulation of the subarctic North Pacific. Water properties in the Okhotsk Sea are very different from those of the North Pacific at most locations along the Kuril Islands, also reflecting the physical barrier. The Okhotsk Sea connection to the Japan Sea through Soya Strait (La Perouse Strait) is important particularly for the salinity balance of the Okhotsk Sea because of the relatively high salinity of Japan Sea waters. This input of salinity into the Okhotsk Sea is likely to be crucial for dense water formation.

Because of its importance in ventilation of the North Pacific, heat and salinity budgets for the Okhotsk Sea, clarifying the rates of dense water formation and the mechanisms are of great interest. However, very little has been done on heat budgets, and almost nothing on salinity budgets.

Early extensive discussions of Okhotsk Sea water properties and circulation available in English are found in Leonov (1960 - water properties) and Moroshkin (1962 - circulation and water properties). The papers summarized below show what we believe to be the state of knowledge of the circulation and water masses. In these many papers, we found relatively little quantitative information, for instance discussions of current transports, water mass modification rates, circulation time scales, and heat/salinity budgets. We also found little quantitative information on variability of water masses. Few data have been collected in the important northwestern shelf and Kashevarov Bank region where modification is important, and interpretation of data even in relatively well sampled regions such as Bussol' Strait, the East Sakhalin Current and West Kamchatka Current requires good understanding and measurement of the large amplitude tides. Important steps for improved communication with Russian experts in this region have been taken; we believe that even with the observations and analyses which they have undertaken, these quantitative questions will not be answered. Hence we have made a set of recommendations for experiments in the Okhotsk Sea in the first chapter of this report.

Appendix B is a translation of two recent reports by V.A. Luchin of FEHRI summarizing Russian papers on the hydrography and currents in the Okhotsk Sea. These were obtained after the working group meeting, and so are included in total since the information in them has not been fully integrated into the working group report.

3.1 Oceanographic observations

Oceanographic observations available outside of Russia are limited both in numbers and quality in the Okhotsk Sea, particularly relative to the extraordinarily well sampled waters around Japan, including the Soya Warm Current region along the northern coast of Hokkaido. Data collection is limited in winter because of severe weather and ice coverage, and has been limited in all seasons in the last two decades because of political conditions. (Only a small portion of the central Okhotsk Sea is outside the 200 nm Exclusive Economic Zone.) A summary of available observations was presented in Part 1, but more details are given here.

The history of oceanographic observations in the Okhotsk sea started with the Russian vessel Vitiaz which made the first observations in 1887. The first Japanese observations were made on Kumotaka-maru of the Imperial Fisheries Experimental Station in summer 1916 - 1917, and extensive observations were carried out in 1927 on the Manshu of the Imperial Japanese Navy. Shigematu (1933) used these data to present a comprehensive current distribution in the Okhotsk Sea based on dynamic height relative to 400 dbar. The first Soviet expedition was carried out in 1932, encompassing the main features of temperature distribution in the Okhotsk Sea. The WDCA data set, which includes no Russian data in the Okhotsk Sea, was shown in Fig. 1.1.1. Over 1,000 stations are available north of 50°N in the Okhotsk Sea. There were active Japanese observational programs in the central Okhotsk Sea prior to 1974; the sparse U.S. observations ceased after 1968 except for U.S. Navy observations in 1974 and 1987. The overall number of observations in this archive dropped precipitously in the 1970's. The density of observations is much higher in the West Kamchatka Current and Soya Current regions than elsewhere. It is apparent from various references, particularly Kitani's (1973), that some important Japanese data are not included in the archive, including the Oyashio-maru cruises of 1969 and 1970.

Although no Russian observations in the Okhotsk Sea are available through WDCA, Moroshkin (1962) indicated that he used 11,000 deep water stations for his synthesis of water properties and circulation, and that cruises of the Vityaz' from 1949 to 1953 were crucial for his work. Luchin and Motorykina (1993) (1.1.3) indicate that 51,607 observations in the Okhotsk Sea for 1930 - 1988 have been made available at the Russian World Data Center, of which only 2,370 are of Japanese and U.S. origin. Since the actual Japanese and U.S. data sets in the Okhotsk Sea include many more than 2,370 stations, this indicates that there is indeed a rich existing data base for the Okhotsk Sea and that avenues to make the Russian portion available should be vigorously pursued. WDCA is working currently with Russian experts to incorporate a large amount of Russian data worldwide, including the Okhotsk Sea, so it is likely that these data will become available in a few years (S. Levitus, personal communication). It is expected that a large quality control effort will be required in order for the data to be of wide use.

Winter observations are very sparse even in the open water regions because of pack ice and ice accretion on ships (Fig 2.3.1). Fig. 2.3.2 shows WDCA observations for January - March of all years. The observations north of 50°N were collected by the Imperial Japanese Navy's icebreaker Oodomari in 1938-39 and by the Kaiho-maru, also in 1938-39. We have no information on winter coverage by Russian vessels.

The coverage of the southern Okhotsk Sea off Hokkaido has been excellent through all the years. Seven winter observation lines (Fig. 2.3.3) have been made twice a year since 1987 by the Hydrographic Department, MSA: in the open sea period from November to December and in the ice period in January on the icebreaker Soya (Ishii, 1991). For all other seasons a fairly dense routine observation network has been occupied by Japanese agencies for many years. The Japan Meteorological Agency usually makes observations in the Okhotsk Sea parallel to the southern Kuril Islands in August. Frequent observations are made by the Japan Fisheries Agency and the Prefectural Fisheries Experimental Stations. The Japanese Fisheries observations for 1985 are shown as an example (Fig. 2.3.4 (i)-(iii)) (JFA, 1989). Through a fisheries exchange agreement with Russia, the JFA has been occupying stations in the southern Okhotsk Sea since 1988 (Fig. 1.2.1). In addition to routine observations, many special programs have been carried out in this region, examples of which are shown in Fig. 2.3.4.

Direct current measurement records are very limited in the Okhotsk Sea. Some observations have been made in the Soya Current Region (Aota and Kawamura, 1978, 1979) and in the central portion of the Okhotsk Sea (Yoritaka, personal communication) and were referred to in Part 1. We have no information on Russian observations.

As unclassified data are abundant in the Soya Current Region, its oceanographic structure and variability are considered separately in Section 2.4.

3.2 Circulation in the Okhotsk Sea

3.2.1 Gross features of the circulation

The circulation of the whole of the Okhotsk Sea has been presented in several papers. Figs. 2.2.6 and 2.3.5 show the eight that we have found, based on dynamic topography (Fig. 2.3.5a - d), GEK measurements (Fig. 2.3.5e), and composite schematics (Fig. 2.2.4 and 2.3.5f,g). All figures indicate cyclonic circulation in general, but more complicated local structures. Favorite et al. (1976) summarized in a table and figure (Fig. 2.3.6) the various current nomenclatures recognized up to that time, based primarily on work by Leonov (1960), Moroshkin (1962), Yasuoka (1968), and Watanabe (1963b).

The nomenclature which we adopt is the East Kamchatka Current for southward flow north of Kruzenshtern Strait, the West Kamchatka Current for northward flow west of Kamchatka, the East Sakhalin Current for southward flow just east of Sakhalin, and the Soya Current for southeastward flow through Soya Strait and along the northern coast of Hokkaido.

In the simplest schemes, the Okhotsk Sea circulation is cyclonic and connected to the cyclonic circulation of the subpolar North Pacific. Flow into the Okhotsk Sea occurs primarily through Kruzenshtern Strait and is fed by the East Kamchatka Current. Flow out of the Okhotsk Sea occurs primarily through Bussol' Strait, whence it feeds the Oyashio and Subarctic Current (Favorite et al., 1976). However, there is evidence for inflow also in Bussol' Strait according to Moroshkin (1962) and Yasuoka (1968), and surface water outflow through the southern Kuril Islands. Flow also enters the Okhotsk Sea from the Japan Sea through Soya Strait.

Important details which differ from one scheme to another are:

(1) the presence of anticyclonic circulation in the Kuril Basin which is suggested in Fig. 2.3.5 a, d, and g, but is difficult to see in the other figures and
(2) the presence and strength of the East Sakhalin Current which is sometimes difficult to discern.

Kajiura (1949) argued that the East Sakhalin Current cannot be identified in the summer dynamic topography.

These discrepancies might be resolved with more data, and also might result from the weakness of the currents in the Okhotsk Sea: even for the conspicuous Soya Current, the mean current speed is 0.5 - 0.9 knots in summer when the current is strong. However, it should be noted that the currents exhibit strong seasonal or shorter variabilities and there are many eddies (e.g., Fig. 2.3.5g and discussion of Soya Current front in Section 2.4). Tidal amplitudes are very large (Section 2.3.5). Also, dynamic computations may not be applicable in shallow shelf regions, and are not accurate if currents are strongly barotropic. In most of the Kuril straits, there appears to be flow into the Okhotsk Sea on the northern side and flow out of the Okhotsk on the southern side (see Appendix B).

There are few numerical simulations of the circulation. Sekine (1990) estimated the wind-induced current in the Okhotsk Sea using a barotropic model assuming inflow and outflow through the Kuril Islands. He suggested that the induced current is confined to the deep portion including the Kuril Basin, and that wind effects would be important only in the strong winter monsoon. Knowledge of fresh water supply from rivers and through the sea surface is very limited and would be essential for a more complete model in which the salinity stratification and mixing in a weakly stabilized ocean are included.

The following sub-sections survey our present knowledge of details of the circulation in the Okhotsk Sea, however with little input from the Russian literature.

3.2.2 Inflow from the North Pacific Ocean and the West Kamchatka Current

It is believed that relatively warm and saline water intrudes through the northern passages of the Kuril Islands, primarily through Kruzenshtern Strait. However, actual observational evidence of this inflow is very limited. Surface temperature in February 1938 (Kurashina et al., 1967) and at 50 m depth in August 1941 (Tabata, 1952) show a warm tongue extending northward from Kruzenshtern Strait. Temperature at the temperature minimum ("dichothermal layer") in the Okhotsk Sea (Fig. 2.3.7) is a more reliable indicator of the strong influence of the warmer/saltier Pacific Water just inside the northern Kuril Islands. Northward advection of the Pacific Water is suggested by Figs. 2.3.7 and 2.3.8, but the existence of a West Kamchatka Current is not very clear. The NOAA/PMEL drifter which came south in early 1991 in the East Kamchatka Current and entered the Okhotsk Sea through Chetvertyy strait clearly turned northward with the West Kamchatka Current (Fig. 2.3.9 from Stabeno, personal communication).

A northward West Kamchatka Current is clear neither in the dynamic topographies of Fig. 2.3.5a - d nor in the GEK field of Fig. 2.3.5e. In fact, southward flow near the coast is suggested by Fig. 2.3.5f. It also might be that this current is weak and masked by tides, local eddies or large seasonal variation. Thorough analysis of existing observations (Fig. 1.1.1) and possibly improved observations are needed to clarify the nature of this current.

3.2.3 Currents in the northern Okhotsk Sea

The currents in the northern Okhotsk Sea are not yet clarified based on literature available to us at this time, which is probably missing Russian information. If the large scale circulation in the Okhotsk Sea is cyclonic, there should be westward flow there. However, it is not known whether the northern margin of such circulation penetrates into the shallow shelf region (as suggested in Fig. 2.3.5f) or is located just at the edge of the deep basin (as suggested in Fig. 2.3.5g). Kitani and Shimazaki's (1971) dynamic topography at the surface relative to 100 db (Fig. 2.3.10) shows a slow current over the shelf which is confined to a thin surface layer 10 - 20 m thick. A notable feature in this figure is associated with Kashevarov Bank, discussed in Sections 2.3.3, 2.3.4 and 3.3.2.

3.2.4 The East Sakhalin Current

Based on ice drift and the expansion of pack ice in winter, a relatively strong southward current exists along the east coast of Sakhalin, at least in winter (Part 1, Section 2.3.1). The current is referred to as the East Sakhalin Current. Deep expressions of the East Sakhalin Current are apparent in isopycnal property plots, so the current apparently extends to the bottom (Fig. 2.3.12).

Along the northern Sakhalin coast the current is relatively strong. Its main flow is believed to leave the coast off Cape Terpeniya (Cape Kita Shiretoko) and to flow eastward or southeastward. The East Sakhalin Current advects relatively fresh water and pack ice to the coast of Hokkaido in winter. The less saline surface water is observed also in summer. Therefore, some part of the East Sakhalin Current appears to continue southward south of Cape Terpeniya. However, the conceptual charts (Figs. 2.3.5f - g) show gyres of opposite direction to each other in Terpeniya Bay, indicating that there is uncertainty even as to direction of flow.

As discussed above, the East Sakhalin Current may be weak or absent in summer (Shigematu, 1933; Kajiura, 1949). Fujii and Abe (1976) analyzed the oceanic conditions off the east coast of Sakhalin for the summers of 1969 to 1974. (In 1969, only surface temperature and salinity data were collected.) Temperature and salinity at the sea surface and at 100 m are shown in Figs. 2.3.11 through 2.3.13. These show large variations from year to year. Surface water with extremely low salinity, from the Amur River and sea ice melt, is commonly found in the vicinity of the northern tip of Sakhalin (Fig. 2.3.13). This low salinity water was transported southward by the East Sakhalin Current in 1971, 1972 and 1973 but not in 1969, 1970 and 1974. In 1971 there was a conspicuous southward expansion of low salinity water along the northern Sakhalin coast, but not along the middle coast. The surface temperature distributions are much noisier than salinity presumably because of seasonal heating. The southward-intruding low salinity water is colder than the offshore water in 1972, but warmer in 1973. It is hard to find the signature of the East Sakhalin Current from surface temperature in 1971. These figures suggest that the East Sakhalin Current is variable and may be weak in summer.

At 100 m, which is below the dichothermal layer which marks the depth of winter convection, the horizontal contrast in temperature and in salinity is weaker (Fig. 2.3.13). A southward, longshore intrusion of relatively saline water is seen in 1970, 1971, and 1972, just as in the surface salinity. As discussed below in Section 3.3.3, dense, saline water is produced in the northwestern shelf region of the Okhotsk Sea. Dodimead et al. (1962) showed that the coldest temperatures on the isohaline 33.8 psu for the whole of the North Pacific occurred in the East Sakhalin Current (his Fig. 198); the lowest temperature was less than -0.5°C along Sakhalin, and less than 1°C in the western Okhotsk Sea. Talley (1991) showed a southward intrusion of fresh, cold, oxygenated water from the northwestern shelf in the East Sakhalin Current area (Fig. 2.3.14), on isopyc-nals ranging from near the surface to about 1,000 m. This isopycnal intrusion was fresh because it was cold; the corresponding salinity at 100 m in Fig. 2.3.13 is high because dense water lies high up on the shelf in this location.

In 1971, a domain of low surface temperature and high surface salinity was seen over Kashevarov Bank, northeast of the northern tip of Sakhalin (Figs. 2.3.11 and 2.3.12). Temperature at 100 m depth on the other hand was relatively high (Fig. 2.3.13), as also seen in Fig. 2.3.7. This structure appears to be created by strong vertical mixing in the vicinity of the bank, probably due to strong tides (Section 2.3.5).

3.2.5 The Soya Current

The Soya Warm Current flows along the northern coast of Hokkaido. Its water originates from the Tsushima Current in the Japan Sea and enters the Okhotsk Sea through the Soya Strait. The water originates from the subtropical water, and is characterized by relatively high temperature and high salinity, although it is significantly modified in the Japan Sea through air-sea interaction. Its typical speed is 0.5 - 0.9 kt (25 - 45 cm/s) off Mombetsu in summer-autumn (Aota, 1975). The highest speed, observed with a GEK, is about 3.0 kt in the vicinity of Soya Strait (Wakao and Kojima, 1962).

The Soya Current is strongly seasonally variable, with maximum flow in summer. It becomes very weak in winter, when it may exist only near the bottom. Southeastward flow along the coast is observed in winter, but the surface water under pack ice is fresh and cold. This flow is believed to be a continuation of the East Sakhalin Current which strengthens in winter.

Details of the Soya Current Region are discussed below in Section 2.4.

3.2.6 Anticyclonic Kuril Basin gyre and anticyclonic eddies in the southern Okhotsk Sea

Wakatsuchi and Martin (1990, 1991) hypothesized the existence of anticyclonic circulation in the Kuril Basin, based on satellite images and in situ data in the southern Okhotsk Sea. Their dynamic topographies at the sea surface relative to 1,000 db for four periods in 1977-1978 are shown in Fig. 2.3.15 (a-d). Although the shape of the circulation is variable and is separated into two smaller sub-gyres in two of the four graphs, it seems to be a permanent feature. The JFA surveys of the southern Okhotsk Sea since 1989 also reveal anticyclonic flow, with variable location and shape, but persistent occurrence (Fig. 2.3.16 (a-d)). On the other hand, well-developed anticyclonic eddies are apparent in winter sea ice and summer-autumn SST satellite images (Isatullin and Nazirov, 1972; Kuzmina and Sklyarov, 1984; Hatakeyama et al., 1985; Rogachev and Lobanov, 1990; Wakatsuchi and Martin, 1990, 1991). Each year 2 - 4 large eddies with diameter of 100 to 150 km are observed in the Kuril Basin. Their location, size and number vary inter-annually. Satellite imagery reveals that these eddies are less stable than eddies on the Pacific side of the Kuril Islands. An individual Kuril Basin eddy can move very rapidly, changing its shape, and decaying in a few weeks, or change to a new eddy. However, there are always anticyclonic eddies in this region throughout the year.

The eddies trap and advect into the central Kuril Basin jets of both Soya Current warm water and cold mixed water from the Kuril straits. These eddies are thus responsible for mesoscale variability in the hydrography and mixing processes resulting in water mass transformation in the basin.

If there is a permanent gyre, it is plausible that the eastward flow of the northern margin of the gyre is continuous with the East Sakhalin Current, which often leaves the Sakhalin coast off Cape Terpeniya (Cape Kita Shiretoko) flowing eastward or southeastward. The situation on the western side of the Kuril Basin gyre is not clear: the figures indicate relatively strong northward flow, whereas there is also evidence that fresher, colder water is brought to the coastal area of Hokkaido by a southward flow from the East Sakhalin Current Region. The anticyclonic gyre or eddies may be important in the problem of how the Soya Current leaves the coast of Hokkaido and how its relatively saline waters are mixed into the Okhotsk Sea.

The oceanographic structure of the Kuril Basin Gyre and its seasonal variations is discussed in Section 3.3.4 in regards to water mass modification in the Okhotsk Sea.

3.2.7 Exchange through the southern passages of the Kuril Islands

The Okhotsk Sea Waters flow out into the North Pacific Ocean through the deep Bussol' Strait and to a lesser extent through other, shallower straits to the south. These waters are important for formation of the Oyashio Water and the North Pacific Intermediate Water. The outflows are discussed in Section 2.5 on the Oyashio.

In the lower layers, the Pacific Ocean waters flow into the Okhotsk Sea through both Kruzenshtern and Bussol' straits. This will also be discussed later with regard to the structure of the deep layer of the Okhotsk Sea.

3.3 Water mass distributions in the Okhotsk Sea

3.3.1 Gross features of the water mass distribution

That the Okhotsk Sea is somewhat isolated from the North Pacific is manifested primarily in its water properties. All of the basic references (Leonov, 1960; Dodimead et al., 1962; Moroshkin, 1962; Yasuoka, 1967, 1968; Favorite et al., 1976) show that the dichothermal layer (temperature minimum) in the Okhotsk Sea is colder than outside, the mesothermal layer (temperature maximum) is much deeper, and that fresh, cold, oxygenated water penetrates much deeper within the Okhotsk Sea than in the East Kamchatka Current which is its primary source. Reid (1965) shows this contrast most strikingly in vertical sections around the subpolar gyre. Because water flows out from the Okhotsk Sea through Bussol' Strait and into the Oyashio, the water mass transformation which produces this striking difference results in a large contrast between Oyashio and East Kamchatka Current Water. The maximum sill depth in the Kuril Islands is 2,300 m, at Bussol' Strait.

Within the Okhotsk Sea, important influences on changing the incoming North Pacific water properties are the relatively saline Soya Current Water, the fresh Amur river discharge, and the sea ice production which each winter transforms relatively fresher surface waters to more saline shelf bottom waters, which flow out into the Okhotsk Sea to mid-depth, producing a characteristic fresh tongue on isopycnals due to the coldness of the waters (Talley, 1991). Also important are mixing processes which are enhanced in the Kuril Straits and over Kashevarov Bank.

Five summer temperature and salinity sections are shown in Figs. 2.3.17 and 2.3.19: one roughly along 150°E and the others roughly along 55°N, 51°N, 49°N and 47°N. A warm summer surface layer is found over a sharp thermocline at 20 to 30 m. Just below the thermocline is a thin temperature minimum. This dichothermal layer is well developed in the northern and western part of the Okhotsk Sea, but is obscure in the vicinity of the Kuril Islands and the Kamchatka Peninsula, where a vertically homogeneous layer appears to be generated (Fig. 2.3.18e). The homogeneous layer suggests that strong vertical mixing occurs there (Moroshkin, 1962; Talley, 1991). Kawasaki and Kono's (1993) map of potential temperature at 26.65 σ_θ clearly shows the effect of mixing around the Kuril Islands (high temperatures), and also flow through Bussol' Strait (Fig. 2.3.19).

The temperature of the dichothermal layer is lower than -1.7°C near the northwestern shelf region. Winter convection reaches to the depth of the dichothermal layer, and the temperature at the minimum represents the temperature of the winter surface mixed layer. Below the dichothermal layer, the water temperature increases with depth, reaching a maximum at about 1,000 m, where the temperature is 2.0°C or more. This is often called the mesothermal layer. Kitani (1973) called this the "deep warm water", and the layer between the dichothermal water and the deep warm water the "transitional water". Below the deep warm water, the temperature decreases gradually. This has been called the Okhotsk Proper Water, but Yasuoka (1967) divided it into two layers, Basin Water and Bottom Water, since another temperature minimum appears at about 2,500 m in the Kuril Basin.

In summer, the surface salinity is very low, less than 32.8 o/oo, indicating the influence of ice melt and/or river discharge. A sharp thermo-cline, halocline, and pycnocline is seen in the summer surface layer above the temperature minimum. Salinity in the dichothermal layer is about 33.0 o/oo. Salinity increases gradually with depth to the bottom indicating North Pacific influence. Salinity between 2,000 m and 3,000 m is greater than 34.5 psu.

In the deep southern Okhotsk Sea, the temperature minimum (dichothermal layer) at 150 cl/t has an oxygen maximum which is occasionally super-saturated (Fig. 2.3.20). This indicates that winter convection reaches to the temperature minimum, and that surface heating in the surface layer caps the dichothermal layer in summer. Below the dichothermal layer, dissolved oxygen decreases with depth, reaching a minimum of about 1 ml/l in the deep warm layer (thermosteric anomaly of about 70 cl/t). Below the deep warm layer, the dissolved oxygen increases again with depth, as appropriate given its North Pacific origin.

Dichothermal layers are also observed in the Bering Sea and the East Kamchatka Current Region, but not in the Japan Sea (Kitani, 1973; Dodimead et al., 1963). Temperature at the Okhotsk Sea temperature minimum was shown in Fig. 2.3.7. It is lowest in the north-west and increases southeastward, reaching 0.5 - 1.0°C in the vicinity of the Kuril Islands. The minimum temperature observed in the source of inflow from the North Pacific into the Okhotsk Sea, the East Kamchatka Current, is about 0°C. So, though the formation mechanism is very similar, the dichothermal layer in the Okhotsk Sea has no direct connection to that in the East Kamchatka Current Region and instead represents the winter temperature of the observed area.

The mesothermal layer (deep temperature maximum) in the Okhotsk Sea differs greatly from those in the Bering Sea and in the East Kamchatka Current: the temperature maximum in the Okhotsk Sea is deep (around 1,000 m), while that outside the Kuril Islands is about 300 m or less. As discussed before, part of the East Kamchatka Current Water enters through the northern passage of the Kuril Islands (Kruzenshtern Strait).

Temperature/salinity relations at various locations in the Okhotsk Sea are shown in Fig. 2.3.21. (The locations are shown in Fig. 2.3.18.) Within the upper part of the transitional layer the T/S relation is not necessarily smooth, often including a secondary maximum and secondary minimum. These undulations suggest that interleaving of waters occurs in the transitional layer.

From this it can be concluded that water mass modification takes place to a depth of about 1,000 m in the Okhotsk Sea, and a thick transitional layer is developed (Moroshkin, 1962). The thickness of oxygen-rich water is also increased during this water mass transformation. As shown in Talley (1991), demonstrable modification actually occurs to about 2,000 m, which is the maximum sill depth through the Kuril Islands; the deeper part of the modification is a result of vertical mixing. As discussed in Section 2.5 on the Oyashio, the development of the transitional layer in the Okhotsk Sea is essential to the formation of the Oyashio Water and the North Pacific Intermediate Water. In the following sections, phenomena which are important in formation and modification of the transitional layer will be discussed.

3.3.2 Vertical mixing over banks, shelf edges and narrow passages

Kitani and Shimazaki (1971) described the detailed oceanic structure of the northwestern Okhotsk Sea, using data obtained from the Oyashio-maru in September 1970. The most striking feature is the low temperature and high salinity found over Kashevarov Bank (Fig. 2.3.22). This low temperature domain has been pointed out already in the discussion on the Kashevarov Polynya in Section 2.3.3, and on the East Sakhalin Current in Section 3.2.4 (Fig. 2.3.7 and 2.3.11). This domain also is characterized by high temperature and salinity at 100 m (Fig. 2.3.23). Temperature, salinity and oxygen sections over the bank are shown in Fig. 2.3.24. It can be seen that the water is nearly homogeneous in temperature, salinity and oxygen over the bank. This suggests strong mixing over the bank, presumably due to strong tidal currents (Section 2.3.4).

T-S relations in the northern Okhotsk Sea from 1970 are shown in Fig. 2.3.25. Just over Kashevarov Bank (sta. 151) the T-S curve is a short straight line, reflecting vertical mixing. It contrasts strongly with those taken at the other stations except for the station which was located on the shelf near the mouth of Penjinskii Bay (Sta. 121). The similarity of the Penjinskii Bay and Kashevarov Bank T-S curves suggests that strong vertical mixing takes place in both regions. Temperature, salinity and dissolved oxygen sections from the northern shelf southward (Kitani and Shimizaki, 1971) show a thick homogeneous bottom layer over the shelf and at the shelf break. Though a sharp thermocline and halocline appears below the thin surface layer, this suggests that strong vertical mixing occurs along the northern shelf regions of the Okhotsk Sea.

As discussed before, thick homogeneous layers occur in the shelf regions along the east coast of the Kamchatka Peninsula and in the vicinity of the Kuril Islands. Mixing of the upper water column around the Kurils was evident in Fig. 2.3.19. Yasuoka's (1968) map of dissolved oxygen at 1,000 m depth near the Kuril Islands (Fig. 2.3.26) shows high oxygen tongues extending both into the Okhotsk Sea and into the North Pacific from Bussol' Strait, indicating that strong vertical mixing reaches to more than 1,000 m in the strait, as earlier indicated by Moroshkin (1962). Talley (1991) also showed high oxygen at 27.4 σ_θ (near 1000 m) in the vicinity of Bussol' Strait (Fig. 2.3.14). Tidal currents might cause strong vertical mixing due to the weakness of stability in the subarctic oceans and seas, especially on shallow shelves and in shallow straits.

3.3.3 Formation and advection of dense shelf water in the northwestern Okhotsk Sea

Kitani (1973a) found highly saline water near the freezing point just above the bottom of the northwestern shelf of the Okhotsk Sea (Fig. 2.3.27), using data from the very small number of Japanese cruises to the shelf region. In this important work, it was concluded that this heavy water is generated in winter due to active ice formation in the coastal polynya of this area (Section 2.3.3). The densest water ever observed was near the bottom (149 m) at 57°22'N, 142°E in August, 1970 from the Oyashio-maru. The water properties were -1.76°C, 33.5 o/oo, with thermosteric anomaly of 102 cl/t (27.05 σ_θ), and dissolved oxygen of 6.1 ml/l. However this observation was not at the bottom, so the actual bottom water could have been denser. Kitani (1973a) extrapolated a bottom thermosteric anomaly of about 100 cl/t (27.07 σ_θ).

This heavy water appears to flow down along the sea bottom into the deep to the west of the Kashevarov Bank, as seen in the temperature and salinity sections (Fig. 2.3.24). Because this water is so cold, it appears as a fresh tongue on isopycnals (Fig. 2.3.14). At 27.0 σ_θ, water with as low a salinity as found by Kitani is not seen in the central Okhotsk Sea, presumably due to mixing of the shelf water plume as it leaves the shelf.

To further illustrate the water mass modification in the Okhotsk Sea, Kitani (1973a) classified the water types in the Okhotsk Sea. The vertically well-mixed water is limited to the Kashevarov Bank region discussed in the preceding sub-section.

Water properties at the temperature minimum (Fig. 2.3.29) show clearly the northern waters near the freezing point (types A and A'); the location of the stations with these properties is shown in Fig. 2.3.28. The very saline, cold waters attain the high salinity through brine rejection from sea ice formation. The highest salinity freezing waters do not join smoothly with the rest of the waters in the Okhotsk Sea. Thus it appears that this salty, dense water may flow down along the bottom of the shelf edge, but its high salinity is mixed away before it flows into the central part of the Okhotsk Sea. It retains its temperature which is near the freezing point. Such water mass modification can be made only by vertical mixing with fresh surface water near the freezing point, presumably in late winter or in early spring. Alfultis and Martin (1987; see Section 2.3.3) estimated the annual rate of the dense water formation to be about 0.5 Sv.

These very cold, saline waters (A and A') are found throughout the northwestern Okhotsk Sea except over Kashevarov Bank where much warmer waters are found (Fig. 2.3.28). Most of the dense shelf bottom water appears to be carried clockwise around the bank and to mix horizontally with slightly warmer and fresher water (type B). The data are too sparse to tell if some of the dense shelf water flows southward through the passage between the northern tip of Sakhalin and Kashevarov Bank, although some of this very cold water is found to the south, east of Terpeniya Bay, suggesting some southward flow. Just off northern Sakhalin are found mostly waters with multiple temperature inversions (type D); these might be influenced by the dense shelf bottom water.

The deep temperature maximum in the Okhotsk Sea is considerably deeper than in the North Pacific, where it lies at about 250 m and 105 cl/t (27.02 σ_θ). This is about the same density as that of the dense shelf water in the northwestern Okhotsk Sea. Temperature and oxygen at 105 cl/t from Kitani (1973a) shows the influence of both the Pacific and northern shelf water (Fig. 2.3.30). Cold water with high oxygen arises in the northwest on the shelf and influences the western Okhotsk and up along the western side of the Kurils. The inflowing Pacific water with which it mixes is much warmer and has much lower oxygen. A secondary source for this isopycnal is possibly suggested by the high oxygen just east of Soya Strait.

While the densest water observed at the shelf bottom is at 100 cl/t (Kitani, 1973a), water mass modification appears to occur down to the deep temperature maximum at about 800 - 1,200 m depth and 60 cl/t (27.5 σ_θ) (Fig. 2.3.20). Mixing in Bussol' Strait appears to be the mechanism for modification of the denser water (Section 3.3.2), although Fig. 2.3.14b also suggests that some mixing in the East Sakhalin Current region is also occurring.

3.3.4 Seasonal variation of the surface and dichothermal layers in the southern Okhotsk Sea

In winter, the sea surface temperature drops nearly to freezing. In spring, surface heating increases the temperature, and salinity decreases due to ice melting and river discharge. The surface temperature reaches a maximum and the salinity a minimum in summer. As evaporation dominates precipitation in autumn, and runoff is low in this season, the salinity then increases. This seasonal variation in surface waters was illustrated by Kitani (1973b) (Fig. 2.3.31). The seasonal change is smaller in the vicinity of the Kuril Islands, reflecting either the moderate winter there or the effects of vertical mixing.

The seasonal variation penetrates into the upper transitional layer below the temperature minimum. Seasonal variation of temperature in the southern Okhotsk Sea in 1964 is shown in Fig. 2.3.32. Winter convection reaches to about 100 m. A sharp thermocline is created in summer. It is interesting that the dichothermal layer (temperature below 0°C) tends to become deeper after the overlying seasonal thermocline develops.

At the temperature minimum, temperature increases from winter to summer, while salinity and density increase (Kitani, 1973b). Salinity and density continue to increase into autumn. This may be explained partly by the seasonal salinity variation at the sea surface. However, as discussed in the next sub-section, the influence of the saline Soya Current Water or the North Pacific Water appear to be important for this increase. The salinity and density increase may explain why the dichothermal water descends into the upper transitional layer in summer and autumn as shown in Fig. 2.3.32.

3.3.5 Water mass modification in the Kuril Basin and the influence of the Soya Current Water

The Kuril Basin contains an anticyclonic gyre (Section 3.2.6), or a vigorous anticyclonic eddy field. Considerable heat loss occurs in this region, and it remains ice-free through much of the winter. As the heat loss is not used for ice formation, it might be used directly for convective cooling of the surface water (Wakatsuchi and Martin, 1990). The circulation exhibits large seasonal variation; the circulations in October, 1977, and November, 1978, are considerably stronger than in June - July, 1977, and July, 1988 (Fig. 2.3.15 from Wakatsuchi and Martin, 1991). Wakatsuchi and Martin concluded the circulation is strengthened in summer and weakened in winter.

Properties at about 27.0 σ_θ (Figs. 2.3.14, 2.3.30 and 2.3.33) suggest that this isopycnal in the Kuril Basin is influenced by the colder, fresher, and more oxygenated water which originates from the shelf bottom water and has flowed southward along the Sakhalin coast. The isopycnal depth is greatest in the center of the gyre, exceeding 800 m (Fig. 2.3.33a). Surface temperature and salinity in November, 1978, (Fig. 2.3.34) show warm, saline water extending northward into the Kuril Basin Gyre, suggesting the influence of the Soya Current Water.

Higher temperature and salinity waters ($T > 2.5$°C and $S > 32.75$ o/oo) were documented in the Kuril Basin region in November, 1978, compared with July, 1978 (Wakatsuchi and Martin, 1991), using volumetric temperature/salinity analysis. The origin of such high temperature and high salinity water can only be the Soya Current. As discussed in the following section, many investigators argue that some part of the Soya Current Water is known to be carried into the Kuril Basin Region in late summer and autumn.

The Soya Current water is saline enough that if it were cooled to freezing, it would be denser than 27.0 σ_θ (Talley, 1991; Wakatsuchi and Martin, 1991). However, Talley (1991) hypothesized, based on the limited winter surface data available for the Kuril Basin, that surface convection to this density probably does not occur, and hence the saline Soya Current water is mixed into the Okhotsk Sea before it can be cooled to near freezing.

Late winter observations in the Kuril Basin are clearly desirable, along with observations and analyses which reveal how the Soya Current leaves the coast and its waters mix into the Okhotsk Sea.

3.3.6 Deep water in the Okhotsk Sea

Below the deep warm layer (mesothermal layer), temperature decreases slightly and salinity and dissolved oxygen increase with depth in the Kuril Basin of the Okhotsk Sea (Fig. 2.3.20). The increases of salinity and dissolved oxygen indicate that the water is supplied from the Pacific Ocean.

Bussol' Strait is the deepest passage through the central Kurils and appears to contain both inflow and outflow (Moroshkin, 1962). Vertical sections of temperature and salinity through Bussol' Strait (Fig. 2.3.35) suggest that the deep water is directly connected to the waters in the Pacific Ocean between 1,500 and 2,000 m. From this, Yasuoka (1967, 1968) hypothesized the vertical flow indicated by arrows.

At 27.4 σ_θ (Figs. 2.3.12 and 2.3.36), which is much denser than any shelf water production in the Okhotsk Sea, and where only the Kruzenshtern and Bussol' Straits contribute to water exchange between the Pacific Ocean and the Okhotsk Sea, there is still clearly modification of the inflowing Pacific waters in the Okhotsk Sea. Yasuoka concluded that two types of waters flow into the Okhotsk Sea through these straits: warmer (2.57°C), less dissolved oxygen (1.20 ml/l) and higher salinity (34.31 o/oo) through Kruzenshtern Strait, and colder (2.08°C), more dissolved oxygen (2.00 ml/l) and lower salinity (34.26) through Bussol' Strait. However, Talley (1991) concluded that the colder, more oxygenated water at Bussol' Strait arises from vertical mixing of overlying waters there, rather than from a different source in the Pacific Ocean.

These and the maps at 27.4 σ_θ shown in Fig. 2.3.12 indicate that even at this density, the waters of the Okhotsk Sea are significantly fresher than in the Pacific, but since there is no indication that waters as dense as this are formed directly in the Okhotsk Sea, vertical mixing of low salinity and high oxygen water from above must be occurring. The isopycnal distributions suggest that the principle site of this mixing is Bussol' Strait.

3.4 Heat and salinity budgets for the Okhotsk Sea

The heat budget for the Okhotsk Sea has been dealt with by Alfultis and Martin (1987), who suggest that the Okhotsk Sea loses heat to the atmosphere during winter (December-March) and gains heat during spring (April), when the atmosphere warms faster than the ocean. The largest term in the balance during the winter is the sensible heat flux, averaging nearly 300 W/m^2 for 1978 - 1982. During the spring, the net incoming shortwave radiation is the largest positive term in the balance and more than offsets the other three terms. The measurements suggest that wintertime polynyas in the Okhotsk Sea, especially the one near Kashevarov Bank, may be important in the heat balance, by allowing direct, efficient heat transfer during winter. The year-to-year variation in the winter-time heat flux can be apparently sizable, however, and is a strong function of the ice cover and position of the Aleutian Low (Wakatsuchi and Martin, 1990).

As mentioned elsewhere, a salinity budget has not been constructed for the Okhotsk Sea. However, the importance of this budget is apparent in that its salinity may well be the reason why the Okhotsk Sea forms quite dense water while the Bering Sea does not. The Okhotsk Sea has a relatively saline input from the Japan Sea, which receives water from the subtropics. Thus determining the exchange with the Japan Sea as well as the other major components of the salinity budget (precipitation/evaporation, runoff from the Amur River, changes in salinity due to ice production and melt) is potentially very important.

3.5 Tides in the Okhotsk Sea

It is well-known to those who work in the Okhotsk Sea that the amplitude of the tides can be extremely large in places. The effects of the tides on vertical mixing over Kashevarov Bank and in the Kuril straits was amply documented in the previous sections. However, there appear to be very few English or Japanese language papers on tides in the Okhotsk Sea.

A large amount of tidal dissipation occurs in shallow seas. Miller (1966) determined that, for the world's oceans, maximum dissipation occurs in the Bering Sea, the Okhotsk Sea, and Hudson Bay, in that order. However, Munk and MacDonald (1960) argued that tidal currents of such great strength cannot be found in the Bering Sea (Kagan and Polyakov, 1977).

Available Japanese tidal data were obtained mainly before World War II (Ogura, 1923; Schureman, 1924). This tidal data was analyzed by Suzuki and Kanari (1986) who produced a tidal model for the Okhotsk Sea. The stations were located along the Kuril Islands (36), the east coast of Sakhalin (17), the Siberian coast (13), and the west coast of Kamchatka (2). Fig. 2.3.37 (A and B) shows Suzuki and Kanari's calculated tidal amplitudes and phases, and tidal ellipses for the different constituents of the tide. It is clear that the northern shelf, Kashevarov Bank, Shelikov Bay and the Kuril Islands are areas of large tidal amplitude. Relatively high amplitudes are also calculated for Cape Terpeniya, the northeastern coast of Sakhalin, and the northern coast of Hokkaido. According to their model, maximum energy dissipation occurs in Shelikov Bay and the northwestern bay, and a somewhat less important site on Kashevarov Bank. They also modeled the currents associated with these tides, shown in Fig. 2.3.37 (c). Shelikov Bay, Kashevarov Bank, Cape Terpeniya, and the Kuril Islands stand out as places where the tidally-produced currents are large.

Because of the very large amplitudes of the tides in the Okhotsk Sea, particularly in the areas which may be of greatest interest for water mass modification (northern shelves, Kashevarov Bank, Kuril Islands, Soya Current), observational programs designed for these areas must take good account of the tides, which probably also account for most of the important vertical mixing. Communication and data exchange with the Russians, who maintain a number of permanent sea level stations, should be imperative. It is suggested in the recommendations of this working group that sea level differences across straits also be used to monitor current transports (in particular the Soya Current). Determining both the tidal effects and monitoring longer term changes in sea level requires that the Russian sea level measurements be an important input. Leveling of the stations which span straits will be needed.

4.0 THE SOYA CURRENT REGION

4.1. Introduction

Soya Current water is supplied from the Japan Sea through the narrow (about 42 km) and shallow (about 55 m) Soya Strait. The Tsushima Current carries Subtropical Water (the Kuroshio Water modified by the shelf water of the East China Sea) northward along the Japanese coast of the Japan Sea. Most of the Tsushima Current Water flows out through Tsugaru Strait forming the Tsugaru Current flowing southward along the Japanese Pacific coast. The remaining water continues to flow along the west coast of Hokkaido, and part of it flows out into the Okhotsk Sea. Though the water is considerably modified before it reaches Soya Strait, the Soya Current Water reflects its origins as Subtropical Water. It is the warmest and most saline water found in the Okhotsk Sea. However, the transport and water properties of the Soya Current exhibit large seasonal variations; the Soya Current almost disappears in mid-winter.

The Soya Current and winter pack ice influence navigation, fisheries, and local climate along the Okhotsk coast of Hokkaido. The literature on the Soya Current Region in the warm seasons is very large, so we confine ourselves primarily but not exclusively to papers appearing after 1980. Thus important papers such as those by Ogura (1927), Maenaka et al. (1943), Iizuka et al. (1952), Tabata (1952), Nasukawa (1961), Wakao and Kojima (1962 and 1963), Iida (1962), Maeda (1968), and Aota (1968) are referred to only briefly when needed.

The geography of the southern Okhotsk Sea is shown in Fig. 2.4.1. The 200 m depth contour runs from Cape Notoro to the north, and separates the shallow western shelf region from the deeper eastern basin region. The shelves to the east of Cape Notoro and of the Kuril Islands are narrow.

4.2 Soya Current forcing

The driving force of the Soya Current was ascribed originally to the sea level difference between the Japan Sea and the Okhotsk Sea by Ogura (1927). Sea level difference between Wakkanai and Abashiri was used by Aota (1975) to calculate the current distribution at Mombetsu and Abashiri assuming a homogeneous sea with a bottom linearly deepening offshore and that the current vanishes far offshore and at the bottom (Fig. 2.4.2; see also Fig. 2.2.13). The sea level at Abashiri tends to have a secondary maximum, reflecting the zonal gradient of atmospheric pressure in winter and the change in the water density in the surface layer as described in Section 2.3.1. As an example, calculated seasonal variations of the along shore components of the surface velocity at Mombetsu in 1973 are given in Fig. 2.4.3 for various distances from shore. Aota (1975) found fairly good agreement between the calculated and velocities observed with current meters and drifters tracked by ice radar. The gross nature of the observed large seasonal variation of the Soya Current discussed in the following sub-sections appears to be explained basically by this mechanism.

4.3 Oceanic conditions in the vicinity of Soya Strait

The Soya Current Water is generally vertically homogeneous. Its temperature changes considerably with season but its salinity does not change and remains higher than 33.6 o/oo. The Soya Current Water characteristics are probably deter-mined by those of the Tsushima Current Water to the west of Soya Strait, but few observations have been made of the oceanographic structures in the vicinity of Soya Strait.

Temperature and salinity through Soya Strait (Fig. 2.4.4), in the Japan and Okhotsk Seas, in April, 1971 are shown in Fig. 2.4.5 (a-e) (Aota, 1971). As seen in Fig. 2.2.20, pack ice usually is gone by early April at Esashi and Monbetsu, and by the end of April at Abashiri. Thus this 1971 survey is representative of conditions just after pack ice disappearance off the western Hokkaido coast. The surface 100 m is homogeneous in the Japan Sea near Soya Strait, with temperature of 4 - 5°C and chlorinity of 18.82 - 18.83 o/oo, except on the shelf near Sta. 30 where fresh water appears to flow out from the Okhotsk Sea through the northern part of Soya Strait. In the vicinity of Soya Strait (Fig. 2.4.5d), the dichothermal layer is observed offshore of Sta. 39, with a core temperature below -1.5°C. Judging from the salinity values, warm and saline water from the Japan Sea lies inshore of Sta. 36. The isotherms and isohalines are almost vertical in Soya Strait where both oceanic and tidal velocities are high and strong vertical mixing appears to occur (Section 2.4.5). In the section off Esashi, the highest temperature is observed near the bottom centered at Sta. 47. The front between the Soya Current Water and the cold surface water or the dichothermal layer deepen offshore, and the cold water tends to over-ride the warm water, indicating that the stratification in this area is due mainly to salinity structure. The influence of intruding Soya Current Water is seen in the surface layer to the west of Mombetsu (Fig. 2.4.6), reflecting the disappearance of the pack ice there by this observation time. The pack ice was still present off Abashiri at this time.

Observations crossing the entire Soya Strait are very few due to territorial problems. One example from August 19, 1933 is given in Fig. 2.4.7. Despite the sparse data, it can be seen that the Soya Current Water extends roughly 15 miles out from Cape Soya. In summer, considerable temperature stratification is established. The thermocline depth is shallower than the sill depth (55 m) of Soya Strait. The stratification seen in the inflowing Soya Current Water thus probably results from that of the surface layer in the Japan Sea.

In winter the densest water in Soya Strait can reach 27.0 σ_θ (Fig. 2.4.8). It therefore appears that water dense enough to influence the transitional layer in the Okhotsk Sea and the North Pacific Intermediate Water can be generated due to winter cooling in the area where the saline subtropical water flows in. However, Talley (1991) showed that water of this high density probably does not survive without mixing to much lower density before it is advected out of the Soya Current and into the Okhotsk Sea proper. Nevertheless, the Soya Current source of saline water is apparently critical for the production of the densest waters in the Okhotsk Sea, which would probably be less dense were there no Soya Current source (Talley, 1991).

Direct current measurements in Soya Strait were made in 1933 (Nakamura et al., 1984) on the Japanese Navy's ship Ohdomari and showed southwestward velocities of order one knot at almost all locations in this summer period, when the Soya Current is expected to be strongest (Fig. 2.4.9). Direct current measurements off Cape Soya in June and August 1973 (Aota et al., 1988) showed mean current speeds of 89 - 97 cm/s in the surface layer and 45 - 63 cm/s in the deep layer. In the period from August 1987 to July 1988, they conducted 1 - 2 day current observations six times at 20 m at the station 5 miles off Cape Soya. The diurnal component predominates in Soya Strait and its magnitude is usually larger than that of the mean current. The horizontal distribution of surface currents has been measured with a GEK in August, 1958 (Fig. 2.4.10). Although tides have not been removed, the velocity appears to be largest near Soya Strait: the observed speed of 3.2 knots is the largest found in the literature. By assuming that inflow occurs across the whole section (2.1 km^2), and that the mean velocity is about 60 cm/s, Aota (1975) estimated a volume transport through Soya Strait in summer of about 1.3 x 106 m^3/s. More detailed information on the inflowing current is required.

4.4 Water masses in the Soya Current region

The most notable water masses in the Soya Current Region in summer are the Soya (Warm) Current Water and the dichothermal water found just off the Soya Current (Figs. 2.4.5d, 2.4.5e, and 2.4.8). Aota (1970) classified the water types from the coast to 40 miles offshore off Esashi and off Mombetsu in the period from April 1968 to December 1969 as: the Soya Current Water, the Dichothermal Water, and the Surface Low Salinity Water. The temperatures of the Soya Current Water and the Surface Low Salinity Water are very variable and exhibit large seasonal variation. Thus, identification of the water mass is usually made by its salinity.

Other investigators have used other terminology. For example, Iida (1964) classified the water types as the Soya Warm Water, the Intermediate Water, the Proper Water, the Offshore Warm Water, and the Low Chlorinity Water. The Intermediate Water corresponds to Aota's (1970) Dichothermal Water. In this water is usually observed a very cold water core. This indicates that the dichothermal water found in this region is not the southern edge of the widely distributed dichothermal layer in the Okhotsk Sea, but that the water has been carried southward along off the east coast of Sakhalin (by the East Sakhalin Current). The boundary between the Dichothermal Water and the Offshore Warm Water has not been investigated in detail. The Proper Water defined by Iida corresponds to the transitional water below the dichothermal layer.

In an investigation of the region off the eastern Okhotsk coast of Hokkaido where the water depth is much greater, Takizawa (1982) defined the water masses a little differently (Fig. 2.4.11). He divided the Soya Current Water into two water masses by their temperature ranges: the Soya Warm Water and the Forerunner of the Soya Warm Water. The Forerunner Water is cold Soya Current Water which flows into the Okhotsk Sea in spring. He also divided the Surface Low Salinity Water into the Okhotsk Surface Water which is generated locally by ice melting and precipitation and the East Sakhalin Current Water which is carried into this region by the southward current off the east Sakhalin coast. The water masses overlap in T-S, and sometimes the separation of these two waters is difficult. However, it is important to remember that the Surface Low Salinity Water has several origins.

In the following, we shall use the simplest terms: the Soya Current Water, the Dichothermal Water, the Transitional Water, and the Surface Low Salinity Water.

4.5 The Soya Current and its seasonal variations off the western Okhotsk coast of Hokkaido in the warm season

The oceanic conditions off Mombetsu on the northern coast of Hokkaido have been investigated by the Sea Ice Research Laboratory, the Institute of Low Temperature Science, Hokkaido University. This area is representative of the Soya Current Region off the western Okhotsk coast of Hokkaido. Many repeated sections off Monbetsu in 1968 - 1970 show the seasonal progression in the Soya Current (Aota, 1975).

In late spring, just after the pack-ice disappears, Soya Current Water intrudes into the Okhotsk Sea along the bottom (Fig. 2.4.12). By May - June, the strength of the Soya Current increases, and the coastal area is occupied with the Soya Current Water, though, for some sections such as in May 1970, the surface water is influenced by river discharge and has relatively low chlorinity and low temperature. There is a sharp front between the Soya Current Water and the Dichothermal Water. However, when the bottom of the Dichothermal Layer is shallow and the Transitional Layer is observed in the section (e.g., March 1969, May 1969, and June 1970), there is no conspicuous front between the Soya Current Water and the Transitional Water. The depth of the front between the Soya Current Water and the Dichothermal Water increases offshore, and the Soya Current Water tends to intrude below the offshore Dichothermal Layer as the former is saltier and denser. Sometimes (early May 1968, late May 1968, and June 1970) isolated cold water appears on the shoreward side of the Dichothermal Layer. As discussed in

Section 4.8.3, frontal eddies are often generated in spring and these isolated waters might represent a large meander or the breaking of the front.

The Soya Current is most developed in August - September, and the sea surface temperature near the shore sometimes increases up to about 20°C. The depth of isotherms in the coastal region decreases offshore, reflecting the thermal stratification in the warm Soya Current Water in summer. However, it should be noted that the depth of isohalines generally increases offshore. This indicates that the contribution of salinity to the stratification is also important in the deeper layers even in summer. The surface cold water belt off the Soya Current Water is recognized in some sections (July 1970 and August 1969), but it is not very conspicuous.

In October - December, the highest temperature and salinity portion of the Soya Current Water usually begins to submerge. The surface water is replaced by the low salinity water in November. This replacement does not necessarily proceed from northwest to southeast along the coast, and sometimes the replacement occurs at Monbetsu earlier than at Esashi. It should be noted that the high salinity Soya Current Water still exists near the bottom in December, though the temperature at its center is considerably colder and the position of its center moves offshore along the bottom.

Though the oceanic structure off Monbetsu exhibits considerable interannual variation (Aota, 1975), seasonal variation is also clear. (The seasonal variation off Esashi is very similar to that off Monbetsu and is not shown here). Aota (1971) showed the seasonal variations of temperature and chlorinity off Monbetsu for three years (Fig. 2.4.13). At the station closest to the coast (5 miles), the surface temperature is almost at freezing by the end of March due to the effect of melting ice. The influence of the fresh water discharge from land is seen in the fresher surface layer to early June. The Soya Current Water can be recognized in the lower layers from the middle of March. The strength of the Soya Current increases, and the maximum temperature and maximum salinity is observed at the end of August. In October, the Surface Low Salinity Water appears, and the Soya Current Water disappears from the surface. The strength of the Soya Current Water recovers at the end of November, but it disappears over the whole depth range in December.

The vertical structure at the 15 mile station in March suggests that winter convection reaches down to about 50 m depth, and the resulting dichothermal layer remains until June though its temperature increases gradually. Below the dichothermal layer, the Soya Current Water exists from March to November. The Soya Current Water dominates in August - September and extends to the surface. From October, the Soya Current Water submerges and its thickness rapidly decreases. In December, relatively high salinity water can be seen only near the bottom.

At the 25 mile station, the Soya Current Water exists only in the deeper layer if we define it as the water of chlorinity higher than 18.4 o/oo. The thickness of the Soya Current Water is largest in summer, and the iso-chlorinity line of 18.2 o/oo outcrops. However the maximum temperature and salinity appear on the bottom in June and July, respectively. This high temperature and high salinity water might be carried offshore along the bottom.

Defining the Soya Current Water as having chlorinity higher than 18.6 o/oo, Aota (1971) investigated the seasonal variation of the Soya Current Water off Monbetsu and off Esashi (Fig. 2.4.14). The area has a maximum value of about 4.5 km^2 in August. It is interesting that this Soya Current area is also observed in November every year, and this reappearance is much more conspicuous off Esashi than off Monbetsu. The reason for this reappearance has not been clarified. The mean current speed of the Soya Current is about 30 cm/s off Monbetsu. If we assume a cross-sectional area of 4.5 km^2, the volume transport of the Soya Current off Monbetsu is 1.3 x 106 m^3/s. This value agrees with the inflow transport through Soya Strait in the previous sub-section. The seasonal variation of transport can be calculated by combining the variation of the cross-sectional area in Fig. 2.4.14. and the current velocity distribution calculated from sea level differences between Wakkanai, Monbetsu and Abashiri (Section 2.4.2). The results are shown in Fig. 2.4.15.

4.6 Oceanic conditions off the northwestern Okhotsk coast of Hokkaido in the pack-ice season

In order to measure currents off Monbetsu when the area is covered with pack-ice, Aota and Kawamura (1978, 1979) set moored current meters in the winters of 1976 - 1977, 1977 - 1978, and 1978 - 1979 (Fig. 2.4. 16). Winter 1976 - 1977 observations are shown in Fig. 2.4.17. Judging from measured temperature and salinity, Low Salinity Surface Water occupied the surface 25 m at both the 4 and 8 mile stations from early December; temperature and salinity began to increase from late February. The Soya Current Water returned on about March 15. The current velocity parallel to the coast decreased gradually from December to February, with some short period fluctuations super-imposed. It should be noted that, even after the Soya Current Water disappeared in winter, strong southwestward currents were observed.

More extensive observations were carried out in winter 1977 - 1978 (Aota and Kawamura, 1978). Just after the current meters were set, sections of temperature and salinity were occupied off Monbetsu and in Soya Strait. Soya Current Water appears to flow through Soya Strait in late December and can be recognized in the bottom layer also off Monbetsu. The upper 25 m consisted of Low Salinity Surface Water at all observation points. Current meter observations during that period showed that southwestward flow dominated even when the surface water was the Low Salinity Surface Water. The current variability was similar to that in winter 1976 - 1977, although sporadic salinity increases in mid-winter were seen only in 1977 - 1978.

Noisy fluctuations of temperature and salinity were observed even in mid-winter at 60 m at the 8 mile station. The salinity increases clearly show the influence of the Soya Current Water, and the current component parallel to the coast tends to increase along with salinity. In winter 1978 - 1979, current meter observations off Monbetsu and off Ohmu show similar variation to winter 1977 - 1978. Velocity increases were similarly often associated with salinity increases. However, it should be noted that the velocity increases are not always accompanied by salinity increases, indicating that the southeastward flow of the Low Salinity Surface Water can be strengthened independently. It is also noted that the correlation of the temperature and salinity variations between the Monbetsu and Ohmu sections is poor. This would indicate that although the Soya Current exists in winter, the flow is intermittent. However, current observations have been located only at the edge of the Soya Water (Fig. 2.4.18). If the observation points were at the center of the Soya Current Water domain, namely near the bottom farther offshore, a less intermittent Soya Current might be observed.

The above figures suggest that cold and relatively fresh waters flow southeastward off Hokkaido in winter, and this flow is independent of the bottom-intensified Soya Current. Pack-ice drifts based on sea ice radar indicate that southeastward flow predominates at the surface in winter. (Useful targets in radar images are small polynyas and/or ice ridges, permitting easy observation of the pack ice drift.) The averaged velocity component parallel to the coast for February 1970, (Tabata, 1971), was 0.7 cm/s on February 4, 5.8 cm/s on February 5, 8.1 cm/s on February 6, 8.1 cm/s on February 19 and 10.5 cm/s on February 20. In early February 1977, the flow was stronger than in February 1970, and 15.8 $\pm$ 2.1 cm/s if we translate Takizawa's (1982) results into along shore velocity components. The flow directions estimated above were all southeastward. The movements of pack ice should be affected by winds also, but the winds were not favorable for southeastward ice movement and moreover were very variable in these observation times. Thus the ice drift speeds appear to reflect the oceanic current speeds.

Ocean currents in the pack-ice season have not been clarified fully. However, it can be concluded that southeastward flow occurs just off the western portion of Hokkaido's Okhotsk coast, and both the Soya Current Water and the Low Salinity Surface Water are carried by this current. The wind-driven circulation in the Okhotsk Sea due to the strong winter monsoon has not been investigated. The Soya Current appears to be driven by the sea level difference between the Japan Sea and the Okhotsk Sea in summer. As the Soya Current in winter is baroclinic, it may be generated by mechanisms other than those of summer.

4.7 The Soya Current off the eastern Okhotsk coast of Hokkaido

A schematic of the Soya Current circulation from Bobkov (1993) (Fig. 2.4.19) shows how it splits at Cape Shiretoko, continues up to the center of Etorohu Island, and passes through the first two Kuril Straits (Nemuro and Kunashiri). Observations in this region however are more limited in line length and station spacing than off the western part of the coast. Observations from different years (May 1955, June 1978, August - September 1973, and October 1973) illustrate the structure of the Soya Current in this region. The saline Soya Current Water can be seen west of Cape Notoro but is difficult to see in Abashiri Bay (Fig. 2.4.20). Off Monbetsu (Fig. 2.4.20b), the Soya Current Water appears at stas. 16 - 18; the coastal surface layer has very low salinity due to river discharge. The temperature of the Soya Current Water is 2 - 5°C except near the surface. Takizawa (1982) called Soya Current Water of such low temperature the Forerunner of the Soya Current Water (Fig. 2.4.11).

Off Cape Notoro, the surface layer consists of Low Salinity Water (Fig. 2.4.20c). The low temperature Soya Current Water is submerged, being found along the sloping bottom at depths of 100 to 300 m. The same situation appears off Cape Shiretoko (Fig. 2.4.20d), but the depth of the Soya Current Water is 200 - 400 m. The shelf along the coast to the east of Cape Notoro is narrow, and the depth of Abashiri Bay is large enough for appearance of the Transitional Layer. The temperature and salinity contrasts between the low temperature Soya Current Water and the Transitional Layer Water are very weak. However, Takizawa (1982) pointed out that the Soya Current Water can be identified by its high dissolved oxygen content (Fig. 2.4.20d).

In observations from June 1978, the Soya Current Water passed Cape Notoro and intruded into Abashiri Bay along the coast (Miyake et al., 1989). The Soya Current Water at 50 m flowed continuously along the coast of Abashiri Bay from Cape Notoro to Cape Shiretoko. Off Cape Notoro the Soya Current Water began to submerge, and the high salinity core was found at about 200 m depth. The high salinity core appears to have left the bottom, shoaling offshore. The only source of high salinity in this region is the Soya Current Water. The high salinity region found along the northern coast of the Shiretoko Peninsula mentioned above can be understood as shoaling and surfacing of the Soya Current Water as it flows along the west coast of the Shiretoko Peninsula.

In summer and early autumn, Takizawa (1982)'s data from 1973 illustrate how high the temperature of the Soya Current Water is, reaching 20°C. The accompanying surface salinity distribution appears to indicate that the Soya Current was flowing along the whole Okhotsk coast of Hokkaido from Soya Strait to Cape Shiretoko. However, the core of highest salinity was submerged although it was shallower than in data from May and June. In mid-autumn of 1973, the Soya Current Water surfaced off Cape Shiretoko, although it is normally submerged by October. The limited data precludes understanding the seasonal variations of the high salinity core of the Soya Current Water in Abashiri Bay. However, it might be explained by a time lag due to water mass advection: over a few months the thick Soya Current Water found off the western coast in summer can be carried to the tip of Cape Shiretoko. This time lag appears to coincide with Wakatsuchi and Martin's (1991) argument that the Soya Current Water intrudes into the Kuril Basin Region in November or so (Section 2.3.5).

The behavior of the Soya Current Water after passing the tip of Cape Shiretoko has not been clarified, though many investigators have discussed this subject (e.g., Nasukawa 1960, Iida 1962, Fujii and Sato 1977, Takizawa and Aota 1978, Hori et al. 1981). Takizawa (1982) summarizes their results in a schematic diagram of the Soya Current (Fig. 2.4.21). Bobkov's (1991) water mass analysis showed that the Soya Current Water can be traced at least to Etorofu Island and may pass partially through Kunashiri Strait; it does reach the northern tip of Etorofu, being transformed through vertical mixing at Chirip peninsula on the north side of Etorofu.

Variability is high off the eastern Okhotsk coast of Hokkaido (Fig. 2.4.22). The 5°C isotherm may be considered to mark the offshore boundary of the Soya Current Water although a relatively narrow zone of mixed water exists between the Soya Current Water and the Dichothermal Water. The lack of variability in the position of the 5°C isotherm west of Cape Notoro reflects the fact that the Soya Current there reaches is bottom-controlled. The isotherm is quite variable east of Cape Notoro after the Soya Current leaves the wide, shallow shelf region.

The submergence of the Soya Current Water has not been fully documented and there are complicated seasonal and interannual variations in the Abashiri Bay region where the Soya Current leaves the coast. The fate of the saline Soya Current Water in the Okhotsk Sea is one of the keys to understanding water mass modification in the Okhotsk Sea. Further investigations in the Abashiri Bay region are recommended.

4.8 The structure and variation of the front marking the offshore-side of the Soya Current

4.8.1 Cold water belt

A cold water belt is usually observed at the surface just offshore of the Soya Current. Iida (1962) modeled it using geostrophic balance modified by frictional force. Maeda (1968) argued that the cold belt is generated by winds through a mechanism similar to coastal upwelling. Miyake et al. (1989) proposed a more delicate formation mechanism including cabbeling. They suggest that relatively dense water found in a domed structure in sigma-t in Abashiri Bay can be produced by cabbeling during horizontal mixing between the Soya Current Water and the Dichothermal Water. They suggest that this denser water downwells and the resulting divergence near the surface pulls relatively cold water up in the dome. However, it is worth pointing out that the shoreward density structure is determined by temperature, while the offshore structure is determined rather by salinity. Thus it seems difficult to connect this dome with vertical advection. It should be noted that the temperature and salinity contributions to density are almost the same order in this region.

The narrowness of the cold water belt means that it can be missed in standard station observations (Aota et al., 1991). A very narrow cold water belt was observed in a NOAA IR image from September 9, 1990 (Fig. 2.4.23). However, it was difficult to see any signature of the cold water belt in vertical sections made at the same time, suggesting that much closer station spacing than is common is required to resolve it.

4.8.2 Structure of the Soya Current Front

The temperature and salinity gradients across the offshore margin of the Soya Current Water are large, and the front can be clearly seen in the vertical sections described in previous subsections. However, the density gradient is usually very weak, and mixed waters are usually observed between the Soya Current Water and the Dichothermal Water.

Detailed vertical sections of temperature and salinity along a line extending northeast off Monbetsu and along the line which runs parallel and 20 miles southeast to it are shown in Figs. 2.4.24 and 2.4.25. In these sections, the Soya Current Water is homogeneous both horizontally and vertically from near the shore to about 15 miles offshore. However, its high salinity core (>34.0 o/oo) is seen a little offshore, below 60 - 70 m depth. Two temperature fronts appear: one at about 20 - 23 miles and the second at 27 miles offshore in Fig. 2.4.24 and at about 18 miles and at 22 - 24 miles offshore in Fig. 2.4.25. The temperature front which lies farther offshore corresponds to the salinity front on both lines. The water between the two temperature fronts might be considered a mixed water of the Soya Current Water and the Dichothermal Water in the middle layers, but it is not in the layers deeper than 60 - 70 m because a high salinity core is found between the two temperature fronts. In addition, patches of low temperature and salinity are found between the two temperature fronts: at 100 m depth at 20.5 miles offshore, at 70 m at 23 miles offshore in Fig. 2.4.24 and at 75 m depth at 17.5 miles offshore in Fig. 2.4.25. Judging from their salinities, the water inside these patches originates in the offshore dichothermal layer.

The Soya Current Water and Dichothermal Layer Water off Mombetsu have the same density from May to December. This means that exchange can occur easily between the two waters in these months.

It should be noted that the gross features of the temperature and salinity sections in Figs. 2.4.24 and 2.4.25 are very similar to each other, but their fine frontal structures are quite different. The fine structure of the front was observed over a 40-hour period in July 1988 (Aota et al., 1991) and was found to evolve significantly.

The physical meaning of these complicated structures in the Soya Current Front has not been clarified. Apparently the spatial and temporal scales of the fine structure are very small: orders of a few tens of kilometers and of a few days.

Large cold patches are sometimes seen in the near-surface layer in the Soya Current Water domain (Fig. 2.4.26 and also in Aota, 1982 and Aota et al., 1991). These cold water patches seem to be cut off from the offshore Dichothermal Layer Water by instability of the Soya Current Front. The frontal waves and their breaking are discussed in the next sub-section.

4.8.3 Frontal waves and breaking

The wave-like patterns of the front and the eddies are easily observable in spring when the pack-ice is just leaving the Soya Current Region, because the pack-ice is a good tracer of the ocean current beneath. For example, a cyclonic ice-ocean eddy was observed off the coast of Esashi-Ohmu (Fig. 2.4.27). The eddy was about 20 km in diameter and was marked by ice belts composed of homogeneous sized ice floes with a diameter of about 10 m. The pack-ice condition at the time that the photograph is taken was favorable because the winds were weak and the ice concentration was low. By this time, the Soya Current had revived and generated an open water area along the Hokkaido coast. Thus, the ice edge represented roughly the offshore boundary of the Soya Current Water.

Ohshima (1988) reported remarkable backward-breaking wave-like patterns in the Soya Current Front in spring and summer, using satellite IR images. The evolution of backward-breaking waves, using the sea ice radar network for April 14-16, 1984, is shown in Fig. 2.4.28. Three backward breaking waves can be seen. The circular eddy shown in Fig. 2.4.27 would have been generated by similar breaking.

The isolated cold, fresh patch near the coast shown in Fig. 2.4.26 was observed just after the ice eddy observation of Fig. 2.4.27.

Wakatsuchi and Ohshima (1990) concluded that this patch was generated by the breaking of the frontal wave. Similar cold patches have been seen in May and July when there is no sea ice to mark the surface eddy (Aota et al., 1982; Aota, 1991). This suggests that breaking may occur also in the warm season.

The wavelengths of the frontal waves observed from 1969 to 1988 were about 50 km and were almost constant along the whole Okhotsk coast of Hokkaido (Fig. 2.4.29). The wavelength is unaffected by pack-ice. Ohshima (1988) investigated differences of the frontal waves between spring and summer: the wavelength in spring is about 45 km, a little shorter than the 50 km wavelength in summer. The wave period and propagation speed in spring is 2 - 3 days and 20 cm/s, and in summer is 1 day and 50 - 60 cm/s. This is related to the current speed of the Soya Current which acts as a carrier of the waves.

Ohshima (1987) suggested the possibility of barotropic instability as a formation mechanism of the frontal waves. Ohshima (1988) and Ohshima and Wakatsuchi (1990) used a simple barotropic model with a simple bottom configuration for the western part of the Soya Current Region. The driving force of the Soya Current was assumed to be the sea level difference between the Japan and Okhotsk Seas through Soya Strait. As the flow passes through the strait, a strong positive vorticity is produced by the frictional torques in the strait and by vortex stretching in the eastern mouth of the strait. This strong vorticity induces barotropic instability, forming a frontal wave. The role of these frontal waves or of the eddies on the water mixing and water mass modification in the frontal region has not been investigated.

5.0 THE KURIL AND MIXED WATER REGIONS

5.1 Introduction

The circulation of the northern North Pacific consists of a cyclonic gyre which encompasses the Gulf of Alaska and the northwestern Pacific and which enters the Bering and Okhotsk Seas (Figs. 2.3.6 and 2.5.1). There are two centers of high upwelling induced by the wind stress curl, one centered in the Gulf of Alaska and the other an elongated region parallel to the Kuril Islands. In a number of papers separation between the western Subarctic gyre and the Gulf of Alaska gyre near the dateline is indicated; this appears to be time-dependent, but there is still much work to be done in observing and quantifying this.

The western boundary current of the North Pacific's subpolar gyre is complicated by the presence of the Kuril Islands. The subpolar circulation driven by the cyclonic wind stress curl would extend unimpeded into the Bering and Okhotsk Seas but for the presence of the islands. The marginal seas have major effects on the waters which circulate through them because of the narrow straits which enhance mixing and because residence times might be longer than if there were no islands. These two particular marginal seas also have major effects because of their large shelf areas, sea ice formation, and river discharge.

In the Kuril Island region, the western boundary current partially enters the Okhotsk Sea where its waters are transformed and joined by Soya Current waters from the Japan Sea. The water which exits from the Okhotsk Sea farther south is considerably different from the water at the northern end of the Kuril Islands. Therefore different names are given to the southwestward-flowing western boundary current in the north (East Kamchatka Current) and in the south (Oyashio). The source of waters in the East Kamchatka Current is the Bering Sea and northern subpolar gyre, and the source of waters in the Oyashio is the Okhotsk Sea, East Kamchatka Current and central subpolar gyre. In Hirano's (1957) general classification of waters in the western subarctic gyre (Fig. 2.5.2), these regions of differing water properties are shown clearly; the East Kamchatka Current is composed of what he calls Central water, whereas the Oyashio water is markedly different because of the Okhotsk Sea influence.

There is some difference of opinion on where to locate the name change from East Kamchatka Current to Oyashio. Reid (1973) defines it to be at 49°N, the location of Kruzenshtern Strait, which is also the definition of Dodimead et al. (1962) who showed the East Kamchatka Current flowing into the Okhotsk Sea just south of the Kamchatka Peninsula. Likewise Kawai (1972) defined the Oyashio as the southward flow along the Kuril Islands which does not enter the Okhotsk Sea. Favorite et al. (1976) defined as the Kamchatka Current (East/Deep and Southwest) all southwestward flow along the Kurils down to Bussol' Strait, which is the main exit for waters flowing out of the Okhotsk Sea. Ohtani's (1991) recent opinion is that the name change should occur at Bussol' Strait because of a shift in water mass properties there. We adopt this convention.

A major feature of the Kuril Island and Hokkaido region is the large eddies which appear to originate as Kuroshio warm core rings and which migrate slowly northeastward. They appear to follow the deep trench, mixing with surrounding waters of the Oyashio and East Kamchatka Current, which cause them to become progressively colder and fresher.

The Oyashio flows southward into the Mixed Water Region (or Perturbed Area) south of Hokkaido, and the water mass front associated with it usually meanders, forming two "intrusions" (Kawai, 1972), or "branches" as they were referred to in earlier literature. We follow Kawai's nomenclature as it is apparent that the Oyashio does not break into two separate southward flows, as implied by the word branch. Kawai's (1972) oft-cited schematic of conditions in the Mixed Water Region is shown in Fig. 2.5.3. Intrusions of Oyashio water are often found very far south in the Mixed Water Region, sometimes reaching to the Kuroshio. Indices of the southernmost extent of Oyashio Water are used in descriptions of the climate of the region. Within the Mixed Water Region, Oyashio Water mixes with water from the Kuroshio and Japan Sea. In the process the intermediate salinity minimum of the subtropical North Pacific (North Pacific Intermediate Water) is created.

The Oyashio Front forms the northern boundary of the Mixed Water Region, extending eastward from just south of Hokkaido. Most of the Oyashio water remains in the subarctic gyre, north of this front, which appears to continue eastward as the Subarctic Front. It is important to note that the Oyashio and Kuroshio do not separate from the western boundary at the same location and that their identifiable fronts extend eastward from the western boundary at very different latitudes.

Along the coast of Hokkaido and in the Mixed Water Region, "Oyashio" has several meanings. It can refer to the boundary current flowing southwestward into the region or the narrow coastal current carrying quite fresh water along the coast of Hokkaido from the southern Okhotsk Sea. It can be the water mass front which extends eastward from Hokkaido which separates waters of subpolar and mixed water characteristics. It can refer to any waters which originate in the Oyashio, commonly identified as any station with water colder than 5°C at 100 m. We therefore distinguish carefully between the Oyashio, the coastal Oyashio, the Oyashio Front, Oyashio Water, and Coastal Oyashio Water.

5.2 The East Kamchatka Current

The southward-flowing East Kamchatka Current originates in flow out of the Bering Sea through Kamchatka Strait, which at more than 4,000 m deep is the deepest passage through the Aleutian Islands and is in fact deeper than the Bering Sea itself. Useful discussions of the East Kamchatka Current in the upper ocean by Dodimead et al. (1962), Reid (1965, 1973), and Favorite et al. (1976) are more complete than can be included here.

Water below 3,500 - 4,000 m depth cannot cycle through the Bering Sea. The direction of flow deeper than this is probably in the same direction as the surface flow, in a very narrow boundary current (Warren and Owens, 1988; Talley and Joyce, 1991). Slightly offshore and extending to the bottom of the Trench, flow might be northward based on its characteristics (Talley and Joyce, 1991). The anticyclonic Kuril eddies migrate slowly northeastward, following the trench (Lobanov and Bulatov, 1993).

5.2.1 Water characteristics north of Kruzenshtern Strait

The East Kamchatka Current, flowing southward along the Kamchatka Peninsula, is the source of Pacific water for the Okhotsk Sea (Part 2, Section 2). Ohtani (1989) shows the full progression of water properties from the Bering Sea down the East Kamchatka Current, into the Okhotsk Sea and in the Oyashio (Fig. 2.5.4) and schematic vertical profiles for properties in the western subarctic domain (Fig. 2.5.5).

Waters in the western subarctic gyre and East Kamchatka Current north of Kruzenshtern Strait, just south of the tip of the Kamchatka Peninsula, are characterized by a near-surface dichothermal layer in summer (temperature minimum) and a slightly deeper mesothermal layer (temperature maximum). Salinity is lowest at the sea surface and increases monotonically with depth. There is a pronounced halocline and thermocline at the base of the temperature minimum. Oxygen content is close to full saturation in the surface layer, decreases downward to a minimum at about 800 m, and then increases to the bottom. Oxygen saturation just below the surface is often much greater than 100% in summer, but may be less than 100% in winter due to rapid turnover (Reid, 1973).

Maps of surface temperature, salinity and density in winter (January-April, 1966) show that the coastal waters in the East Kamchatka Current are relatively fresh, very cold, and less dense than the offshore waters (Fig. 2.5.6 from Reid, 1973). The highest surface salinities and densities of the subpolar gyre lie in the center of the cyclonic circulation, which is elongated parallel to the Kuril Islands.

In winter the temperature minimum often occurs at the surface; in the 1966 winter data, this region is roughly the same as that occupied by geopotential anomalies north and west of the offshore contour of 1.05 (Fig. 2.5.6a). Thus the near-surface vertical temperature minimum reflects the winter surface temperature; the minimum occurs just above the base of the winter mixed layer. Winter and summer sections off Kamchatka from Reid (1973) (Fig. 2.5.7) show this seasonal contrast.

The thermocline and halocline are essentially coincident in this "western subarctic domain", using Dodimead et al.'s (1962) terminology, or "central water" using Hirano's (1957) term. Just below the thermocline is found the temperature maximum. Depth, temperature, and thermosteric anomaly at the temperature maximum outside the Okhotsk Sea are discussed thoroughly by Reid. The coldest, deepest temperature maximum occurs in the Okhotsk Sea. The continuity of the East Kamchatka Current waters from inside the Bering Sea to the southern tip of Kamchatka are apparent. Equally apparent is the influence of the Okhotsk Sea on properties farther south along the Kuril Islands.

Salinity, potential temperature and oxygen at a thermosteric anomaly of 100 cl/ton (σ_θ of 27.07), discussed also by Reid (1973), likewise show the Bering Sea origin of the East Kamchatka Current water and the gradients encountered along the Kuril Islands south of Kruzenshtern Strait.

The oxygen distribution in the western subarctic gyre is of interest: in winter, the surface layer is not fully saturated (Reid, 1972). However, summertime measurements often show extremely supersaturated water associated with the temperature minimum (Talley, Joyce and deSzoeke, 1991), probably due to the summer warming (Moroshkin, 1962). Reid (1982) showed that oxygen saturation is a useful indicator of the previous winter's mixed layer depth and density (Fig. 2.5.8); saturation is a better indicator than a fixed density change and a much better indicator than a fixed temperature change from the sea surface. Oxygen is also useful as an indicator of winter ventilation on isopycnals. However, since the oxycline, halocline and thermocline are very intense in the subarctic gyre, it is difficult to map precisely the high oxygen regions of near-surface isopycnals. The use of the continuously-profiling CTD with a functioning oxygen probe which can be calibrated is necessary for improvement in this indicator of winter ventilation.

5.2.2 Circulation north of Kruzenshtern Strait

Geopotential anomaly at the sea surface relative to 1,000 dbar (Fig. 2.5.6a) shown by Reid (1973) is representative of other displays of the same, and is based on a more detailed and synoptic data set than most other presentations (e.g., Dodimead et al., 1962; Favorite et al., 1976). Reid observed at 55°N a swift, narrow western boundary current, of 20 - 30 nm width, with geostrophic velocity at the surface relative to 1,500 dbar of 87 cm/s, and transport of 23 Sv relative to 1,500 dbar. His extensive discussion indicates that this was much swifter and narrower than estimated by Allen (1964) with summer data whose contrasting transport was 8 Sv. Fig. 2.5.7 from Reid shows the difference in thermocline depth in these winter and summer sections which results in the large difference in transports.

Additional estimates of transport appear to be few (see Table). Miyake et al. (1991) used the Akademik Korolev CTD section of May-June, 1987, extending southeastward from just south of the tip of Kamchatka (Talley et al., 1991) and obtained a transport of 50 Sv relative to the bottom. On the other hand, we obtain a smaller estimate of 24 Sv using the same data and also referencing to the bottom, using the maximum cumulative southward transport as our choice. Transport relative to 2,000 dbar from this section is 19 Sv, with a maximum velocity of 40 cm/sec and reaching maximum transport 65 nm from the 300 m isobath.

Rogachev et al. (1993) report a small transport of 9-10 Sv for the East Kamchatka Current in fall, 1990, and moreover also give transports for sections in the northern Kurils; these latter transports are about half of this (4 - 5 Sv), possibly reflecting flow into the Okhotsk Sea. Their synoptic survey clearly shows the importance of eddies (Fig. 2.5.12 below).

Several other CTD sections crossing the East Kamchatka Current were available so transports were computed from them as well; these CTD casts extended only to 2,000 dbar, dictating our choice of reference level. The sections were collected as part of a joint program between Russia, Canada and the U.S.A. (INPOC) on FERHRI's vessel Priliv. The Octo-ber, 1992, section along 155°E was dominated by a large offshore eddy, as discussed below in 5.2.3, and so the transport calculation is difficult to interpret. The section eastward along 50°N, with no eddy, yields a transport of 15 Sv. The fall, 1992, WOCE cruise on the R/V Vickers (Taft and Johnson, personal communication) also had an eddy offshore and a relatively small transport; the maximum southward transport including the eddy was 19 Sv relative to the bottom.

It must be emphasized that there is no knowledge of the strength of barotropic transport for the East Kamchatka Current and that the actual transport could be larger than indicated in the table.

East Kamchatka Current Transport off southern Kamchatka

Ship	Date	Transport (Sv) (/reference level)	Max surface speed (cm/sec)	Notes
(Allen, 1964)	Summer 1963	8 (/1,500 m)		
R/V Argo (Kamchatka Strait)	February 1966	23 (/1,500 m)	87	
Akademik Korolev	June 1987	19 (/2,000 m)	40	weak eddy
Akademik Korolev	"	24 (/bottom)	40	"
(INPOC) at 51°N	Fall 1990	9 (/1,000 m)		
Priliv (INPOC) along 50°N	October 1992	15 (/2,000 m)	20	counter-current
Priliv (INPOC) along 155°E	"	11 (/2,000 m)	11	eddy
Priliv (INPOC) along 50°N	April 1993	11 (/2,000 m)	27	
Priliv (INPOC) along 155°E	"	15 (/2,000 m)	18	shifted offshore
R/V Vickers (WOCE)	August, 1992	13 (/bottom)	15	eddy

Favorite et al. (1976) calculated the expected western boundary current transport due to interior Sverdrup transport for each month. Fig. 2.5.9 shows their estimated January and June transports, which are representative of all of their monthly maps for these seasons. The Sverdrup transport for the East Kamchatka Current should be greater than 20 Sv in January and 5 - 9 Sv in June, in rather amazing agreement with the two geostrophic estimates given by Reid (1973), but not in accord with the new estimates relative to 2,000 dbar shown in the Table.

Sekine (1988) computed the annual variation in Sverdrup transport (Fig. 2.5.10) in a study of the causes of an anomalous southward intrusion of the Oyashio (Ishikawa, 1984, 1988) (see Section 5.3.4 below). Along the northern line, which should characterize the Sverdrup forcing for the Oyashio/East Kamchatka Current, he found a large annual cycle. In winter and spring, the Sverdrup transport is northward (southward western boundary current) and the Sverdrup transport peaks at 40 - 60 Sv. In summer and fall, the sign is reversed and the transport is much smaller (less than 10 Sv). During years of anomalous southward intrusion of the Oyashio, which implies a strengthened Oyashio, he shows stronger northward Sverdrup transport. It is not clear what the relation between the Sverdrup transport and the Oyashio transport should be, either in magnitude (because of the possibility of recirculation) or in phase. The relative transports listed above for the East Kamchatka Current are much smaller than Sekine's maximum transports. They also do not show the sort of seasonal cycle implied by the Sverdrup transport, although the number of direct transport estimates in the table is admittedly small. The discrepancy might result from either underestimation of the actual transport due to lack of direct current measurements, or that the western boundary current transport reflects some average of the annual cycle, which would be close to 15 - 20 Sv.

Transport into the Okhotsk Sea from the East Kamchatka Current through Kruzenshtern Strait has not been estimated to our knowledge, noting that our coverage of the Russian literature is extremely limited. Moroshkin (1962) suggests that most of the inflow into the Okhotsk Sea occurs through Kruzenshtern Strait. D. Swift and Riser (personal communication) calculate a net outflow of about 4 Sv, which might have a large seasonal variability (up to 12 Sv is hypothesized). If the Soya Current transports 0.5 - 1.0 Sv into the Okhotsk Sea, then the net inflow from the Pacific to the Okhotsk could be 3 - 9 Sv, with the larger transport occurring in winter. If there is any accuracy to the 2,000 dbar reference level, it would appear that little more than half of the transport (5/8 in summer and 11/20 in winter) of the East Kamchatka Current actually flows into the Okhotsk Sea. If the actual reference level should be deeper, and the transport higher, than an even smaller fraction enters the Okhotsk Sea. The remaining transport must remain in the subpolar gyre, perhaps in the subarctic current suggested by Favorite et al. (1976).

5.2.3 Circulation between Kruzenshtern Strait and Bussol' Strait: large eddies

While some of the East Kamchatka Current flows into the Sea of Okhotsk through Kruzenshtern Strait, some of the remainder may continue southward with some entering through Bussol' Strait (Moroshkin, 1962). Approximately half might not circulate through the Okhotsk Sea, assuming the validity of the Swift/Riser exchange estimates and the conservative estimates of East Kamchatka Current transport given in the previous sub-section. Favorite et al. (1976) show schema-tically a "Southeast Kamchatka Current" veering offshore from the Kuril Islands south of Kruzenshtern Strait, and a "Southwest Kamchatka Current" which is the deeper part of the East Kamchatka Current which cannot enter Kruzenshtern Strait because of its depth.

The flow along the northern Kurils has not been well observed. Drift bottle releases from 1893 to 1913 showed southwestward flow all along the Kurils (Kajiyama, 1936). The region is dominated by large eddies, as apparent in satellite photographs from 1980 (Fig. 2.5.11, from Bulatov and Lobanov, 1983). The October, 1992, INPOC section referred to in Section 5.2.2 had current reversals suggestive of such large eddies, and papers in progress using extensive new synoptic CTD surveys of the Kuril Island area (both INPOC and JFA) show such large eddies there (Fig. 2.5.12 from Rogachev et al., 1993). These eddies are a ubiquitous feature of the region, being present on four separate INPOC surveys in different years, all with excellent station coverage. The eddies appear to have a long lifetime but there is disagreement about whether subsequent surveys were observing the same eddies each time. Lobanov et al. (1991) and Lobanov and Bulatov (1993) tracked such eddies using satellite images, suggesting general northeastward drift and origin as Kuroshio warm core rings (Fig. 2.5.13); remnants of the warm core remain in some of the eddies observed off of the southern Kurils, but the suggestion is that warm cores are replaced by cold cores north of Bussol' Strait due to entrainment of the Okhotsk and East Kamchatka Current waters which have a dichothermal layer.

5.3 The Oyashio

The Oyashio forms south of Bussol' Strait from waters exiting the Okhotsk Sea which join subarctic waters, possibly of East Kamchatka Current origin. In the previous subsection it was suggested that more than half of the subarctic circulation does not pass through the Okhotsk Sea. Since the Okhotsk Sea water is considerably modified from the subarctic water, and because there is intense vertical mixing around the Kuril Islands (reviewed below), the Okhotsk Sea water and subarctic gyre water are very different (reviewed below).

The basic features of the Oyashio as it enters the Mixed Water Region are depicted by Kawai (1972) (Fig. 2.5.3): southwestward flow along the southern Kuril Islands, two branches or intrusions as the Oyashio passes Cape Erimo (southern end of the east coast of Hokkaido), northeastward flow out of the region, and intrusion of cold water of Oyashio origin southward along the Honshu coast. The Kuroshio warm core rings and the inflowing Tsugaru water in this figure point to the importance of mixing and complicated, variable dynamics in this region.

The Oyashio has several definitions in the Mixed Water Region. One definition of Oyashio Water is the water found off the southern Kuril Islands and Hokkaido in which salinity increases monotonically to the bottom. Its southern boundary can be called the Oyashio Front, which is also the western part of the Subarctic Front if the Oyashio Front is defined as the water mass boundary. Next to the Hokkaido coast, the Oyashio (current) is defined as a boundary current with recognizable baroclinic shear, which may be reduced as the Oyashio separates and turns eastward in the Oyashio Front. Oyashio influence in the Mixed Water Region is often defined by the location of the 5°C isotherm at 100 m; this location might be farther south than the Oyashio Front defined as the main water mass boundary.

As described in the following subsections, several principal issues for study for the Oyashio are: (1) rate of formation of Oyashio Water and relative importance of Okhotsk Sea Water, mixed water in the Kuril Straits, and East Kamchatka Current water, (2) the average picture of transports all along the western boundary from Kamchatka to southern Hokkaido, (3) the relation of Oyashio transport to the southernmost intrusions of Oyashio influence into the Mixed Water Region, (4) the effect of large offshore eddies on Oyashio transport and the properties of Oyashio water, and (5) the vertical structure of the Oyashio.

5.3.1 Water characteristics between Bussol' Strait and southern Hokkaido: origin of the Oyashio Water

The Okhotsk Sea waters exiting Bussol' Strait join the subarctic waters and form the Oyashio (Fig. 2.3.16). The "Oyashio Water" thus formed is a mixture of Okhotsk Sea waters which are modified by mixing in the Kuril straits and East Kamchatka Current water. The Okhotsk Sea Water can often be found inshore of the East Kamchatka Current water as the Oyashio flows southward along the Kurils (Fig. 2.5.14 from Kawasaki et al., 1991).

The water which is found in Bussol' Strait and which may be the primary Okhotsk Sea Water found in the Oyashio is actually a "mixed" water in comparison with that inside the Okhotsk Sea (Moroshkin, 1962). Kawasaki and Kono (1990, 1993b) show how the vertical profiles of temperature vary around the central and southern Kuril Islands (Fig. 2.5.15). The dichothermal layer in the Okhotsk Sea is denser and a little colder than in the East Kamchatka Current water (classified by Hirano as central water; Fig. 2.5.2). The mesothermal layer which is apparent in the East Kamchatka Current water is much colder in the Okhotsk Sea. For stations along the Kuril Islands, vertical mixing is apparent (Fig.

2.5.15b). This mixed water is carried out of the Kuril straits and becomes the Okhotsk Sea portion of the Oyashio water. This Oyashio water is midway in properties between East Kamchatka Current water and southern Okhotsk Sea water (Fig. 2.5.4 from Ohtani).

The Oyashio water, with a large proportion of Okhotsk Sea water in it, is markedly fresher and more oxygenated than East Kamchatka Current water. Ishikawa (1988) shows that normally the Oyashio carries Okhotsk Sea water to the 41°30'N line (Fig. 2.5.16), but that East Kamchatka Current water is found in the Oyashio intrusions at 41°30'N during years when anomalously large amounts of Oyashio water are found in the Mixed Water Region (Section 5.3.4 below).

Along the eastern coast of Hokkaido is often found a layer of cold, fresh water which is only about 100 m thick and extends a few tens of kilometers offshore. Its origin is ice melt in the southern Okhotsk Sea, which presumably exits through the southern Kuril straits, including Nemuro, Kunashiri and Etorohu. This Coastal Oyashio Water is usually defined to have temperature less than 2°C and salinity less than 33.0 psu (Hanawa and Mitsudera, 1986; Fig. 2.5.23).

5.3.2 Circulation between Bussol' Strait and Hokkaido

A traditional view of the circulation south of Bussol' Strait is that the Oyashio flows along the western boundary until it meanders eastward off the southern coast of Hokkaido (schematic from Favorite et al., 1976, shown in Fig. 2.3.6). Then it is assumed to return northeastward into the subarctic gyre and then eastward across the Pacific. The Oyashio south of Bussol' Strait actually is much more complicated than this because of the presence of large anticyclonic eddies. Figs. 2.3.16 shows four recent synoptic surveys from the JFA Hokkaido (Kawasaki et al., 1991; Kawasaki and Kono, 1990, 1993). All show many eddies of 100 - 200 km diameter lying between the predominantly southwestward coastal flow and northwestward flow offshore. From these surveys, typical transports for the eddies are 3 - 10 Sv and transport for the Oyashio is 7 - 12 Sv, all relative to 1,500 dbar. These quasi-permanent eddies may result in a large portion of flow through Bussol' Strait being pulled offshore to feed an offshore branch of the Oyashio (Gladyshev, 1993). The variable location and intensity of the eddies may control the position and distribution of volume transport between the Oyashio branches (Bulatov and Lobanov, 1992).

That the eddies can shift a significant part of the Oyashio transport well offshore is demonstrated with the southern eddy in 1991 (Fig. 2.3.16c) and in 1989 (Fig. 2.5.14). The latter ring, labeled WCR-86B by Yasuda et al. (1992) and which was also the ring tracked by Lobanov et al. (1991) (Fig. 2.5.15a), had a core of slightly saline water and was pulling fresher water from the Okhotsk Sea around and into it. The Oyashio transport apparently was diverted around the ring, with only 3 Sv remaining inshore.

There are few published measurements, either direct or indirect, relevant to estimating the flow through the southernmost straits of the Okhotsk Sea. Based on drift bottle recoveries, Kajiyama (1920) stated that in summer, when the Soya Current is stronger, much of its water flows out through Kunashiri and Etorohu Straits, with a much smaller portion through Nemuro Strait (Fig. 2.5.17 from Kajiyama, 1936; Uda, 1936, 1938). Current thinking is that Soya Current water does not flow through these shallow straits, but that cold, fresh water originating from ice melt in the southern Okhotsk Sea creates this shallow coastal layer. Making modern measurements in the southern straits could be formidable, since the tidal flows through these straits are apparently quite large (see Section 3.4). Bogdanov (private communication) has suggested that tidal currents in the vicinity of Etorohu Strait, for example, might be considerably greater than two knots (100 cm/sec). (This estimate is based on a number of unpublished current meter records of a few days duration each.) Preliminary analysis of POI surveys of Bussol' and Friza straits showed that the flow is strongly baroclinic (Gladyshev, 1993), with seasonal variation in volume transport and thermohaline structure.

Since the southern straits are generally quite shallow (e.g. Favorite et al., 1976), the net, long-term mass transport through the straits is likely to be considerably smaller than through the deeper straits. Whether the stronger tides in the southern straits lead to significant long-term transports via rectification is unknown and seems to be a worthy problem for investigation.

5.3.3 Oyashio circulation off Hokkaido

Off the southeastern coast of Hokkaido, the Oyashio usually flows southwestward ("first intrusion"). Offshore of this there is often a warm core ring (Kawai, 1972) which originates as a Kuroshio warm core ring, is cooled by wintertime air-sea interaction, and may move impulsively northward to the location separating the Oyashio intrusions (Yasuda et al., 1992). The 1989 data clearly show this typical situation (Fig. 2.5.14). Numerous other descriptions of the region based on data from other years and seasons also show this configuration, although the currents are highly variable.

Transport estimates for the Oyashio in this region are based mainly on velocity relative to 1,500 dbar. Three routinely-repeated sections have been used to compute time series of transports: the section extending southeastward from Kushiro, Hokkaido (the Akkeshi line), the zonal section at 41°30'N, and the meridional section at 144°E. Kawai (1972) presented a section of velocity relative to 1,000 dbar along 144°E (Fig. 2.5.18), in which are apparent the Oyashio as it flows southwestward close to Hokkaido and eastward at about 41°N after separating at the southern tip of Hokkaido. The contrast in the Oyashio's relative surface velocity, about 20 cm/sec, with that of the Kuroshio, 50 - 60 cm/sec, is typical, although this Kuroshio velocity is on the low side: typically it is 100 cm/sec and it can reach 250 cm/sec. The Oyashio is much more density-compensated than the Kuroshio, and its vertical structure is still not fully explored; only a few moorings have been deployed to study it at depth.

Current meter deployments in the surface layer of Oyashio were reported by Kashiwai and Kono (1990). In 1987 - 1989, a current meter was deployed at about 500 m depth in 1,700 m of water along the Akkeshi-line, at 42°30'N, 145°0'E (Kawasaki and Kono, 1990). During most of the two-year deployment (Fig. 2.5.19), flow was southwestward along the isobaths, but in early 1988, a warm core ring passed over and reversed the flow, suggesting that the currents have a barotropic component here. One result from the 1980's deployment is that the measured surface current is usually stronger than the geostrophic current relative to depth: for instance 60 - 70 cm/sec as opposed to 40 cm/sec.

Deep current meters have been deployed along the Akkeshi-line since 1991 at two locations with near-bottom current meters in water depths of about 1,100 and 3,500 m (Fig. 2.5.20); shallower current meters are also mounted on the deeper mooring (Kawasaki and Kono, 1993c). These moored measurements should continue for the foreseeable future. The first two years of data show a fairly steady flow directed southwestward along isobaths near the bottom on the 1,100 m deep mooring. During the first year, there was little coherence between the mid-depth and bottom current meters on the 3,500 m deep mooring. However, during the second year of deployment, there was strong coherence between the near-surface and mid-depth current meters and somewhat weaker coherence with the bottom current meter; current speeds drop towards the bottom. Again this suggests a barotropic component for the Oyashio, but its importance is time-dependent.

The only available top-to-bottom, highly-resolved hydrographic section along the Akkeshi-line was made in summer, 1985 (Talley et al., 1991). The section was dominated by a warm core ring, such that it is difficult to even determine what to call the Oyashio (Fig. 2.5.21).

There was a very shallow southward coastal current of fresh water, which could be termed the coastal Oyashio. There is little hint of the first Oyashio branch. The warm core ring extended out to station 18 and its vertical shear was in the same sense to 6,000 m, suggesting a barotropic component to flow in this area and that the Kuril Trench may be important in guiding the flow. The ring's transport was 25 - 29 Sv relative to the bottom. Southward transport offshore of the ring, which might be considered thus to be the Oyashio transport, was 12 Sv relative to the bottom.

Additional deep sections are being made near this location as part of the WOCE current meter array deployed here; the new data along with the continued data return from the Akkeshi-line current meters should yield much information about the true magnitude of the transport of the Oyashio and its depth dependence.

Routine hydrographic measurements have been made for many years along the 41°30'N line (Fig. 2.5.22). Recently current meters have been deployed along this line at two sites where the first intrusion of the Oyashio is normally found. The hydrographic structure normally shows the strong front between the Tsugaru warm water and the Oyashio water (at 143°E in Fig. 2.5.22b) and the two intrusions of the Oyashio (e.g., Uehara and Miyake, 1993). Comparison of geostrophic velocities for the first Oyashio intrusion, computed relative to 2,000 dbar or the deepest common level, with current meter measurements at 500 m shows that the geostrophic estimate is significantly lower than the current meter measurement if the station separation is 1°; the difference is reduced if the station separation is reduced to 20', presumably because of problems computing geostrophic velocities over the steep bottom slope (Uehara and Miyake, 1993). At the offshore mooring, deeper current meters, at 1,000 and 3,000 m, showed marked coherence with the Oyashio when it passed directly over the mooring (Fig. 2.5.22c); the direction of the 3,000 m flow appears to be mostly parallel to isobaths (Miyake et al., 1993).

5.3.4 Oyashio Water in the Mixed Water Region

The Mixed Water Region, or Perturbed Region in some literature, is the region of confluence of Kuroshio, Oyashio and Tsugaru Waters. Kawai's (1972) schematic (Fig. 2.5.3) shows the two intrusions of the Oyashio (loops east of Hokkaido), the meandering Kuroshio and its warm core rings, and the relatively saline Tsugaru Water in the northwestern part. The southern boundary of the region is the northern Kuroshio front and the northern boundary is the Oyashio front. The eastern boundary is not well-defined, but could be taken to be Shatsky Rise.

As stated above, the Oyashio Water in this region can be defined either as that water found north of the Oyashio Front (salinity increasing monotonically to the bottom), or that with temperature lower than 5°C at 100 m. In the latter case, there can often be complicated vertical structure in temperature and salinity, and this kind of Oyashio Water can be found as far south as the Boso Peninsula (e.g., Ogawa et al., 1987; Ogawa, 1989; Okuda, 1986; Yang et al., 1993a,b).

Water properties in general in the Mixed Water Region are complex. The principal sources are the Oyashio, the Tsugaru Warm Current and the Kuroshio. The Oyashio carries both Okhotsk Sea and East Kamchatka Current (Central) water, and also has a relatively fresh shallow coastal layer originating from ice melt. Water from the Oyashio is called Oyashio, Subarctic or Subpolar Water. Water from the Kuroshio is called both Kuroshio and Subtropical Water. Air-sea interaction within the region in winter creates new upper waters, as does mixing between the incoming waters.

Hanawa and Mitsudera (1986) presented six classes for the Mixed Water Region waters (Fig. 2.5.23), differentiating between the various sources of surface layer waters. They showed the relative freshness of Oyashio water relative to Tsugaru and Kuroshio water, and the very fresh, cold coastal waters. Hasunuma (1978) showed that a particular type of water is found in the region, which he called the Transition Water, and which is formed by vertical mixing between the Subtropical Water which overruns the Subarctic Water, creating the intermediate salinity minimum which is usually referred to as North Pacific Intermediate Water. He showed that another salinity minimum is created when water from Tsugaru Strait overruns denser water in the Mixed Water Region. Talley (1991) and Talley et al. (1995) suggest that stations be classed as subarctic, subtropical, Tsugaru and transitional (Fig. 2.5.24); the last is a mixture of the first three, with much of the mixing occurring in the overrun process described by Hasunuma. Yasuda et al. (1994) have a very similar classification.

The southernmost extent of Oyashio water in the Mixed Water Region has been used to great advantage as an indicator of climate in Japan (Uda, 1949, 1964). Oyashio water has been found as far south as the Izu Islands just south of Honshu, lying between the Kuroshio and Honshu coast (Masuzawa, 1972). The southward intrusion has been discussed more recently by Iida and Katai (1974), Okuda (1986), Okuda and Mutoh (1986), Ogawa et al. (1987), and Yang et al. (1993a,b). Kawai (1955, 1972) showed that the area occupied by Oyashio water, as defined by the 5°C isotherm at 100 m, does not necessarily vary in relation to the area of Kuroshio water. Ishikawa (1988) showed the area of what he defined as the Oyashio region in the Tohoku area since 1972; the area was especially large in 1974, 1981 and 1984 (Fig. 2.5.25). During those years, oxygen at 100 cl/ton along the repeated section at 41°30'N was markedly lower than in other years, indicating a larger proportion of East Kamchatka Current water in the Oyashio, relative to the amount of Okhotsk water. Sekine (1988) examined the North Pacific winds and concluded that the Aleutian low was more strongly developed and shifted southward during years of abnormal southward intrusion of the Oyashio (Fig. 2.5.10). Ekman transport was also intensified off Japan. However, he also concluded that Tsugaru water and the Kuroshio warm core ring could block the southward intrusion of Oyashio water, as apparently occurred in other years of the strong Aleutian low (1968, 1980, 1982, 1983).

5.4 Formation of North Pacific Intermediate Water: the role of the Okhotsk Sea and Oyashio

A problem that is receiving attention again of late is the formation of the salinity minimum of the subtropical gyre. The basin-wide patterns of this well-known feature were discussed in Sverdrup et al. (1942) and in more detail by Reid (1965). Reid attributed the salinity minimum to downward diffusion of low salinity in the subpolar gyre and lateral exchange along the boundary between the subtropical and subpolar gyres. Hasunuma (1978) showed that an intermediate salinity minimum arises in the Mixed Water Region where Kuroshio water overruns Oyashio water. Talley (1993) mapped the property distributions at the salinity minimum (Fig. 2.5.26), showing that its salinity is lowest and oxygen highest in the Mixed Water Region, and hypothesizing that the salinity minimum forms only in this region based on the high levels of finestructure through the minimum in this region compared with other regions. None of these discussions included transport calculations, nor did they indicate a mechanism for determining density of the salinity minimum water, which lies within a remarkably small range of 26.7 - 26.8 σ_θ through most of the subtropical gyre except in the western boundary current region.

The current context of the discussion of NPIW formation is North Pacific ventilation: where it is ventilated, how dense and deep the ventilated waters extend, the rate of ventilation, and the distribution of the ventilated water. It should be clear from the preceding subsections that the Okhotsk Sea significantly modifies the Pacific water which flows through it. It is believed at this time that the Okhotsk Sea produces the densest water in the North Pacific and that the Okhotsk Sea ventilation and vertical mixing in the Kuril Straits reduce the salinity and increase the oxygen on isopycnals down to about

2,000 m (Kitani, 1973; Alfultis and Martin, 1987; Talley, 1991, Wakatsuchi and Martin, 1991). Upon flowing out of the Okhotsk Sea, this water is advected by the Oyashio where it joins East Kamchatka Current Water which is warmer, more saline, and has lower oxygen; together the two waters are called Oyashio Water. Where the Oyashio reaches the Mixed Water Region, a portion of the Oyashio Water intrudes southward, often as far as the Kuroshio front. The main part of the Oyashio Water turns eastward north of the Oyashio Front and remains in the subpolar gyre. Thus most of the newly ventilated water remains in the subpolar gyre, but some escapes to the subtropical gyre via the Mixed Water Region.

Alteration of Oyashio Water in the Mixed Water Region occurs through mixing with these other two sources of water and through air-sea interaction. East of the northern part of Honshu, where the Tsugaru Warm Water often forms a coastal eddy (Fig. 2.5.3), wintertime densities as great as the main salinity minimum density are normally found in late winter (Fig. 2.5.27) (Nagata et al., 1993). In another, small, region on the south coast of Hokkaido (Funka Bay), water of the salinity minimum density is also found most winters; however the very small size of the bay suggests that its waters are not very important for the salinity minimum formation.

The earliest Japanese discussions assumed that the North Pacific Intermediate Water salinity minimum is formed in the Mixed Water Region and that its density is set by the winter mixed layer density. Uda (1935a) hypothesized an Oyashio undercurrent to explain the disappearance of Oyashio Water in the Mixed Water Region. However, no evidence has been found for such an undercurrent and the idea is now generally disregarded. It appears that the Oyashio Water in the Mixed Water Region is mixed into the warm core rings (Fig. 2.5.28; many examples in Mutoh et al., 1975 and Mutoh, 1977; Talley et al., 1994; Gladyshev, 1992) and into the Kuroshio (Fig. 2.5.29 from Yasuda et al., 1993) and undergoes a major displacement downward, with an increase in density as well. Just south of Hokkaido it also is overrun by the Tsugaru Water, creating a local salinity minimum and sometimes a temperature minimum (Hasunuma, 1978). The relative importance of these different sites for overrun of the Oyashio water by the Kuroshio water is not yet determined.

The principal mechanism setting the density of the salinity minimum has not been identified although candidate processes have been hypothesized. Talley et al (1994) map the nominal winter mixed layer density in the Mixed Water Region (Fig. 2.5.30) and show that it is indeed slightly lower than that of the salinity minimum. Hasunuma (1978) argued that the older Japanese idea, that the surface mixed layer density sets the salinity minimum density, is inaccurate but Talley (1993) hypothesized that the winter mixed layer density of the Oyashio Water in the Mixed Water Region actually does set the initial salinity minimum density, and that vertical mixing results in an increase of the salinity minimum's density soon after formation, thus producing the required density slightly greater than 26.7 σ_θ. Kozlov and Kuzmin (1984) and Kuzmin (1989) argue that cabbeling would be effective in increasing the density of the winter surface water in the Oyashio front area, and that intense downward motion would result, forming the low salinity intermediate layer (Kilmatov and Kuzmin, 1991). Nagata et. al. (1993) argue that the winter surface density in the Tsugaru warm eddy region, which can reach 26.7 σ_θ very locally may be an important factor. This is still an active area of research.

Vertical mixing is likely to be an important process in the Mixed Water Region, and may affect the density of the salinity minimum which exits the MWR to the east. Interfacial layers between overlying saline Kuroshio water and underlying fresher Oyashio water are often very well defined. Shonai and Miyake (1993) showed that double diffusive processes might be important in the Mixed Water Region and decreasingly important towards the east crossing the Pacific (Fig. 2.5.31). Salt fingering occurs where warm salty water overlies colder fresher water and results in an increase in density of the colder fresher water (the salinity minimum) as it acquires salt.

"New" NPIW which exits the Mixed Water Region to the east is a mixture of Kuroshio and Oyashio water, containing approximately 40% Oyashio water and 60% Kuroshio water which carries old NPIW (Talley et al., 1993). The renewal rate of NPIW then must be associated with the amount of Oyashio water which enters the mixed water region and exits into the subtropical gyre. Talley et al. estimate a net transport of 6 Sv of new NPIW (between 26.65 and 27.4 σ_θ) eastward across 152°E; thus the transport of Oyashio Water into the subtropical gyre is estimated to be something less than 3 Sv. Thus the bulk of Oyashio Water remains in the subpolar gyre north of the Subarctic Front. Exchange rates across the front east of the Mixed Water Region have not been estimated.

Some principal remaining questions for NPIW formation are: (1) quantifying the relative importance of various hypothesized processes for formation of the salinity minimum itself, (2) detailed observation of the process, and (3) more robust formation rate and transport estimates based on time series rather than single synoptic sections.

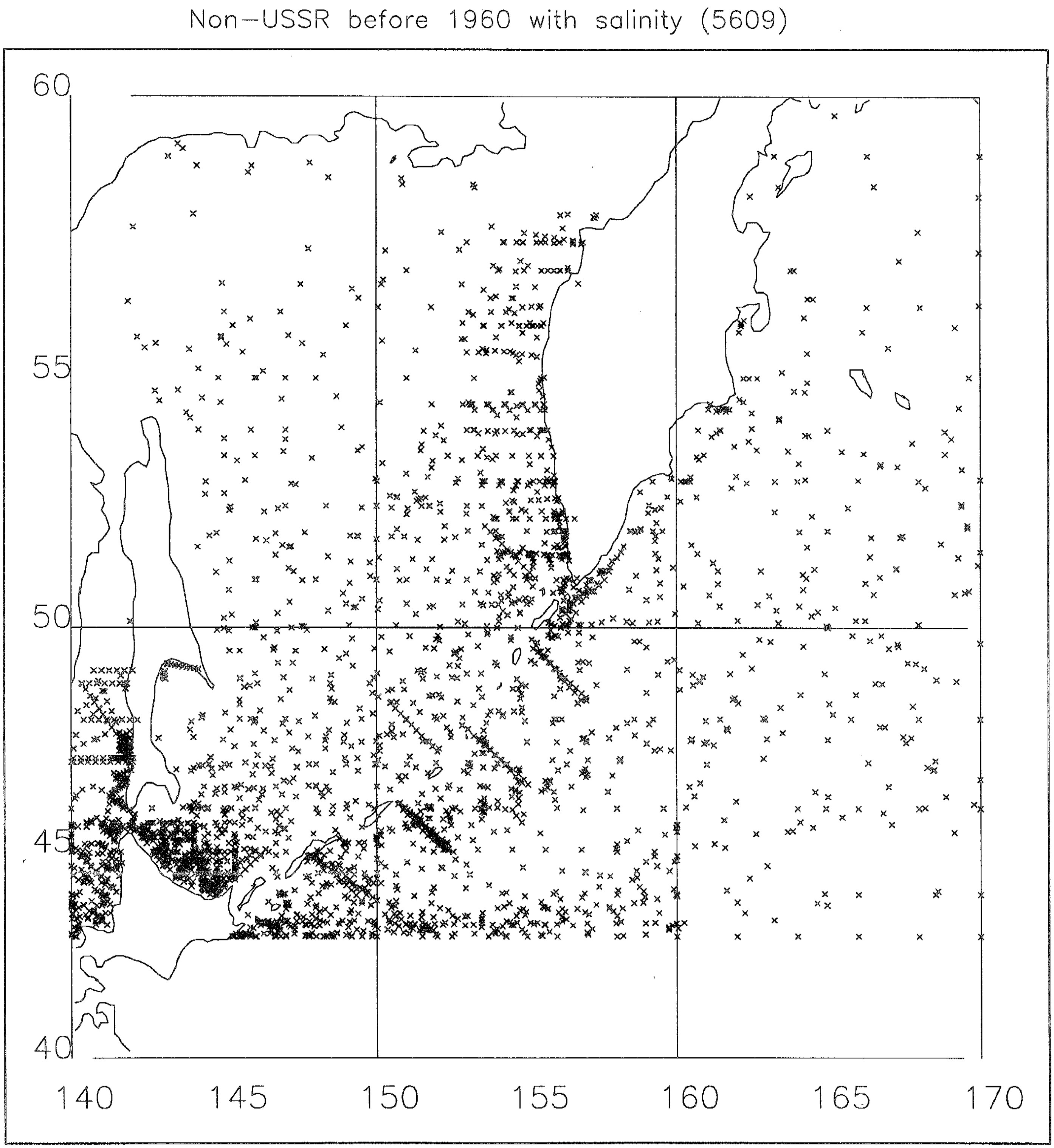


Fig. 1.1.1. WDCA bottle data stations with temperature and salinity for the northwestern Pacific: (a) prior to 1959

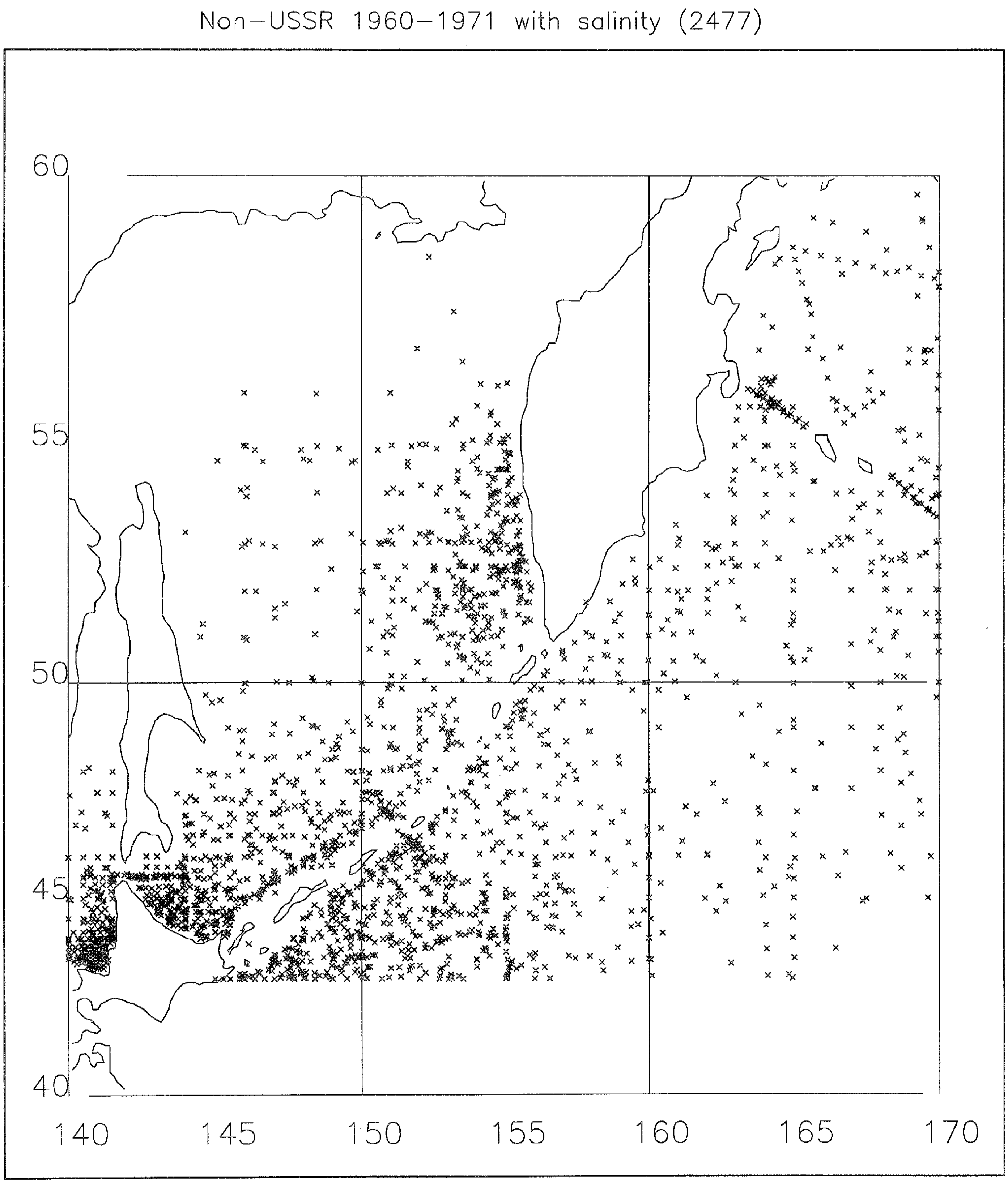


Fig. 1.1.1 (b) 1960-1971

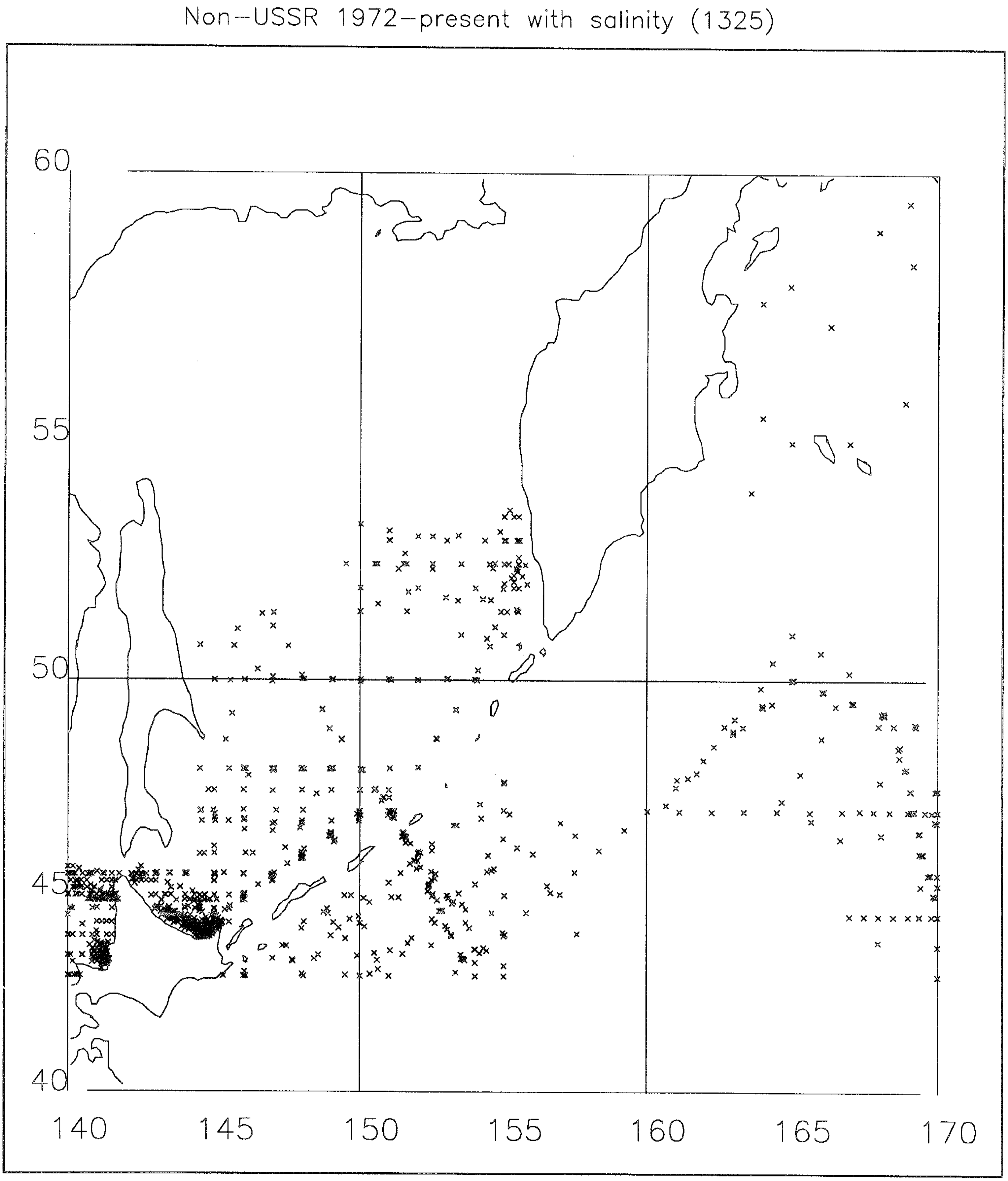


Fig. 1.1.1 (c) 1972-present

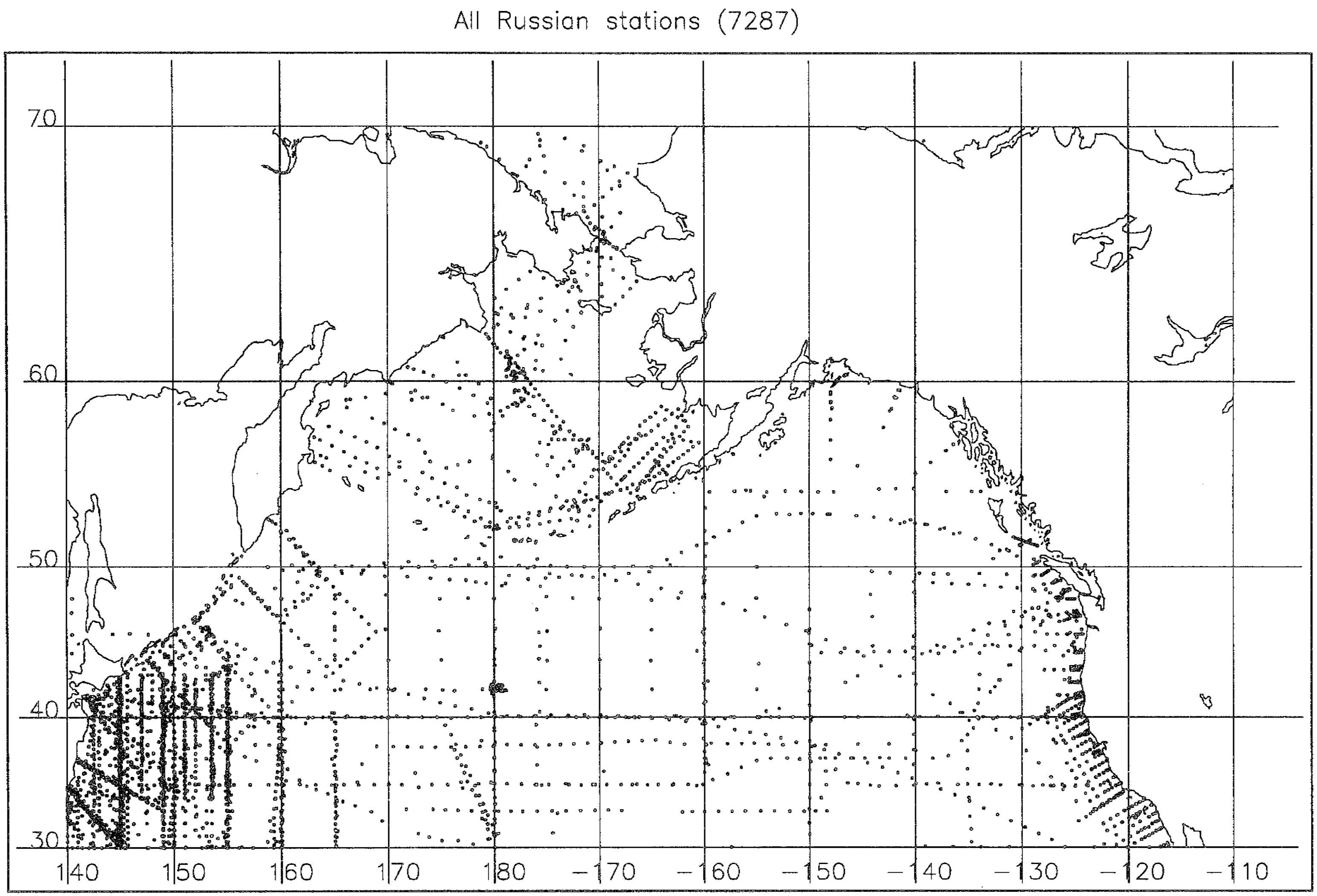


Fig. 1.1.1 (d) all Russian bottle stations for the North Pacific which are at WDCA.

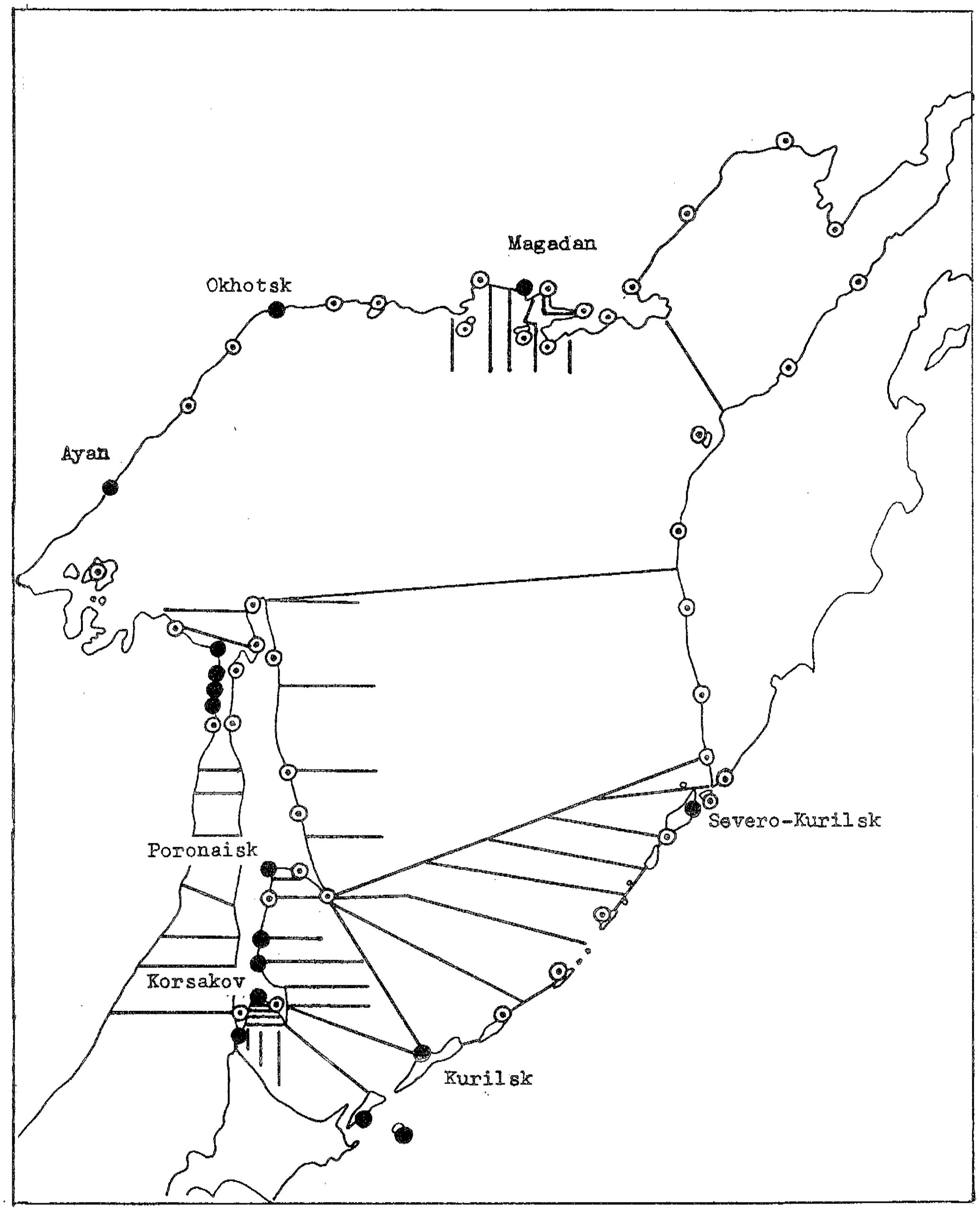


Fig. 1.1.2. Permanent coastal stations and standard hydrographic sections maintained by the Russian Committee on Hydrometeorology (Sakhalin, Kamchatka, Kolyma RHAs and FERHRI). Filled black circles have sea level measurements.

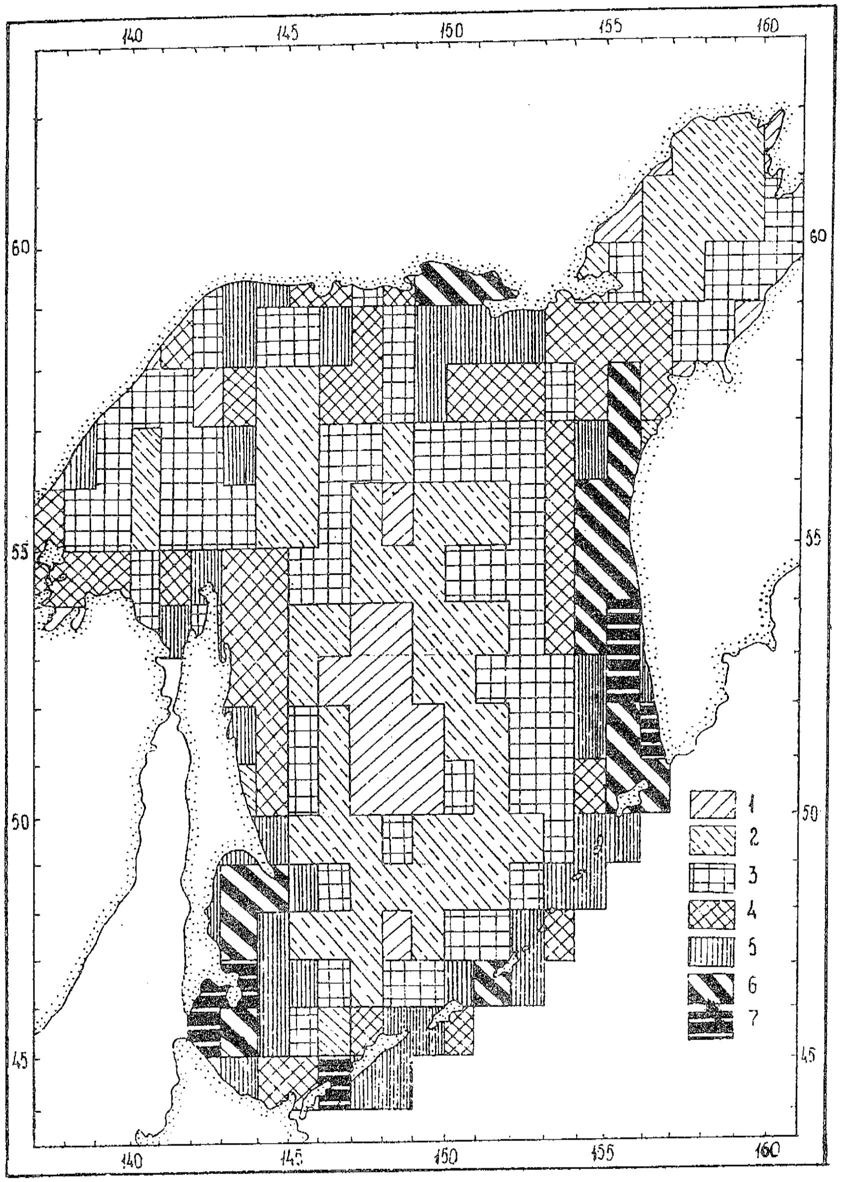


Fig. 1.1.3. Distribution of observations in the Okhotsk Sea in the FERHRI data base, including Russian and non-Russian data (Luchin and Motorykina, 1993).

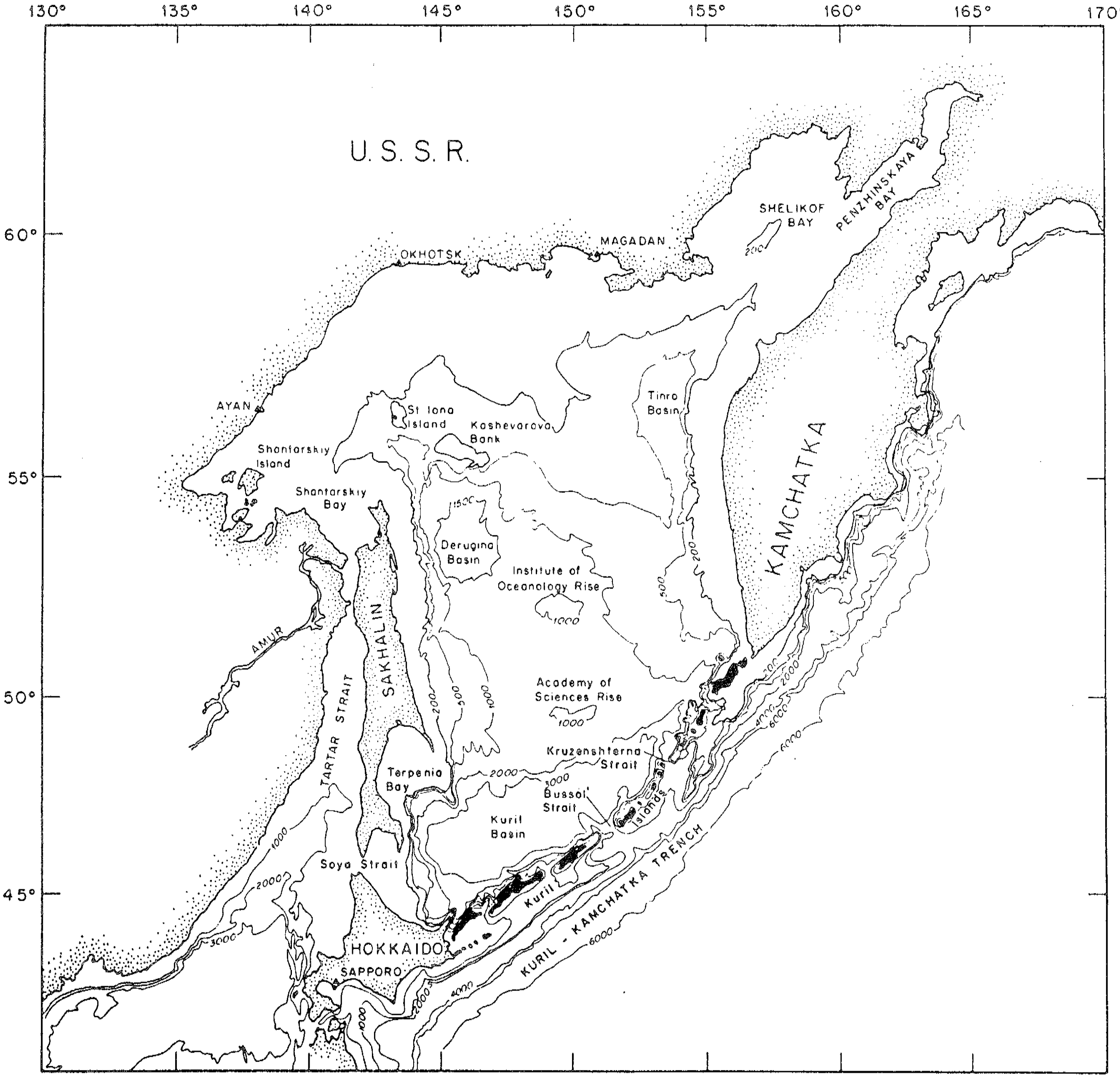


Fig. 2.1.1. Bathymetry of the Okhotsk Sea (Alfultis and Martin, 1987).

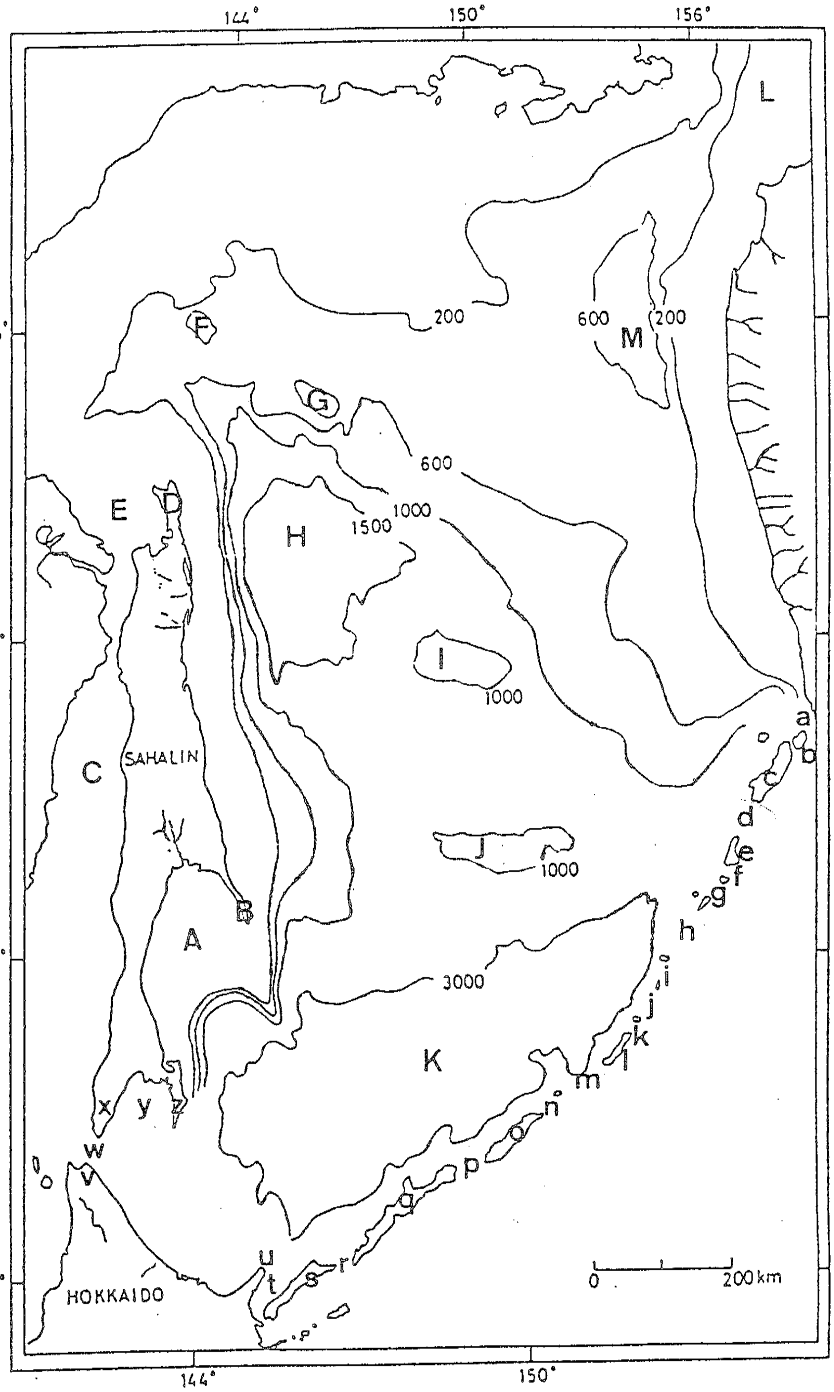


Fig. 2.1.2. Principal features of the Okhotsk Sea and Kuril Islands. Letters refer to the Russian and Japanese names in Table 1.

Fig. 2.2.1. Japanese coastal sea ice observing stations (Akagawa, 1969). Duration of the observations differs from station to station; only one or two years of data are available for some stations.

(1) From the island off 55°N off Siberia, clockwise: I. Santar, Ajan, Okhotsk, Nagaeva, Penjnal Bay (Shelskhova), KAMCHATKA P., Khirusova, Isa, Vorovskja, Kikfikl, Ust-Boltsereck, Ozernoja

(2) Kuril Islands from north to south: I. Paramushire, I. Shimushiru, I. Uruppe, Shana, I. Etorofu, I. Kunashiri, I. Shikotan, I. Shibotsu

(3) Sakhalin, from north to south: C. Elizavety, Ryvnovsk, Pogobl, Nogiik, Aleksandrovsk, Nyivo, Pograkomblnat, Pllvo, SAKHALIN, Poronaisk, Uglegorsk, C. Terpenlje, Iginskii, Vzmore, Starodovsk, Holmsk, C. Svobodnyl, Korsakov, Nevelsk, C. Anlve, C. Krllon

(4) Japan Sea, along Russia from north to south: Grossevisl, C. Zelotol, C. Sosunove

(5) around Hokkaido, clockwise: Wakkanai, Esashi, Omu, Monbetsu, Abashiri, Nemuro, Kushiro

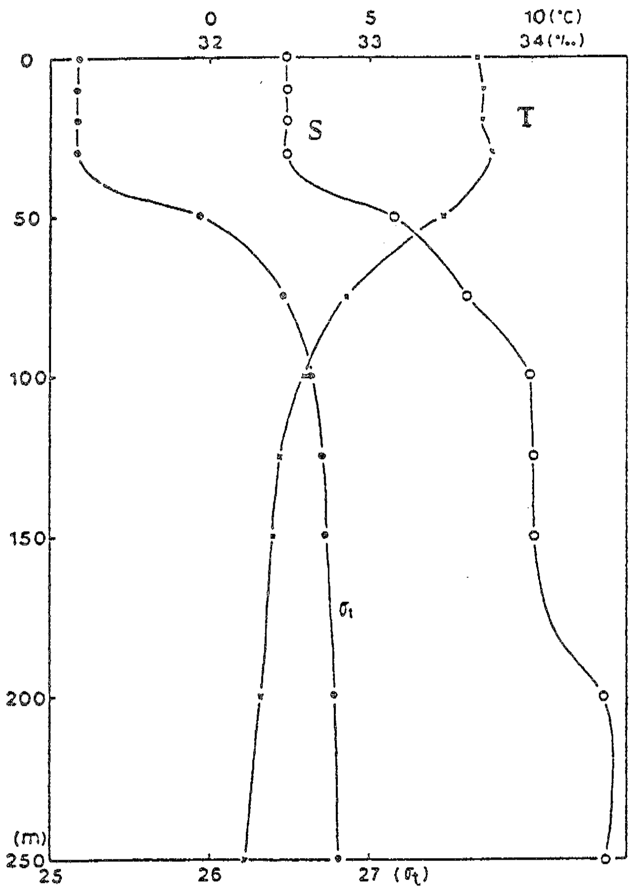


Fig. 2.2.2.

Vertical profiles of temperature, salinity and sigma-t just off the east coast of Sakhalin (46°56'N, 145°01'E) on November 3, 1978 (Nakamura et al., 1985; Aota and Uematsu, 1989).

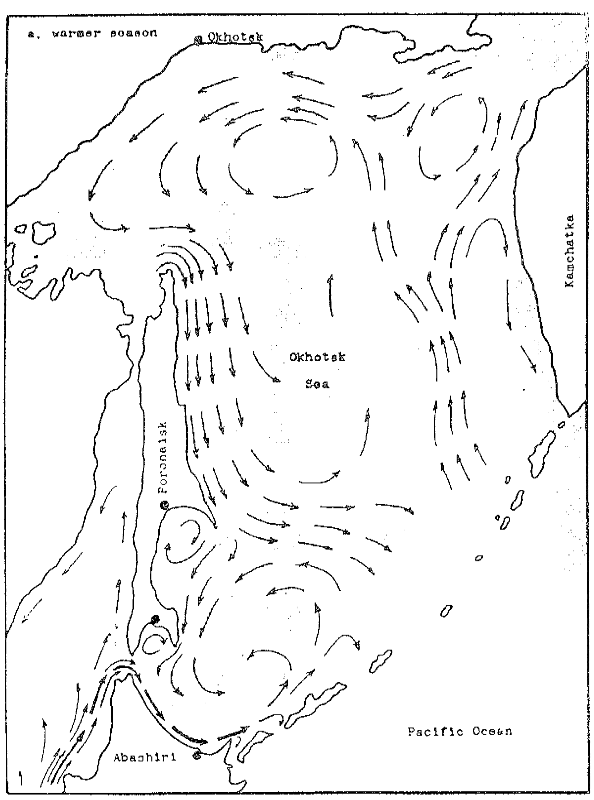


Fig. 2.2.3.

Schematic view of the current systems in the Okhotsk Sea in the warmer season (Watanabe, 1963b). The shaded area represents the region where occurrence of surface water having chlorinity less than 18.00 per mil is larger than 50%.

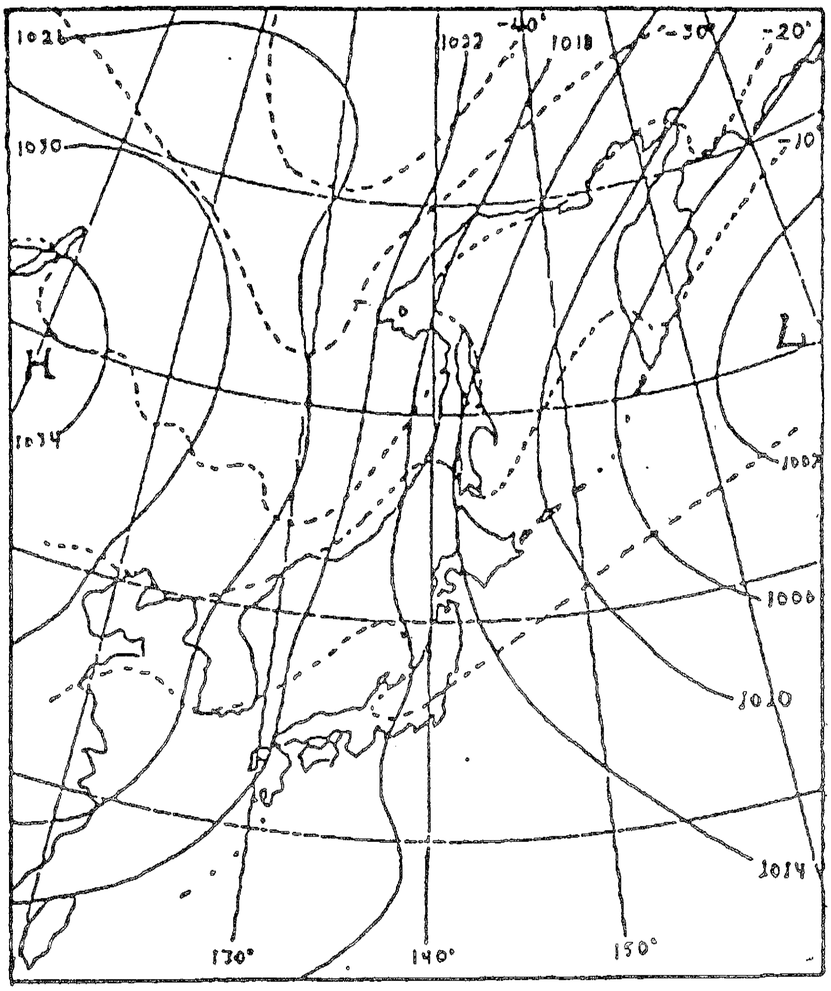


Fig. 2.2.4. Distributions of the mean surface pressure (mb) and mean surface temperature (°C) in January (Watanabe, 1959).

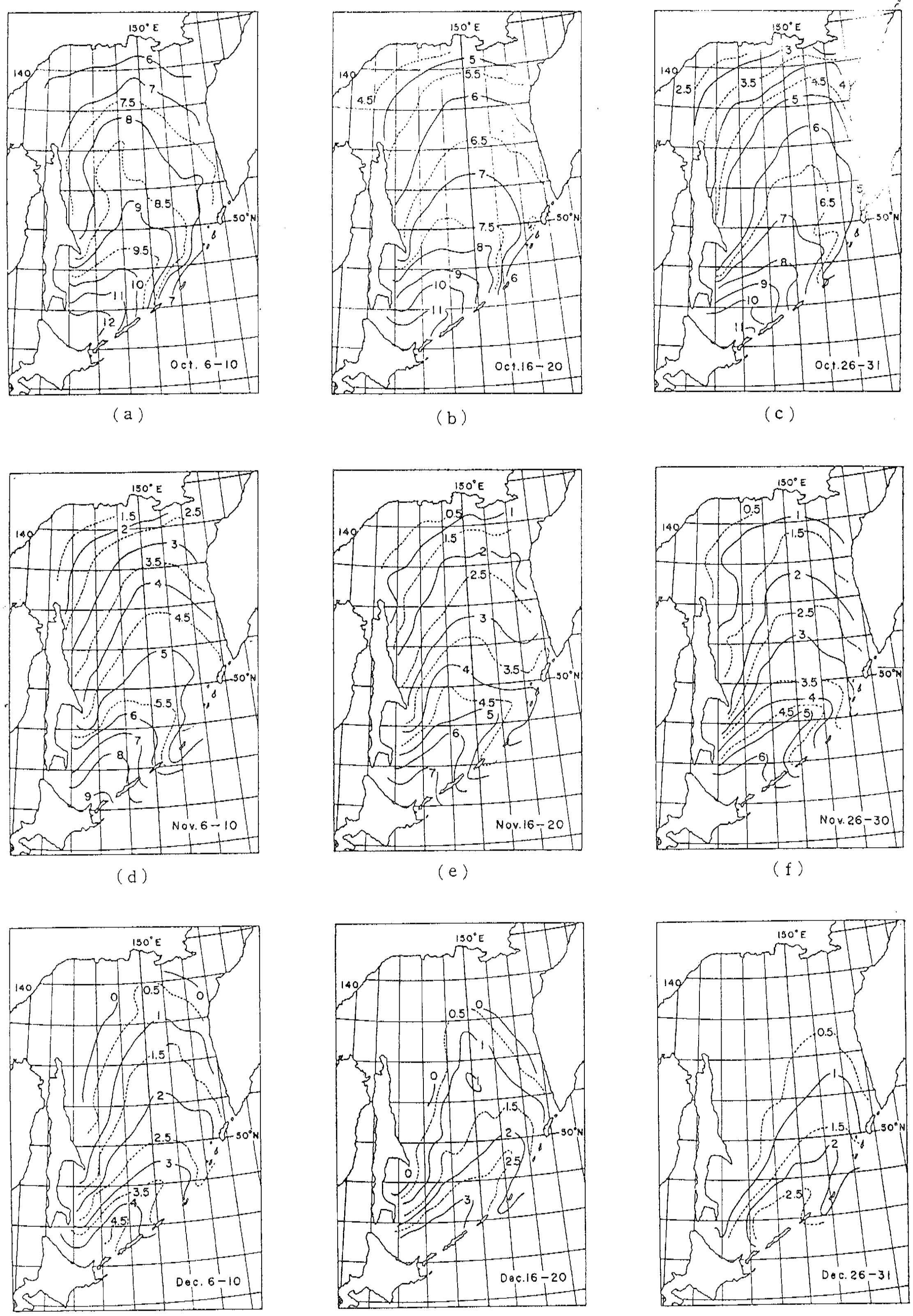


Fig. 2.2.5. Sea surface temperature distributions in the cooling season (October to December) averaged for 11 years from 1960 to 1970 (Akagawa, 1972).

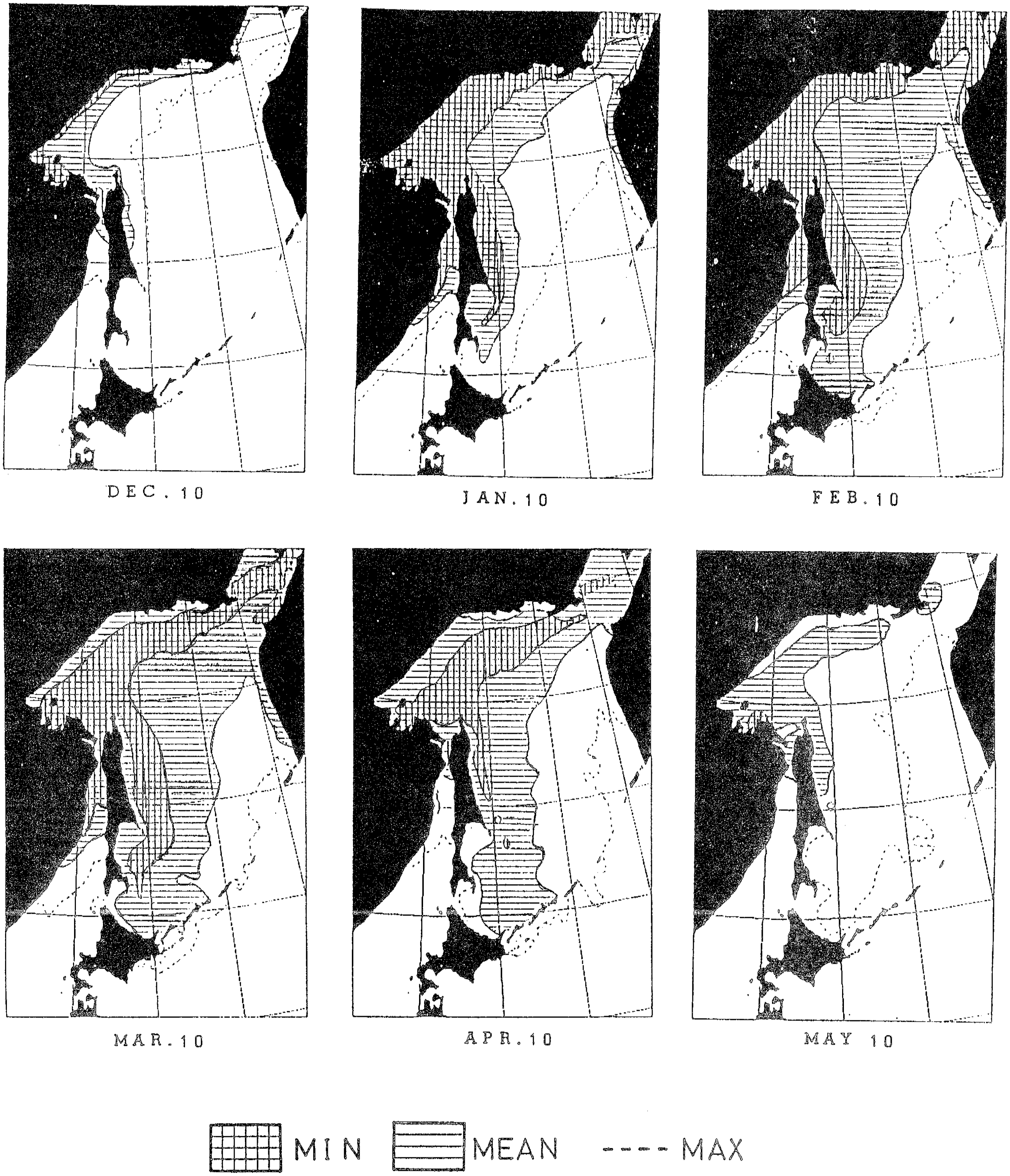


Fig. 2.2.6. **Mean, maximum and minimum ice extents in the Okhotsk Sea for the first 10 days from December to May for the period from 1971 to 1990 (JMA, 1990).**

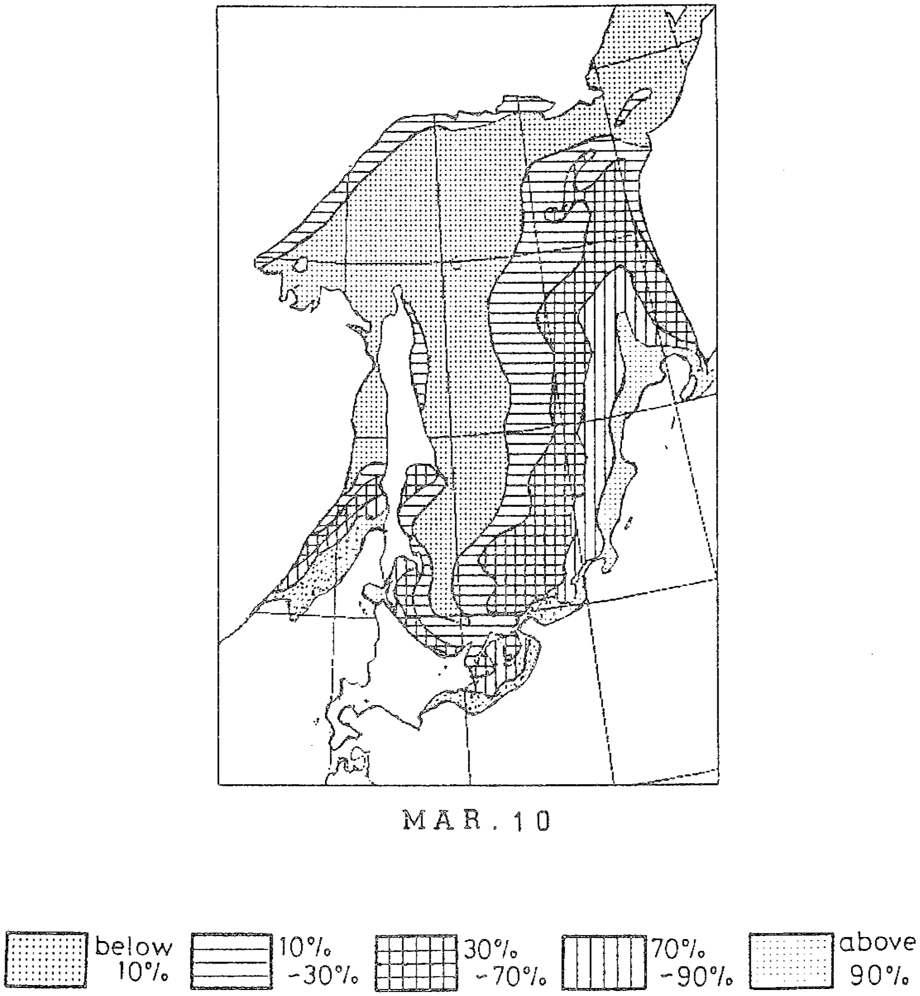


Fig. 2.2.7.

Distribution of existence probability of open water in the first 10 days of March for the period from 1971 to 1990 (JMA, 1990). Existence probability is divided into 5 ranks as shown below the figure.

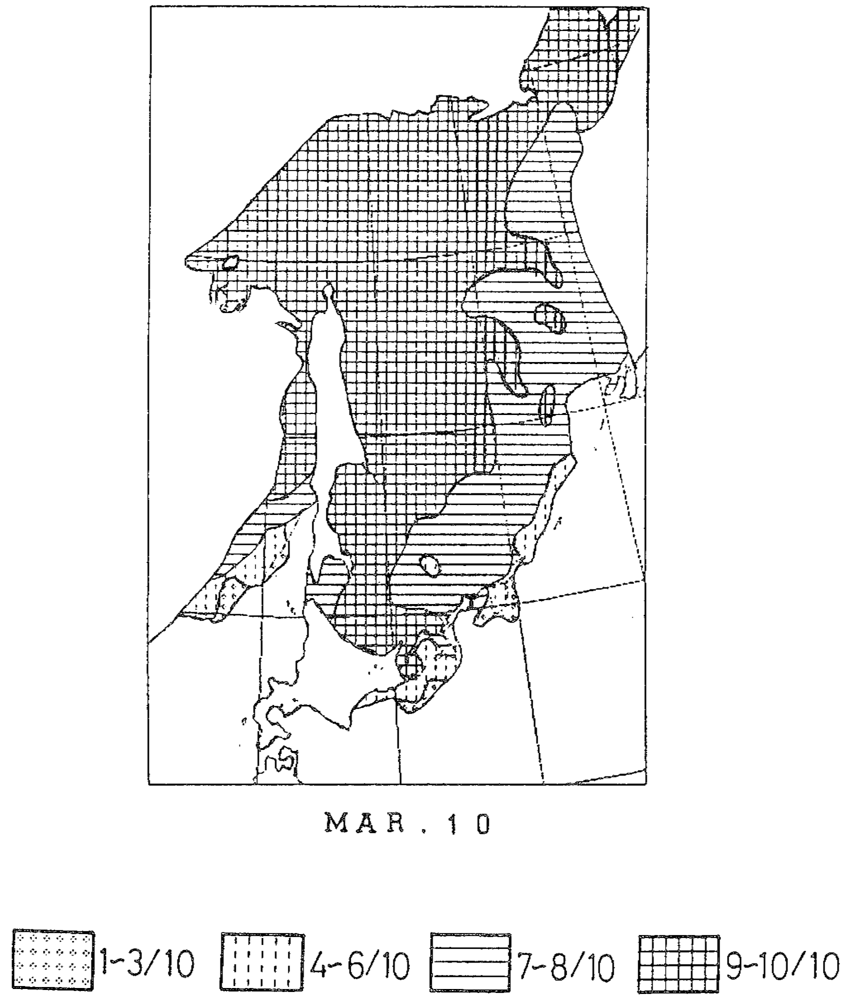


Fig. 2.2.8.

Distribution of mean sea ice concentration in the first 10 days of March for the period from 1978 to 1990 (JMA, 1990). Concentration is divided into 4 ranks as shown below the figure.

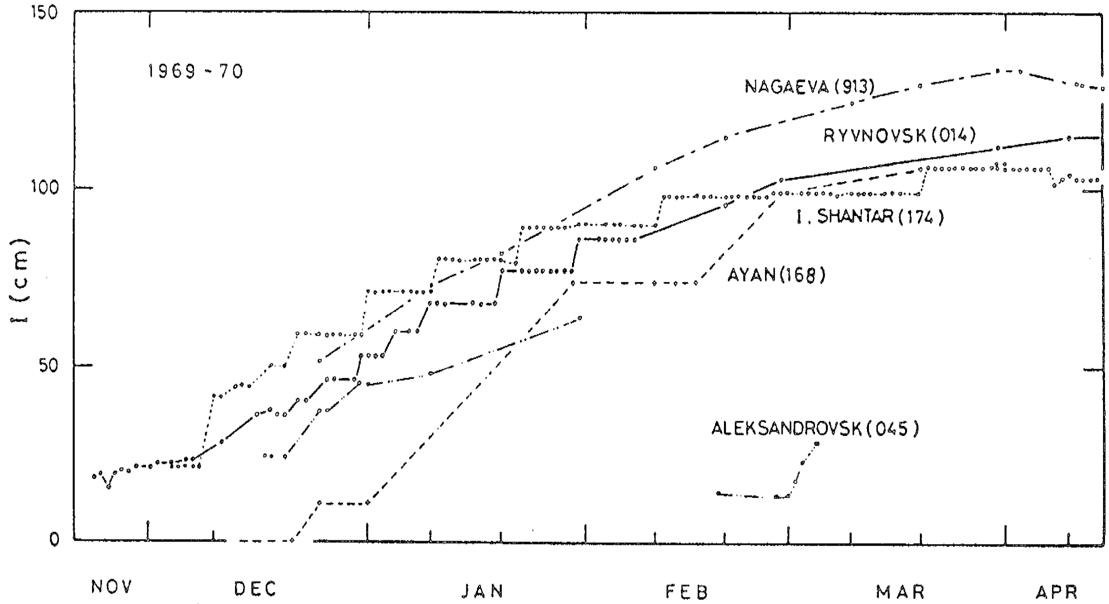


Fig. 2.2.9. · **Evolution of sea ice thickness at several coastal observation points in the northern Okhotsk Sea in winter 1969-1970 (Tabata et al., 1980).**

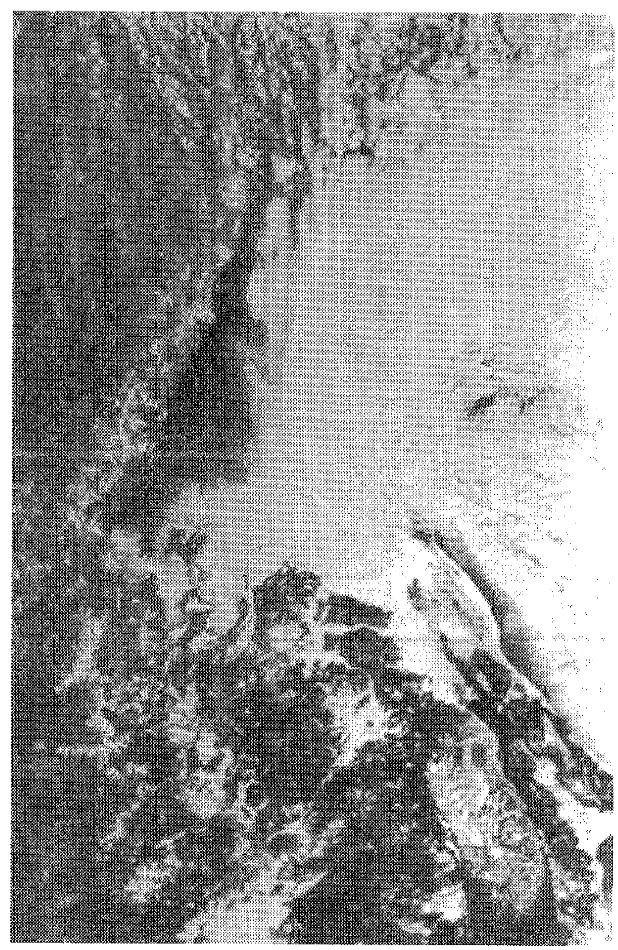


Fig. 2.2.10.

AVHRR observations of the Okhotsk Sea on March 3, 1982 (left) and on March 10, 1982 (Alfultis and Martin, 1987).

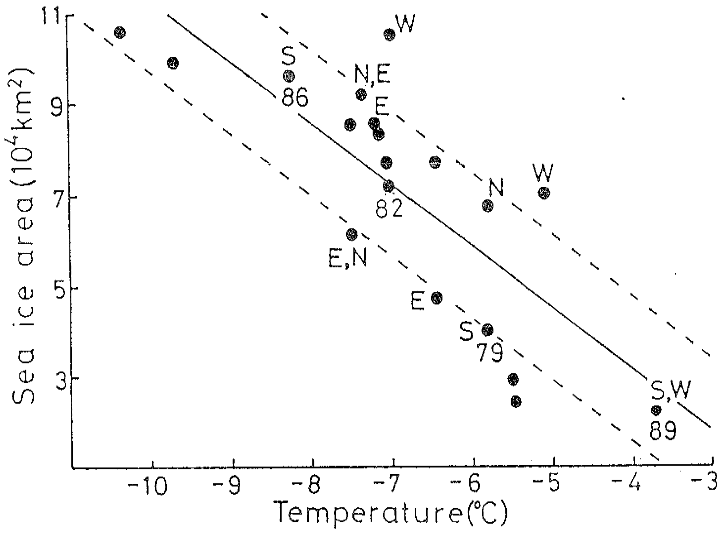


Fig. 2.2.11. Correlation between the area of sea ice cover in the Okhotsk Sea south of 46°N at the end of February and the surface air temperature averaged for January-February of the same year at Abashiri (Sato et al., 1989). When the average wind in January-February is strong, the prevailing wind direction is indicated with capital letters.

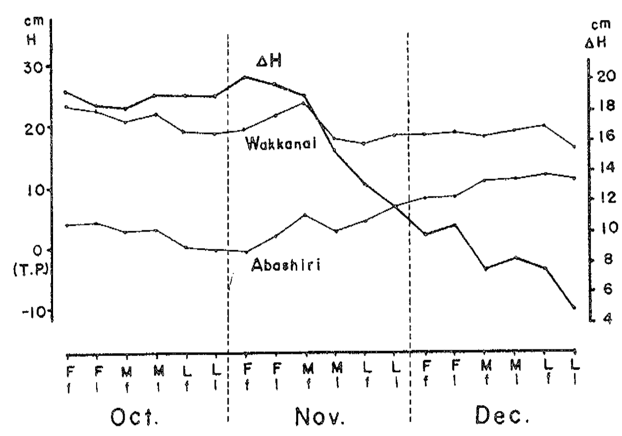


Fig. 2.2.13. Variations of the 5-day mean sea level at Wakkanai and Abashiri during October through December, and difference between two stations. Mean values for the period 1956-1970 are shown (Akagawa, 1977).

(Fig. 2.2.12 on next page)

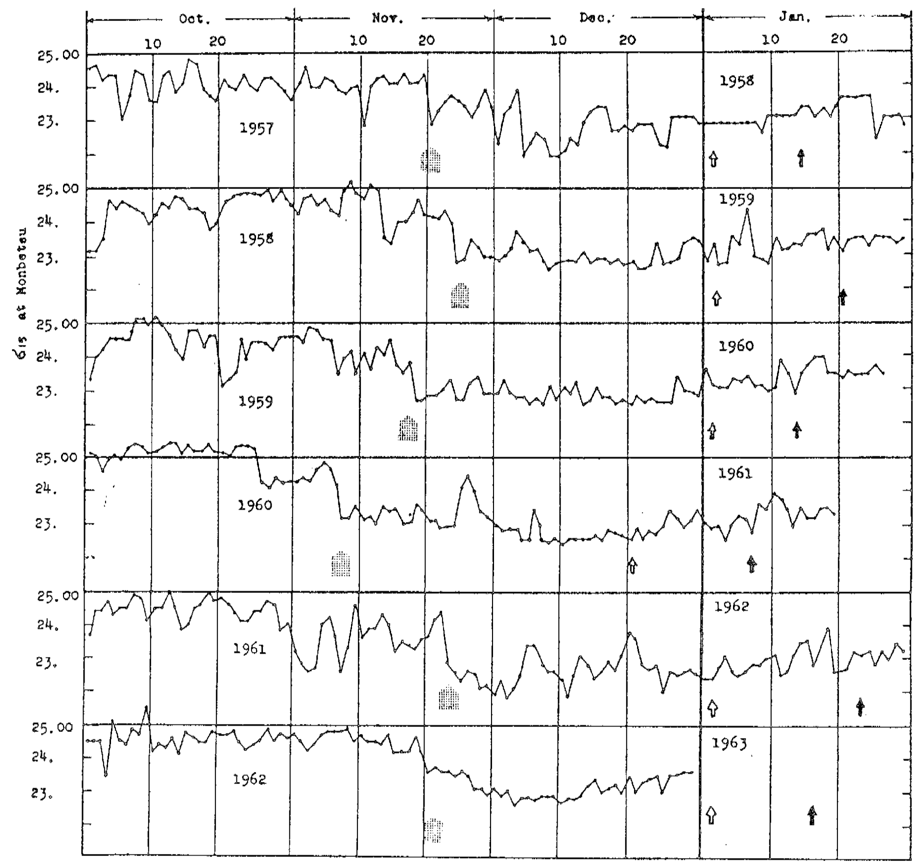


Fig. 2.2.12. Variations of daily salinity at Monbetsu during October through December for 1958-1963 (Watanabe, 1963b). Salinity has been converted to sigma-t at 15°C. The wide shaded arrow indicates the sudden drop of salinity, the white arrow the first local ice formation, and the black arrow the first appearance of drift-ice.

(Fig. 2.2.13 on previous page)

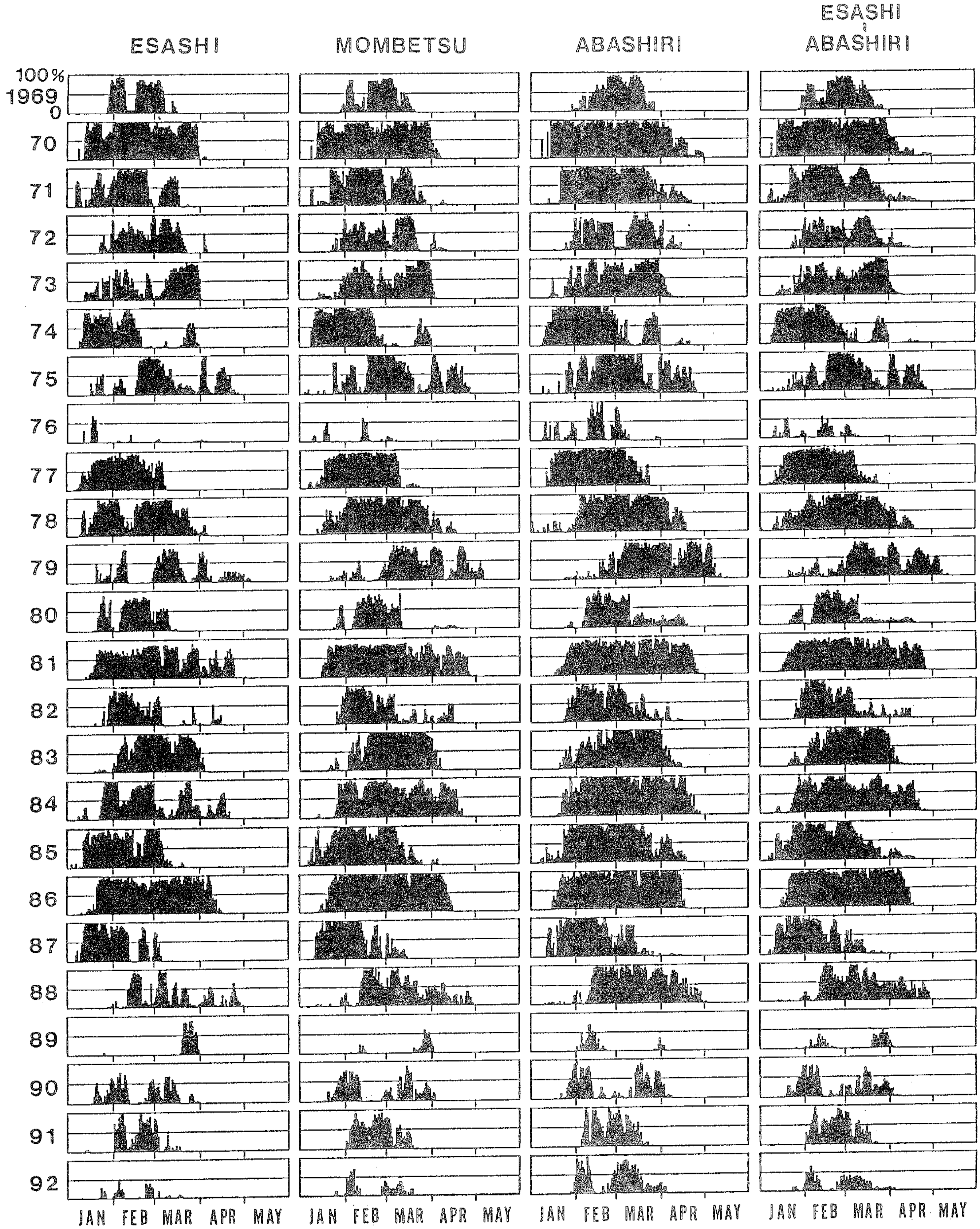


Fig. 2.2.14. Variations of sea ice concentration for each radar image (Esashi, Monbetsu, and Abashiri) and all observation areas of the sea ice radar network of the Sea Ice Research Laboratory, Hokkaido University, for 1969-1992 (courtesy of Aota).

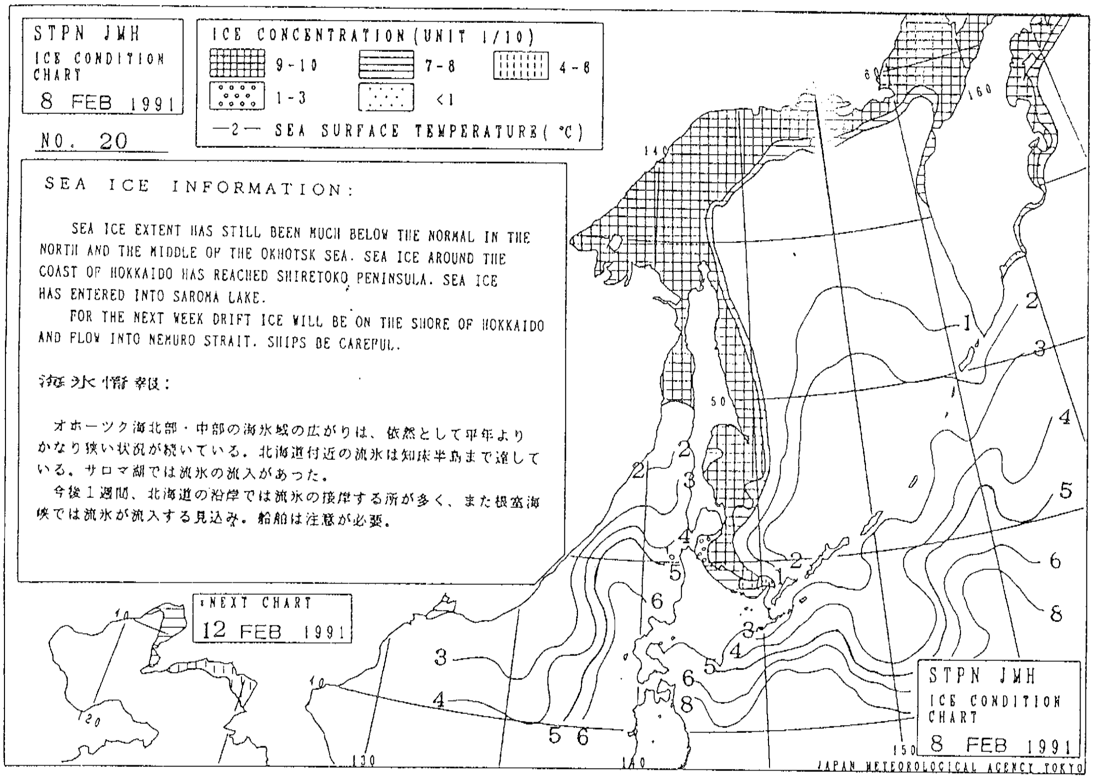


Fig. 2.2.15. Example of sea ice information published by the Japan Meteorological Agency twice a week (Kamihira et al., 1991).

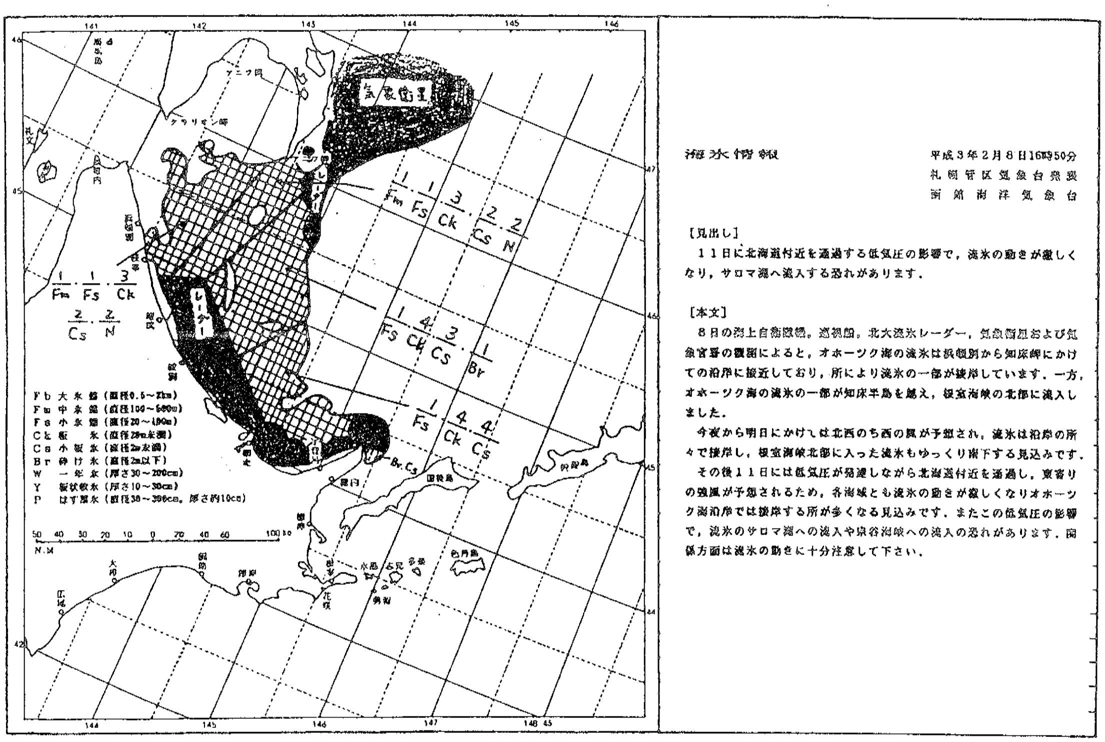


Fig. 2.2.16. Example of sea ice information published by the Sapporo Meteorological Observatory and the Hakodate Marine Observatory every day (Kamihira et al., 1991).

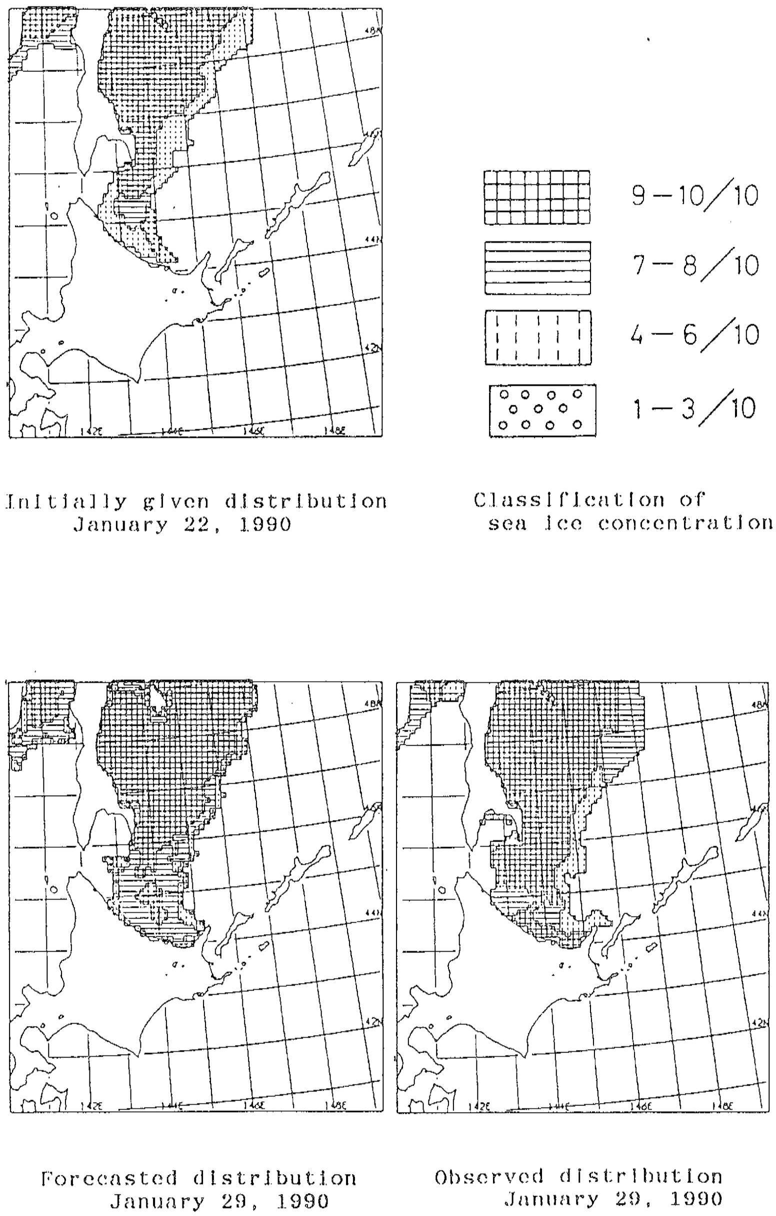
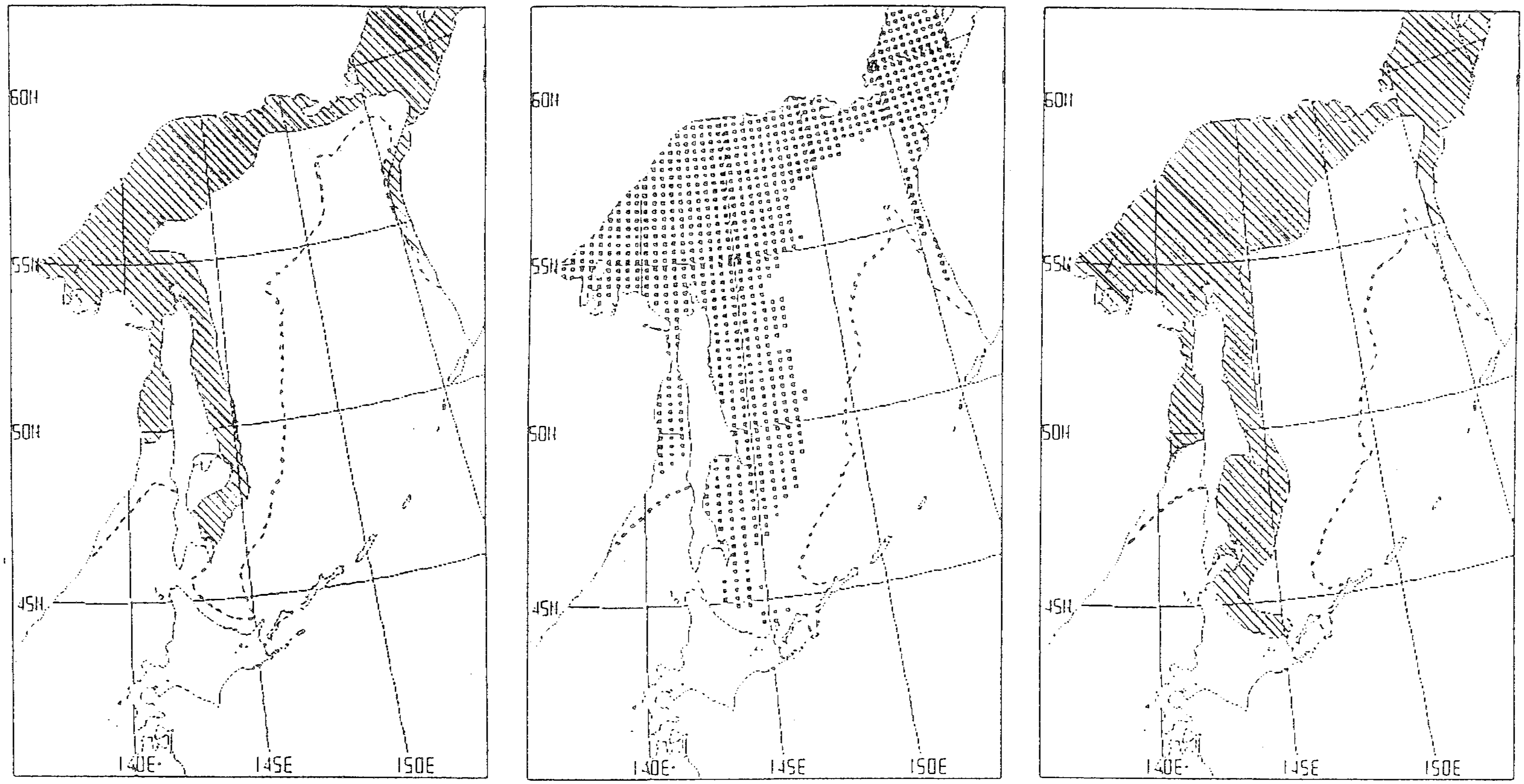


Fig. 2.2.17. Example of the JMA one week forecast for increasing sea ice (Kamihira et al., 1991).

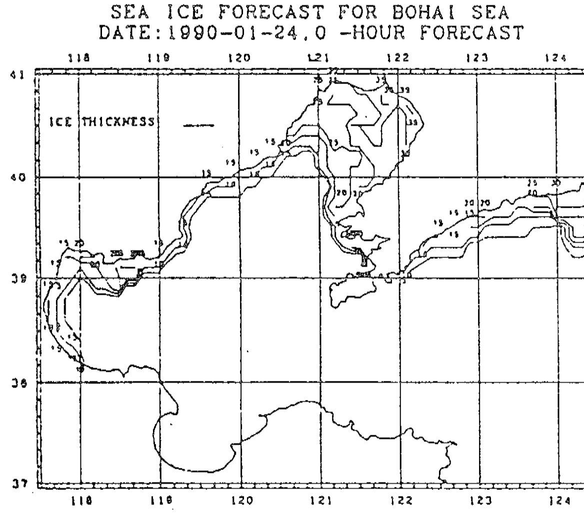


Initially given distribution
January 20, 1991

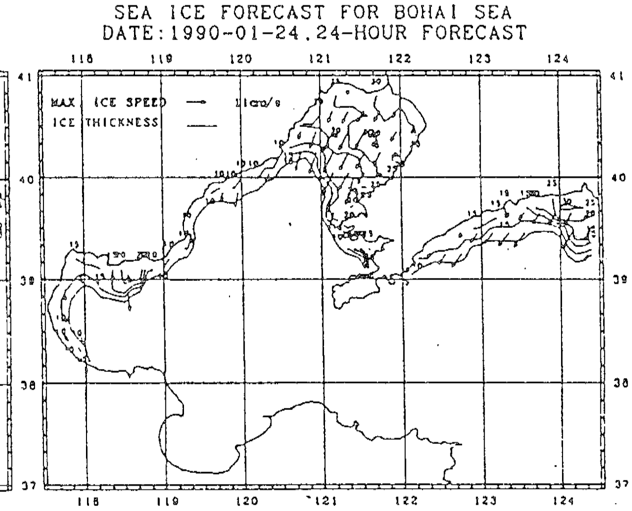
Forecast distribution
February 20, 1991

Observed distribution
February 20, 1991

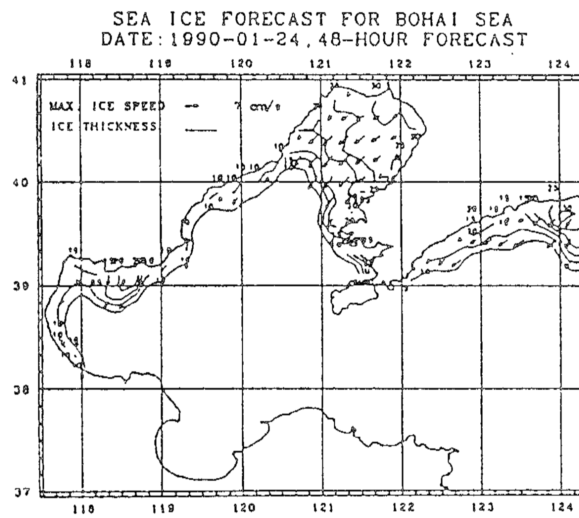
Fig. 2.2.18. Examples of the JMA one month forecast for increasing sea ice (Sato and Kano, 1992). The dotted line in the figure indicates the climatological mean position of ice edge.



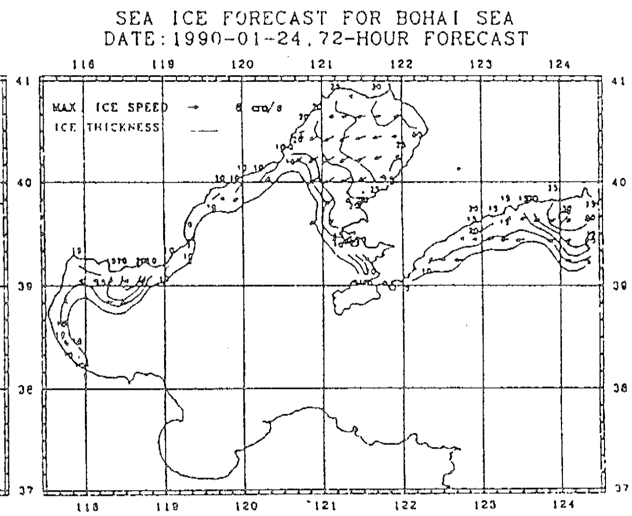
(a)



(b)

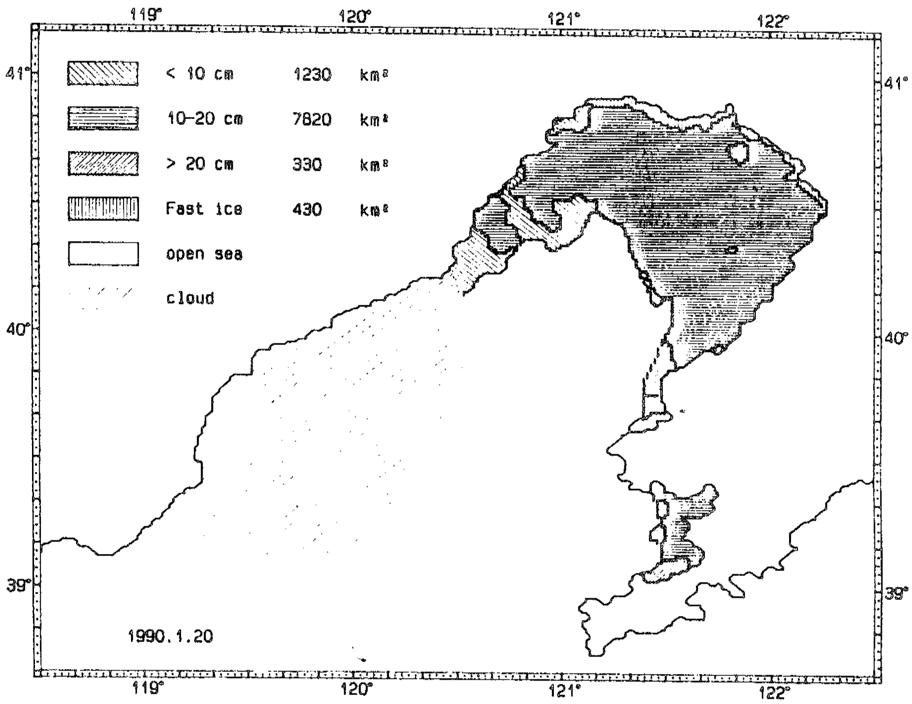


(c)

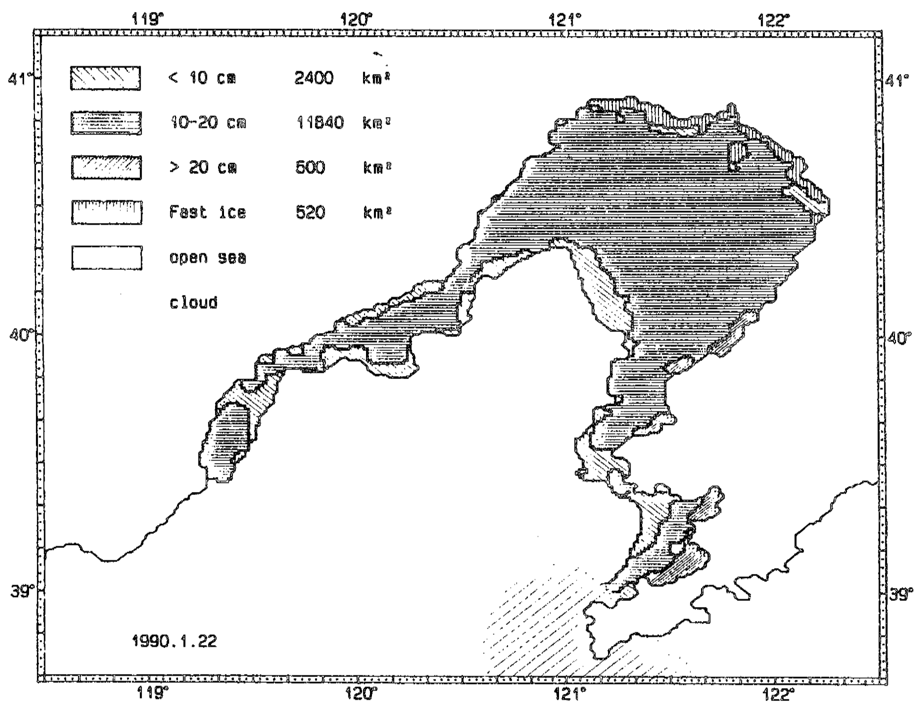


(d)

Fig. 2.2.19. A 3-day forecast for the Bohai Sea for the same period as the observations of Fig. 2.2.20.
(a) synthetic analysis of initial ice thickness on January 20, 1990
(b) 24 hour forecast for ice drift (arrow) and thickness (isoline), valid on Jan. 21
(c) 48 hr forecast, valid on Jan. 22
(d) 72 hr forecast, valid on Jan. 23 (National Research Center for Marine Environmental Forecasts, Beijing, China).

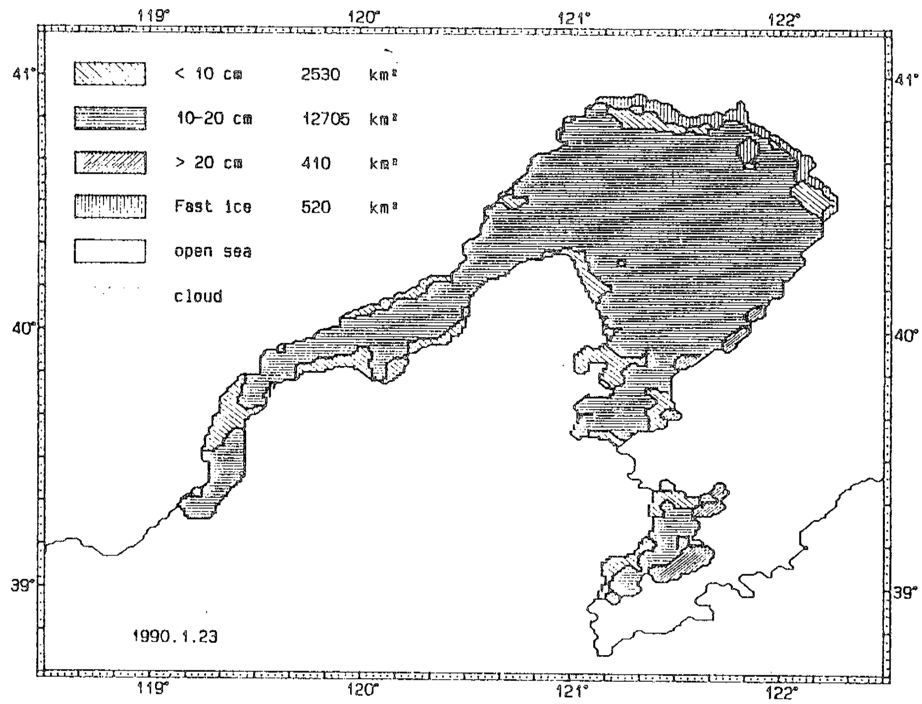


(a) Jan. 20, 1990

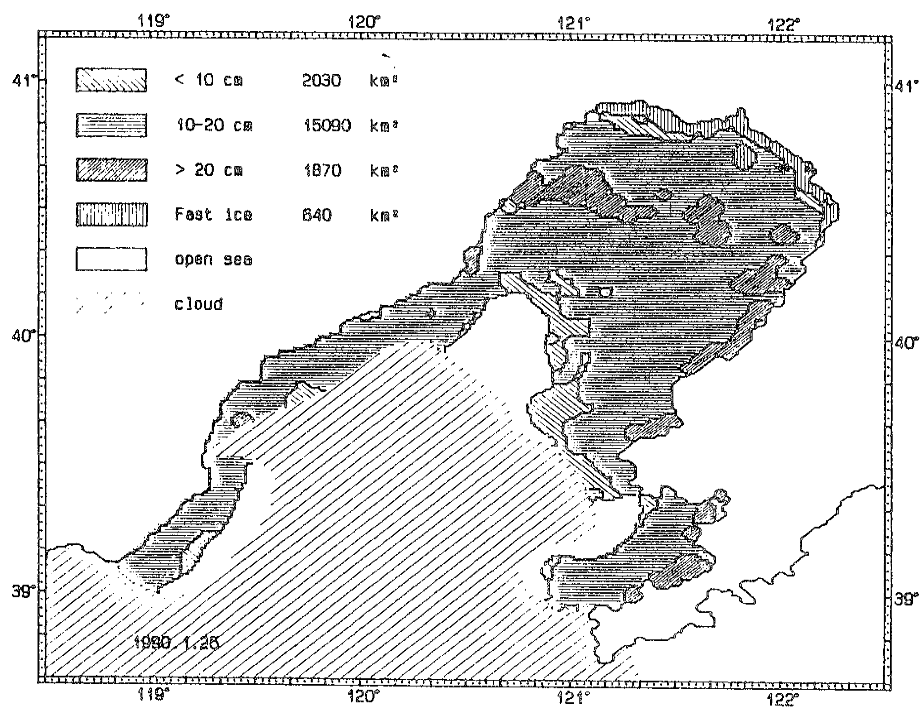


(b) Jan. 22, 1990

Fig. 2.2.20. Ice thickness analyzed on the basis of satellite imagery in the Bohai Sea (Huang et al., 1990, 1992).



(c) Jan. 23, 1990



(d) Jan. 25, 1990

Fig. 2.2.20. (c) (d)

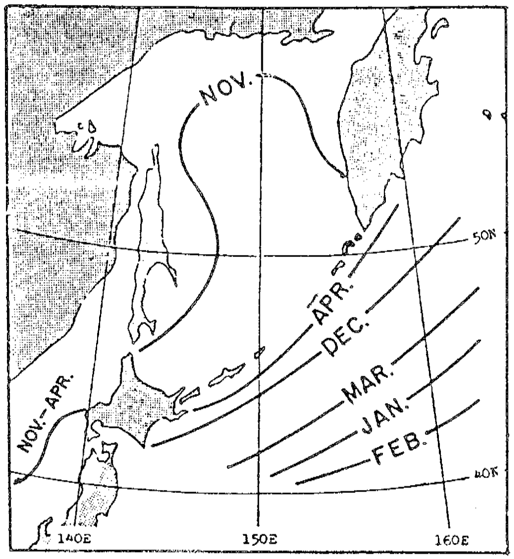


Fig. 2.3.1. Seasonal variation of the margin of the area where ice accretion on ships occurs (Sawada, 1969).

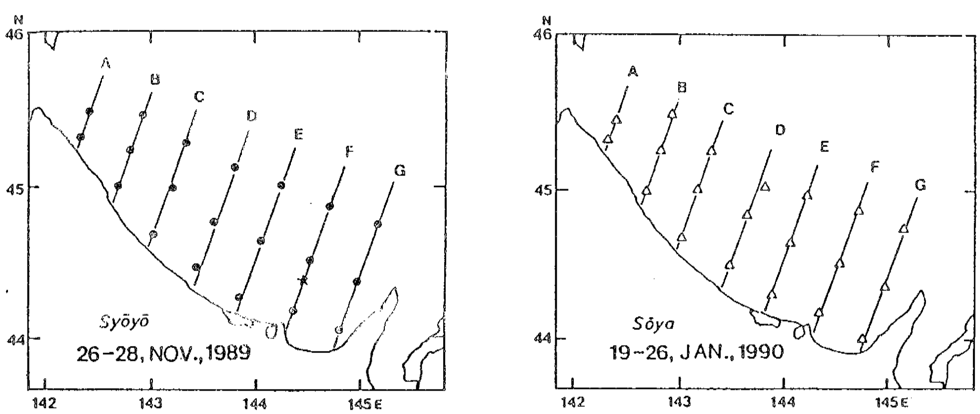


Fig. 2.3.3. Observation lines occupied by the Hydrographic Department twice a year (Ishii, 1991).

(Fig. 2.3.2. on next page)

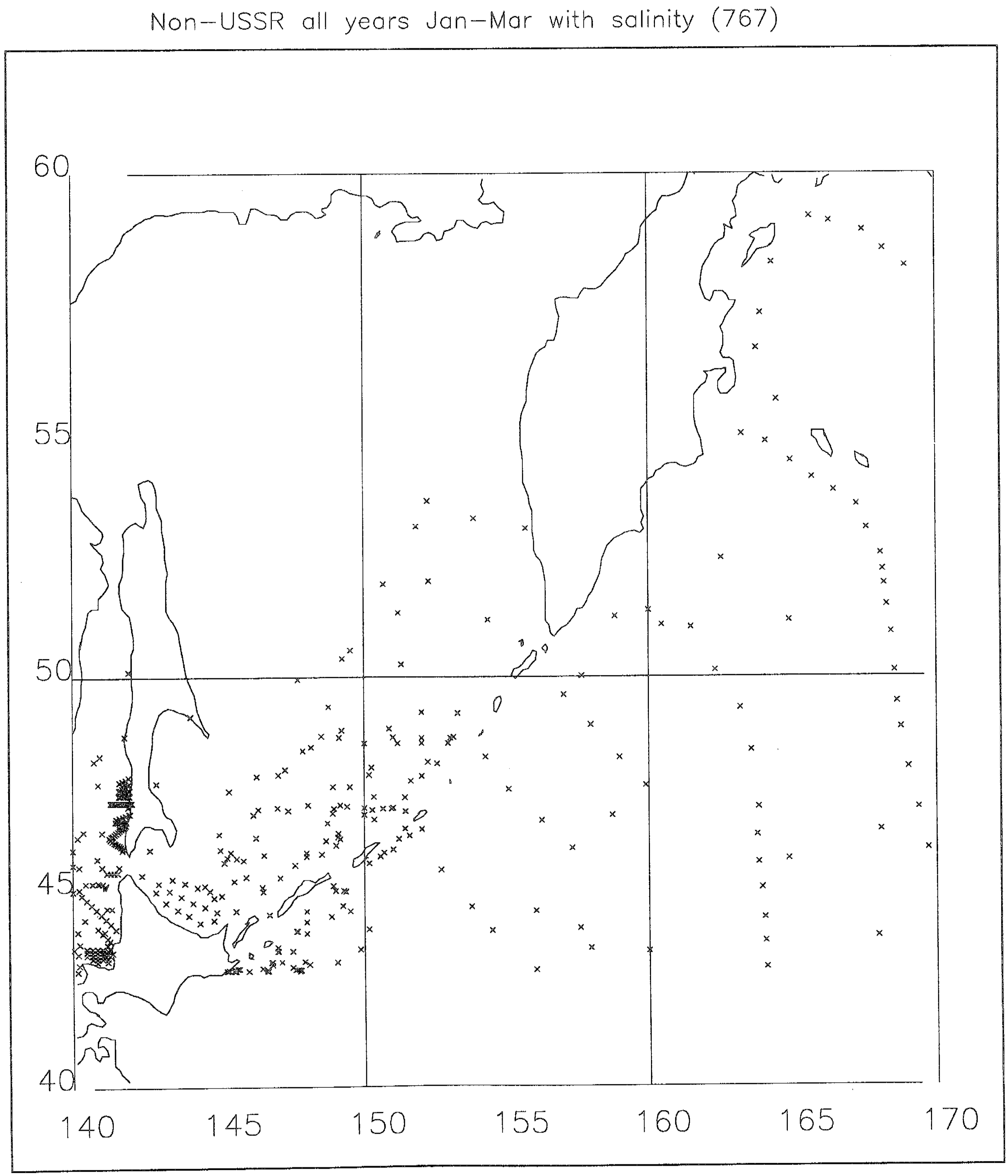


Fig. 2.3.2. WDCA observations for January-March of all years.

(Fig. 2.3.3 on previous page)

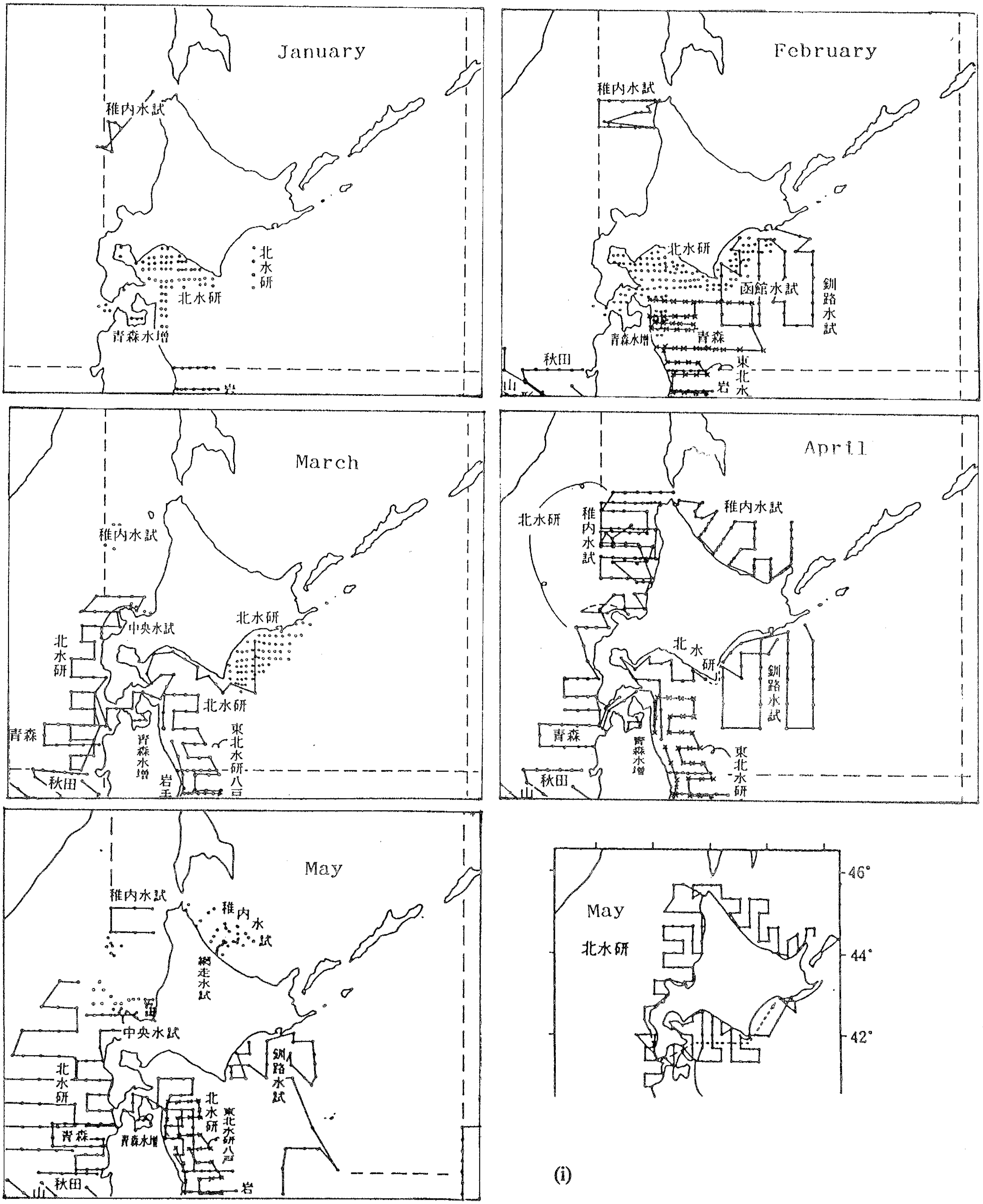


Fig. 2.3.4. Observation lines occupied by Japan Fisheries Agency and the Prefectural Fisheries Experimental Stations adjacent to Hokkaido for each month of 1985 (JFA, 1989).

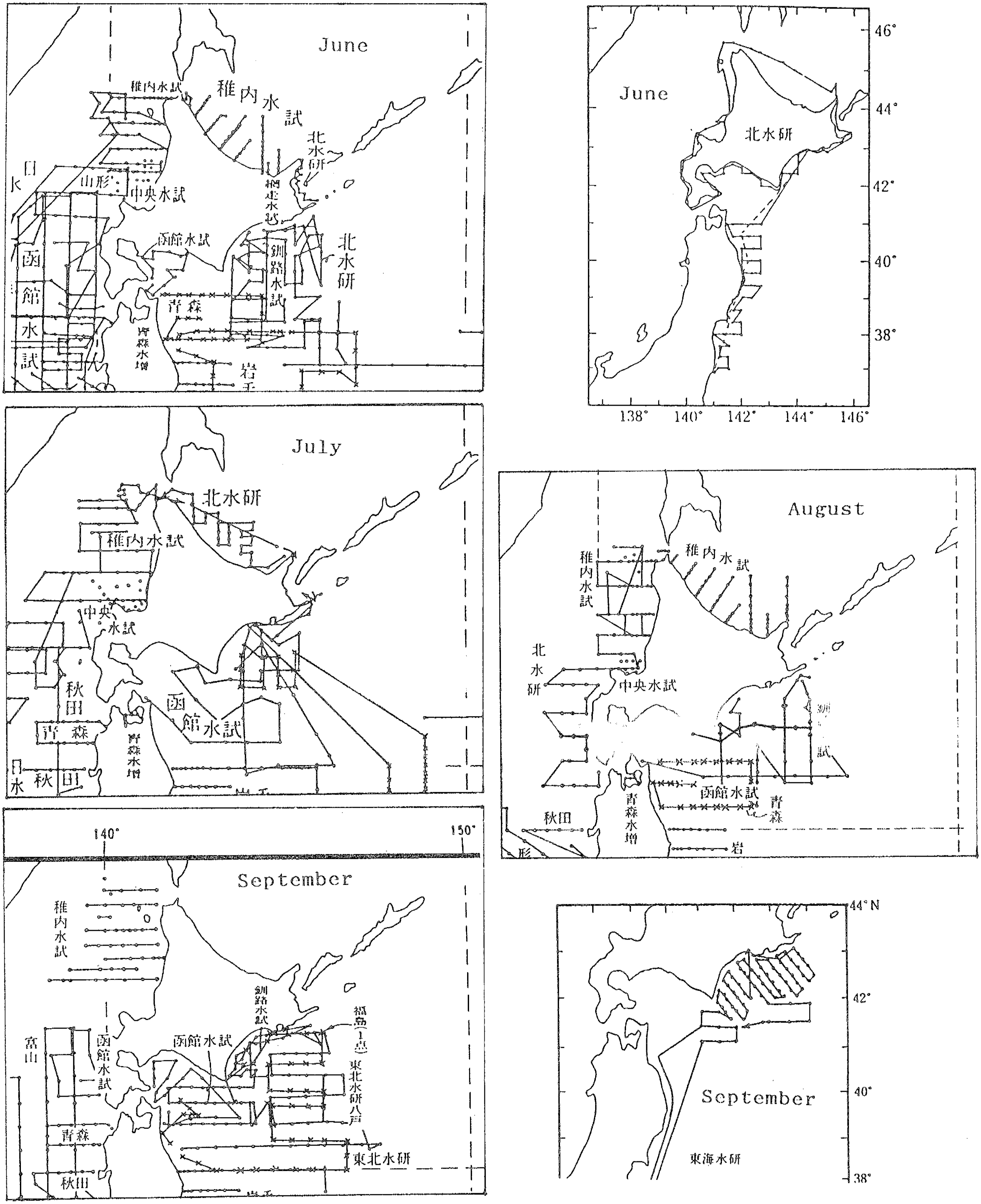
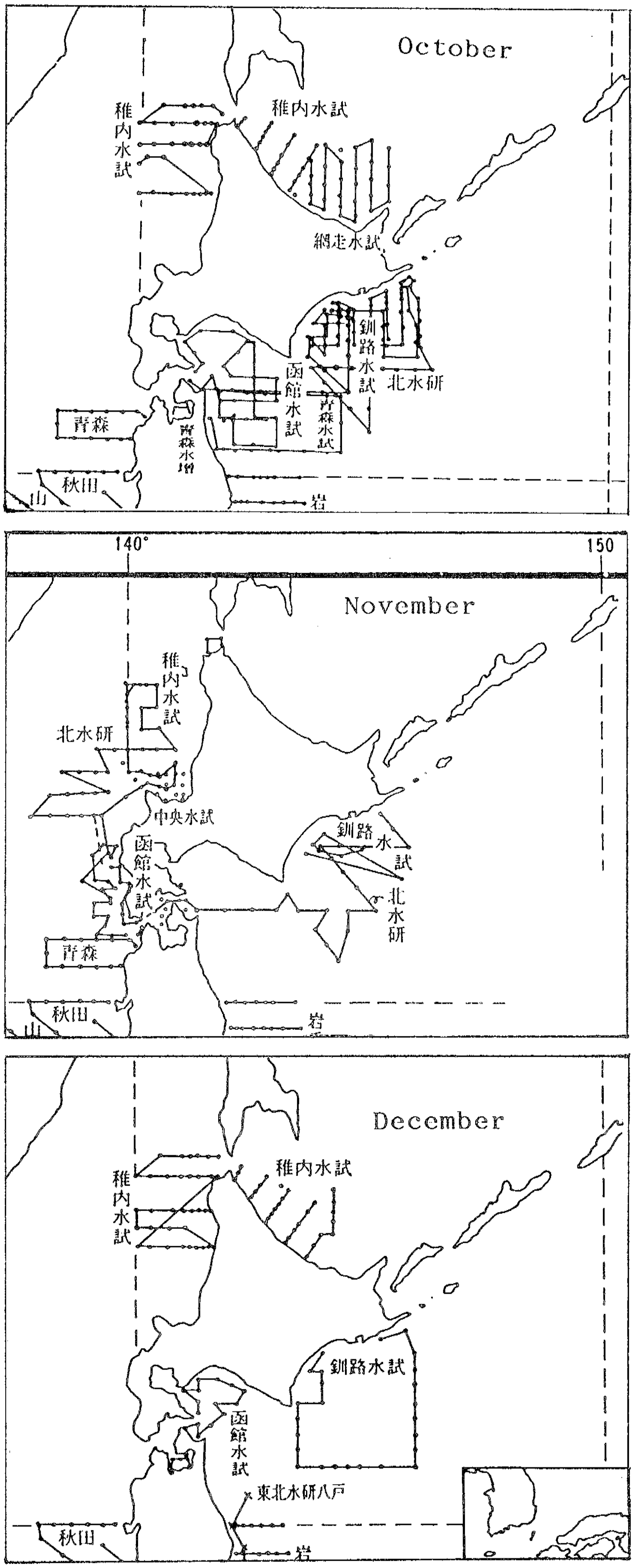

June
稚内水試
北水研
中央水試
網走水試
函館水試
釧路水試
青森
青森水増
函館水試
July
北水研
稚内水試
中央水試
秋田
函館水試
青森
青森水増
August
稚内水試
北水研
中央水試
函館水試
青森水増
秋田
青森
September
140°
150°
稚内水試
釧路水試
函館水試
富山
青森
秋田
東北水研八戸
東北水研
東海水研
46°
44°
42°
40°
38°
138°
140°
142°
144°
146°
44° N

Fig. 2.3.4 (ii)


October
稚内水試
稚内水試
網走水試
釧路水試
北水研
函館水試
青森水試
青森
秋田
山
岩
140°
150
November
稚内水試
北水研
中央水試
函館水試
釧路水試
北水研
青森
秋田
山
岩
December
稚内水試
稚内水試
釧路水試
函館水試
東北水研八戸
秋田
岩

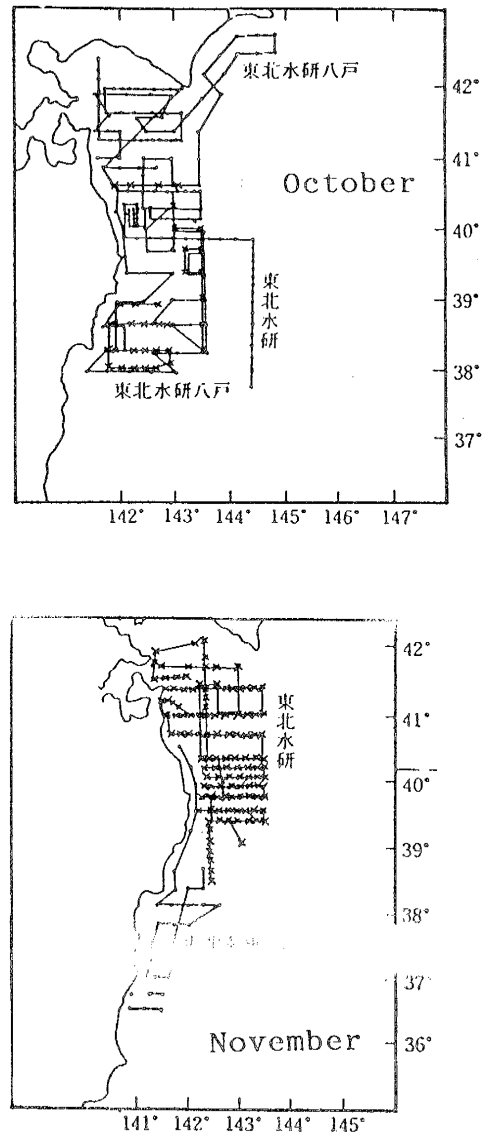

東北水研八戸
October
東北水研
東北水研八戸
42°
41°
40°
39°
38°
37°
142°
143°
144°
145°
146°
147°
東北水研
42°
41°
40°
39°
38°
37°
36°
November
141°
142°
143°
144°
145°

Fig.2.3.4 (iii)

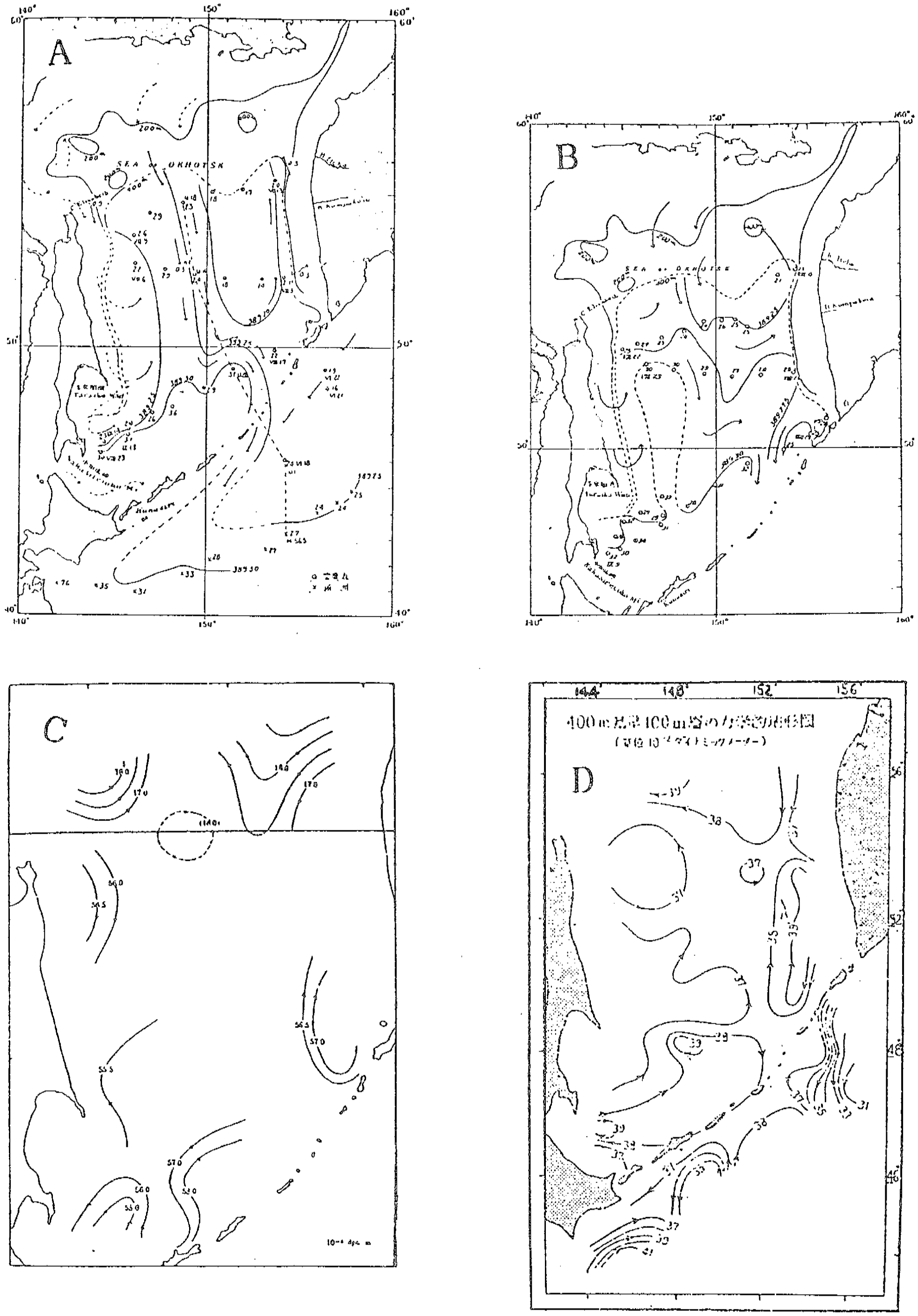


Fig. 2.3.5. Circulation pattern in the Okhotsk Sea given by various investigators. A through C are the dynamic topography at the sea surface referred to the 400 db surface
A and B: in August-September, 1916 and 1917, respectively, by Shigematu [1933]
C: in July-August by Akiba et al. [1959]
D: is the dynamic topography at 100 m referred to 400 db surface (in July-August, 1942 by Kajiura [1949])

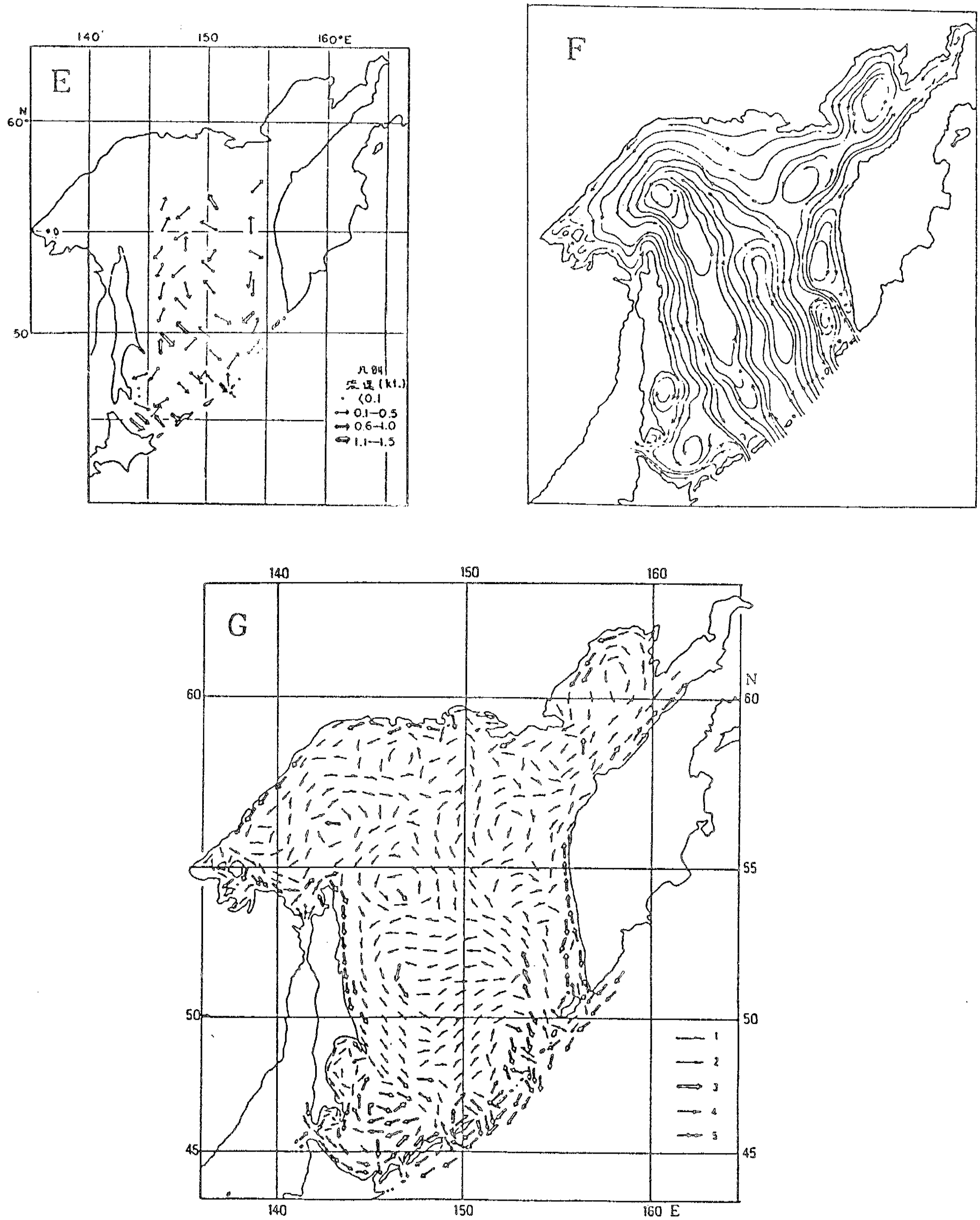


Fig. 2.3.5 E: is based on GEK measurements (Iida, 1969)
F: (Leonov, 1960)
G: (Moroshkin, 1962) are schematic circulations based on synthesis of the available knowledge.
Fig. 2.2.~~4~~3 in the previous chapter presented an additional view.

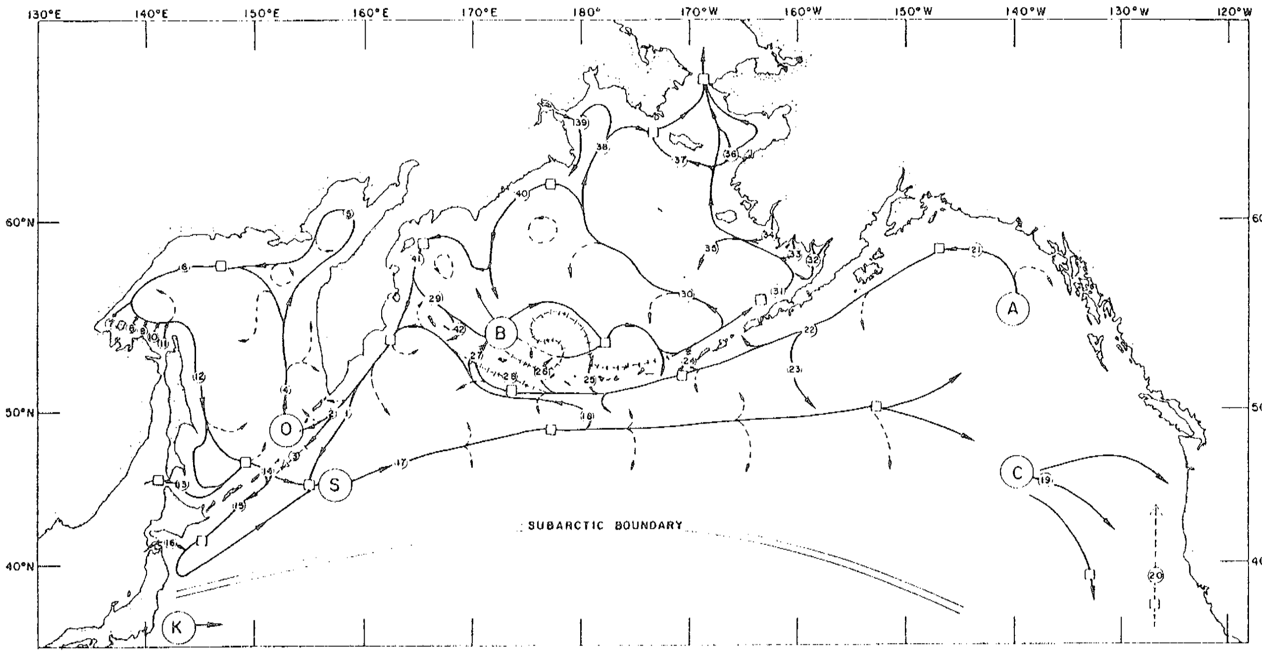


FIGURE 42. Location of recognized currents in the Subarctic Pacific Region (1—Southeast Kamchatka; 2—Southwest Kamchatka; 3—East Kamchatka Deep; 4—West Kamchatka; 5—Penzhinsk; 6—North Okhotsk; 7—Udsk; 8—Tugurk; 9—Ul'Bansk; 10—Amur; 11—West Sakhalin; 12—East Sakhalin; 13—Soya; 14—Kuril; 15—Oyashio; 16—Tsugaru: 17—Subarctic; 18—Western Subarctic; 19—California; 20—California Undercurrent; 21—Alaska; 22—Alaskan Stream; 23—Aleutian; 24—Amukta; 25—Amchitka; 26—Buildir; 27—Near; 28—Alaskan Stream Undercurrent; 29—Commander; 30—Transverse; 31—West Alaska; 32—Kvichak; 33—Nushagak; 34—Kuskokwim; 35—Pribilof; 36—Yukon; 37—St. Lawrence; 38—Navarin; 39—Anadyr; 40—Olyutorskiy; 41—East Kamchatka; 42—Copper).

Fig. 2.3.6. Currents in the Subarctic Pacific. Figure 42 from Favorite et al. (1976).

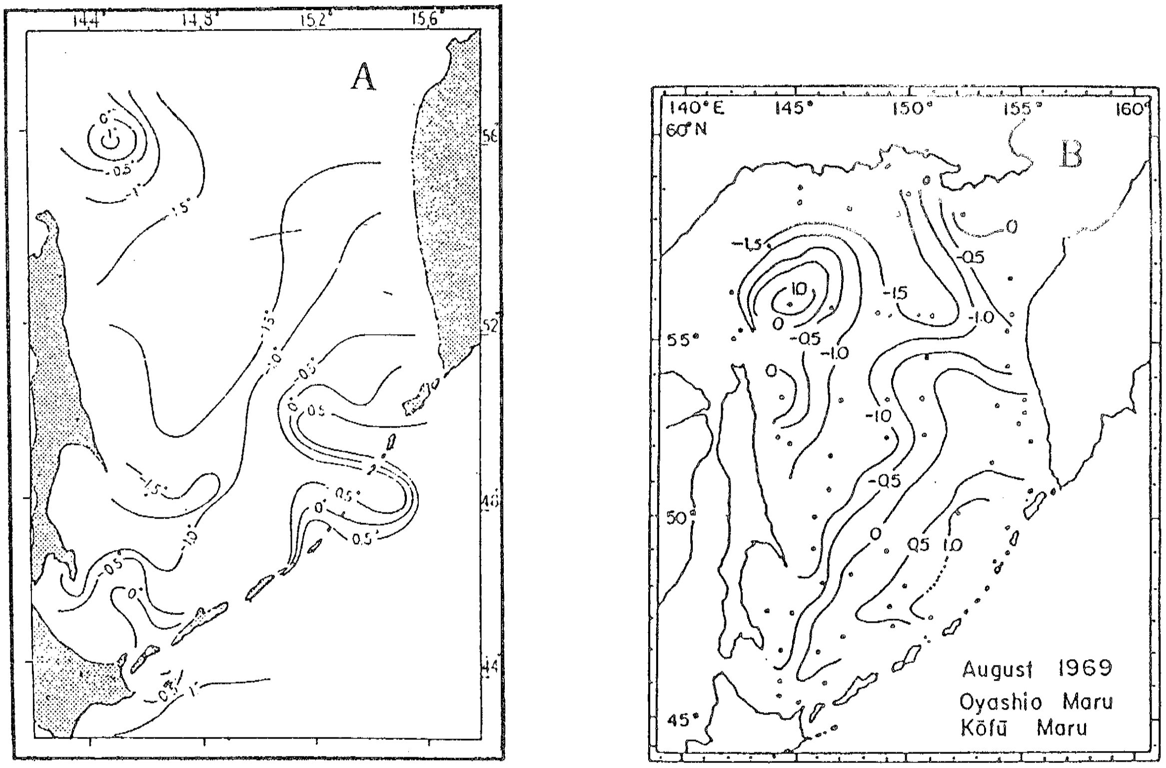


Fig. 2.3.7. A: Temperature (°C) at the temperature minimum (dichothermal layer) in August, 1969 (Kitani, 1973a). B: The same in July-August, 1942 (Kajiura, 1949).

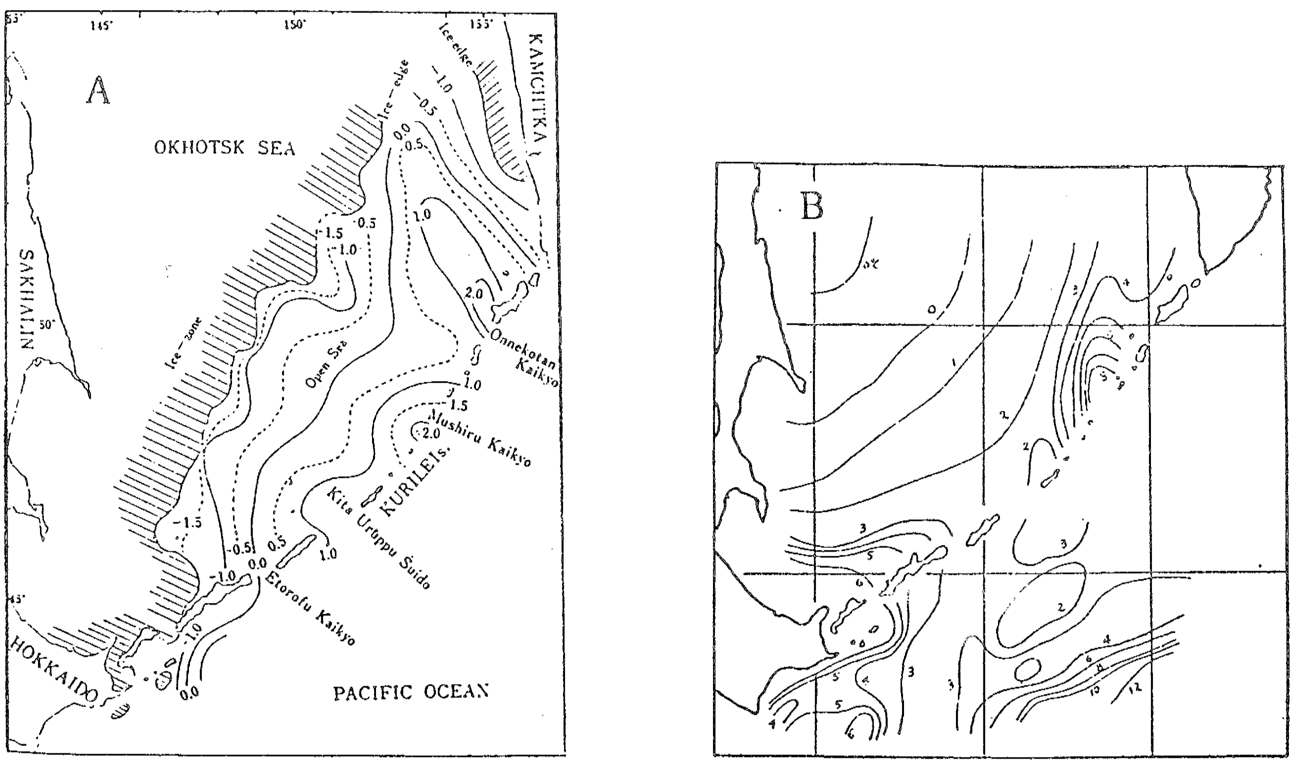


Fig. 2.3.8. A: ice limit and surface temperature (°C) in February, 1938 (Kurashina et al., 1967). B: temperature at 50m in August, 1941 (Tabata, 1952).

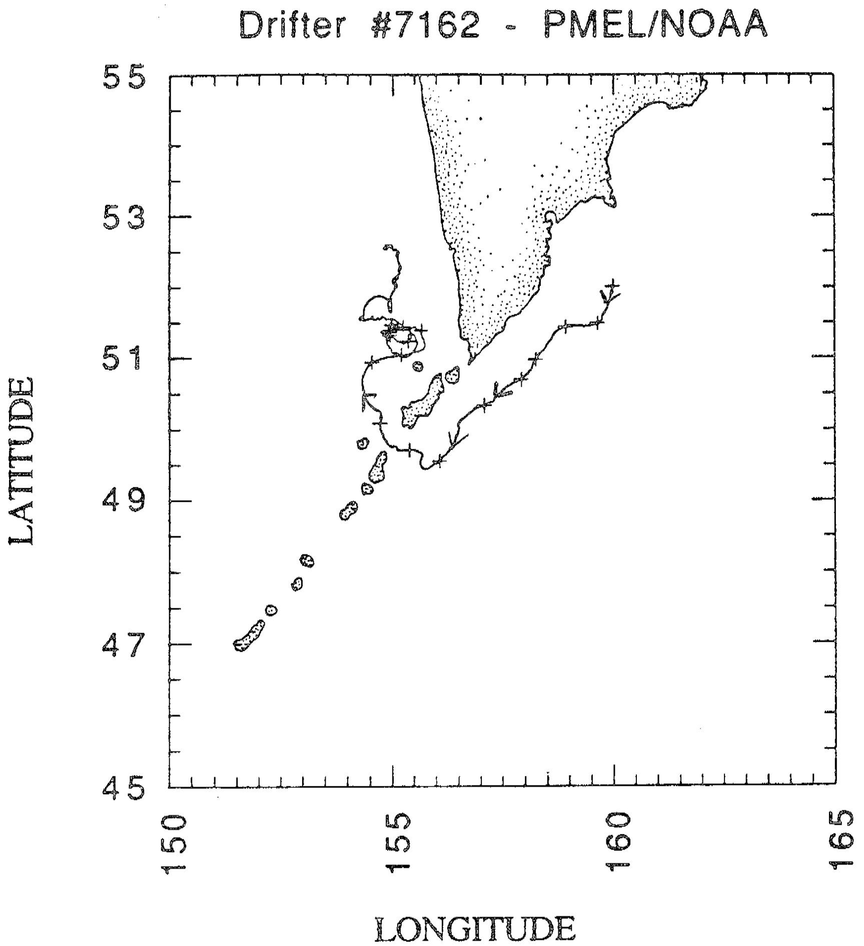


Fig. 2.3.9.

Surface drifter track in early 1991 (NOAA/PMEL drifter #7162; courtesy of P. Stabeno).

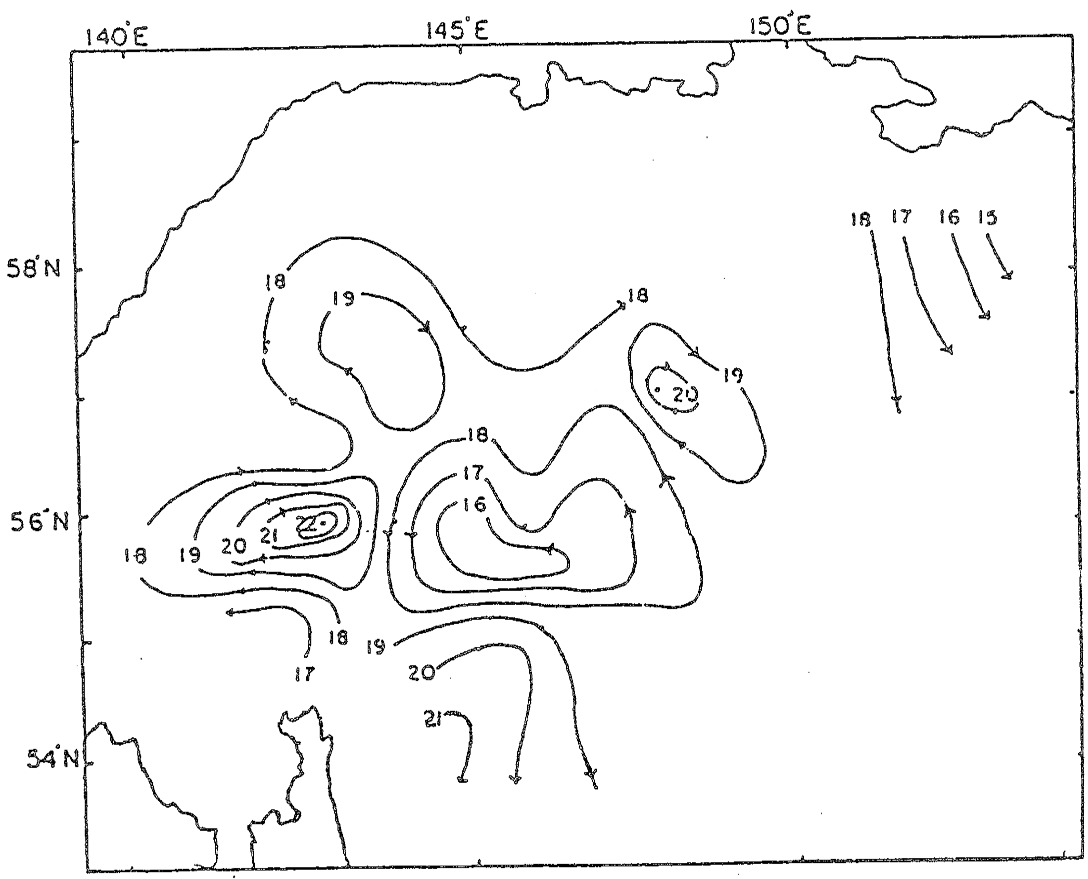


Fig. 2.3.10.

Dynamic topography (in 10-2 dyn m) of the surface relative to 100 db in September, 1970 (Kitani and Shimazaki, 1971).

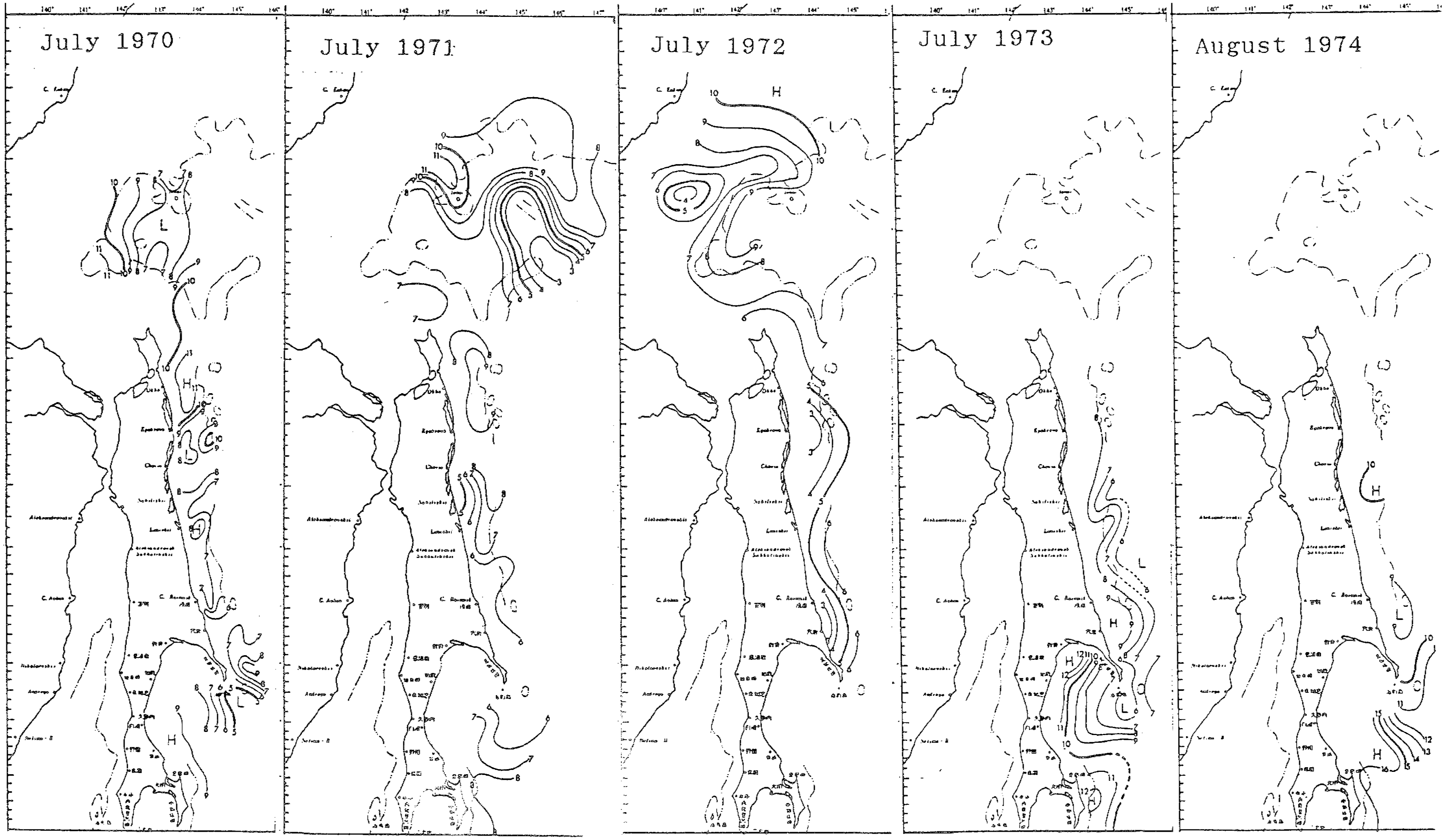


Fig. 2.3.11. Sea surface temperature (°C) off the east coast of Sakhalin in summer from 1965 to 1974 (Fujii and Abe, 1976).

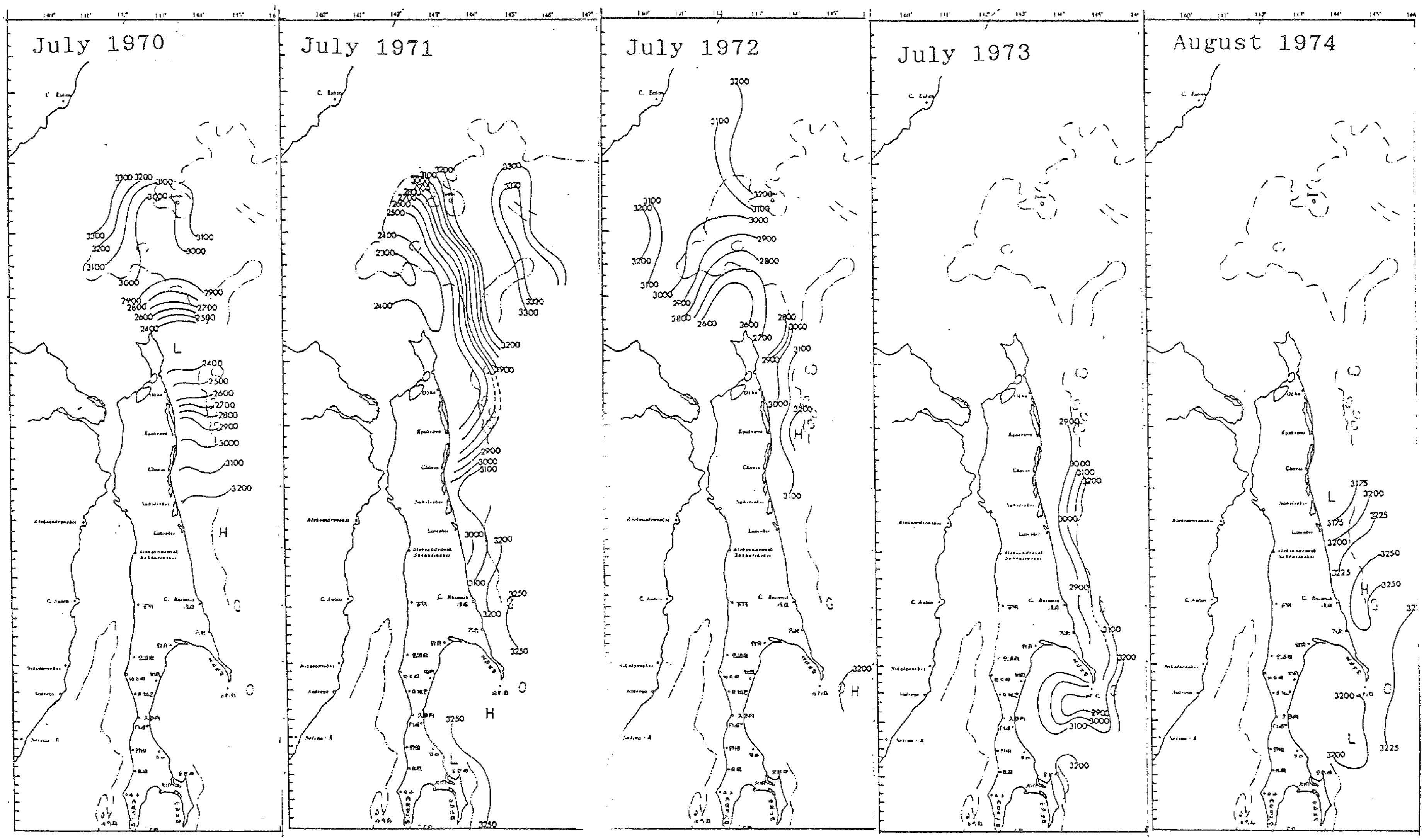


Fig. 2.3.12. Sea surface salinity off the east coast of Sakhalin in summer from 1965 to 1974 (Fujii and Abe, 1976).

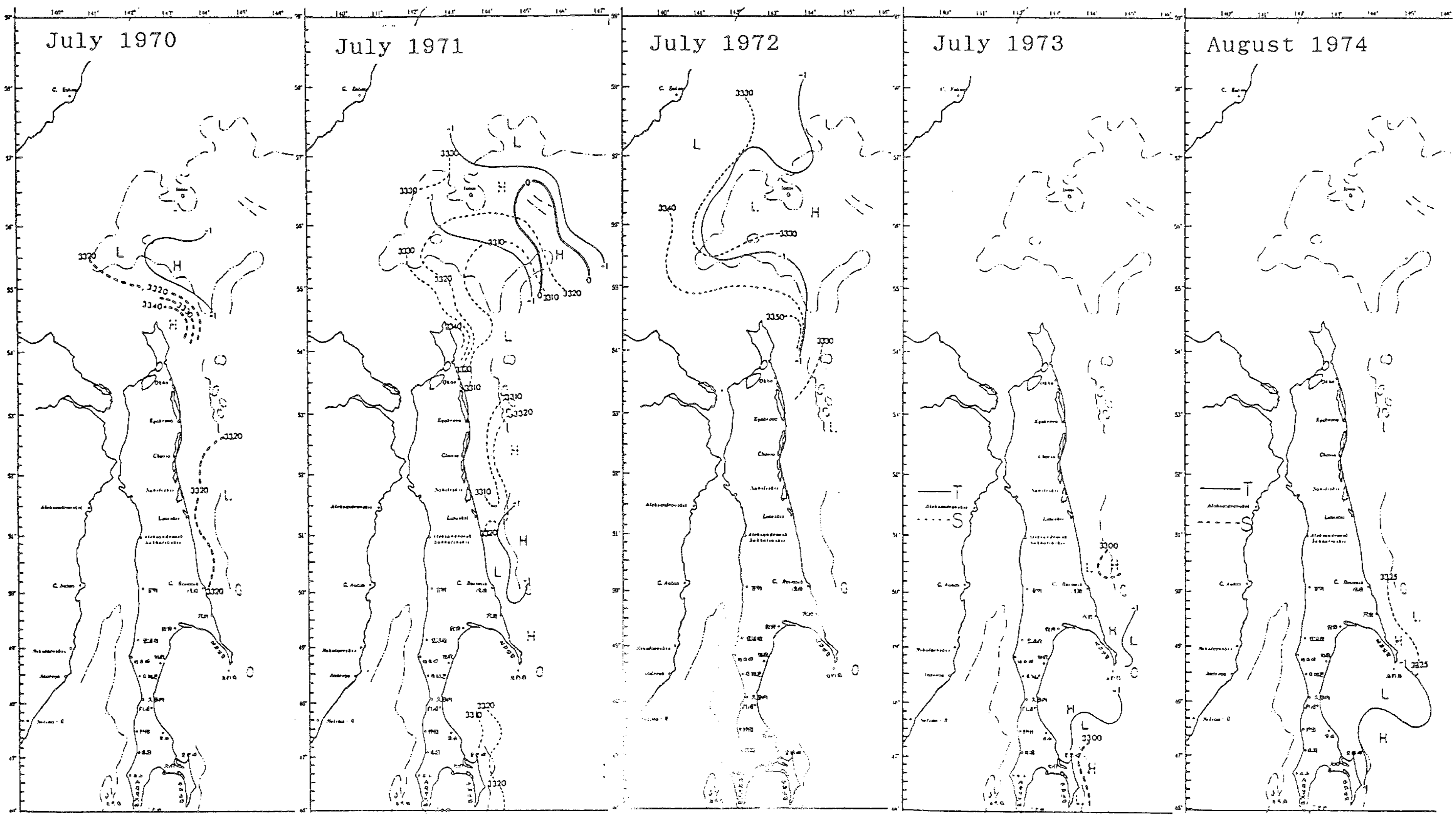


Fig. 2.3.13. Temperature (°C) and salinity at 100 m off the east coast of Sakhalin in summer from 1965 to 1974 (Fujii and Abe, 1976).

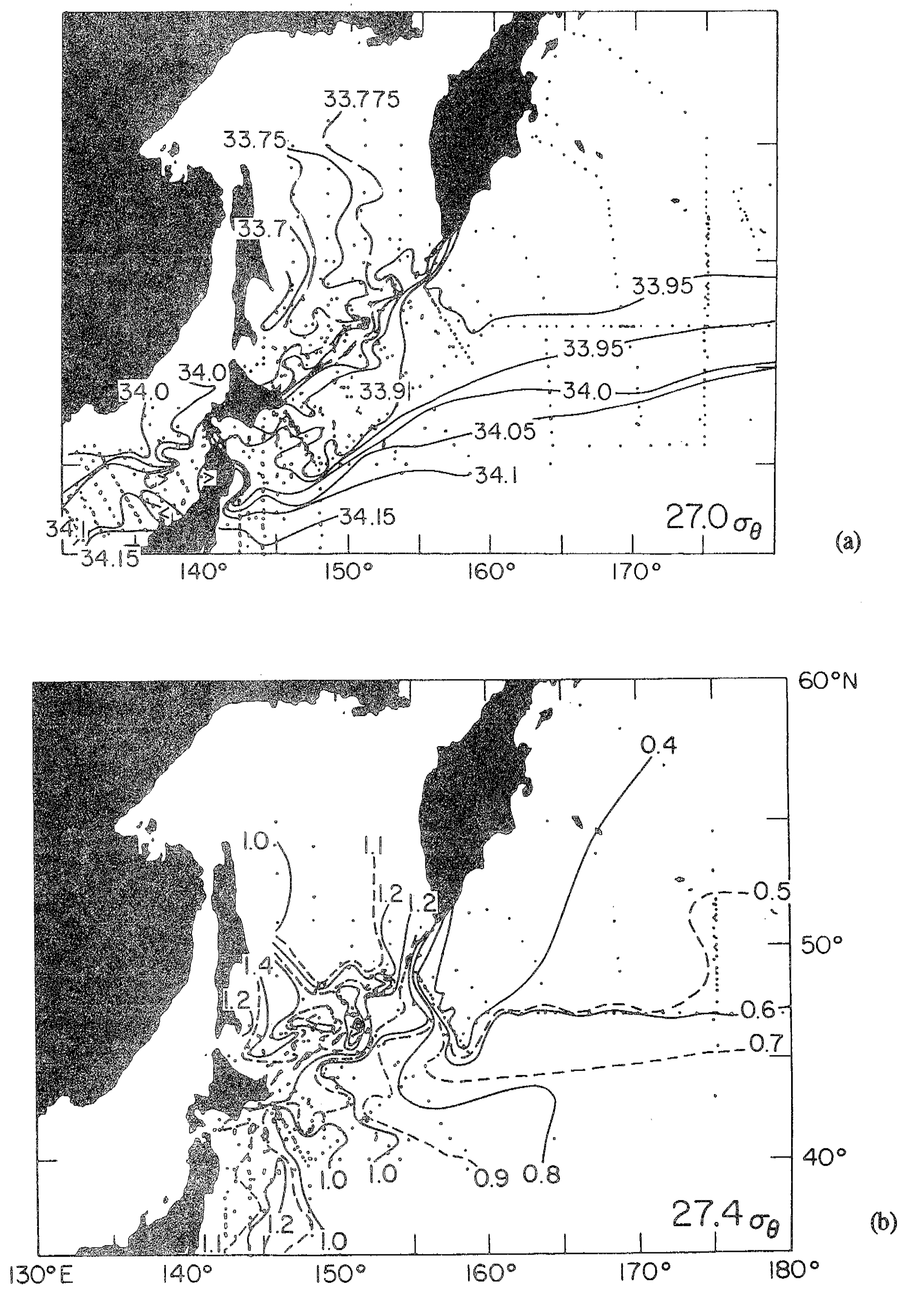


Fig. 2.3.14. (a) Salinity at 27.0 σ_θ and (b) oxygen at 27.4 σ_θ (Talley, 1991).

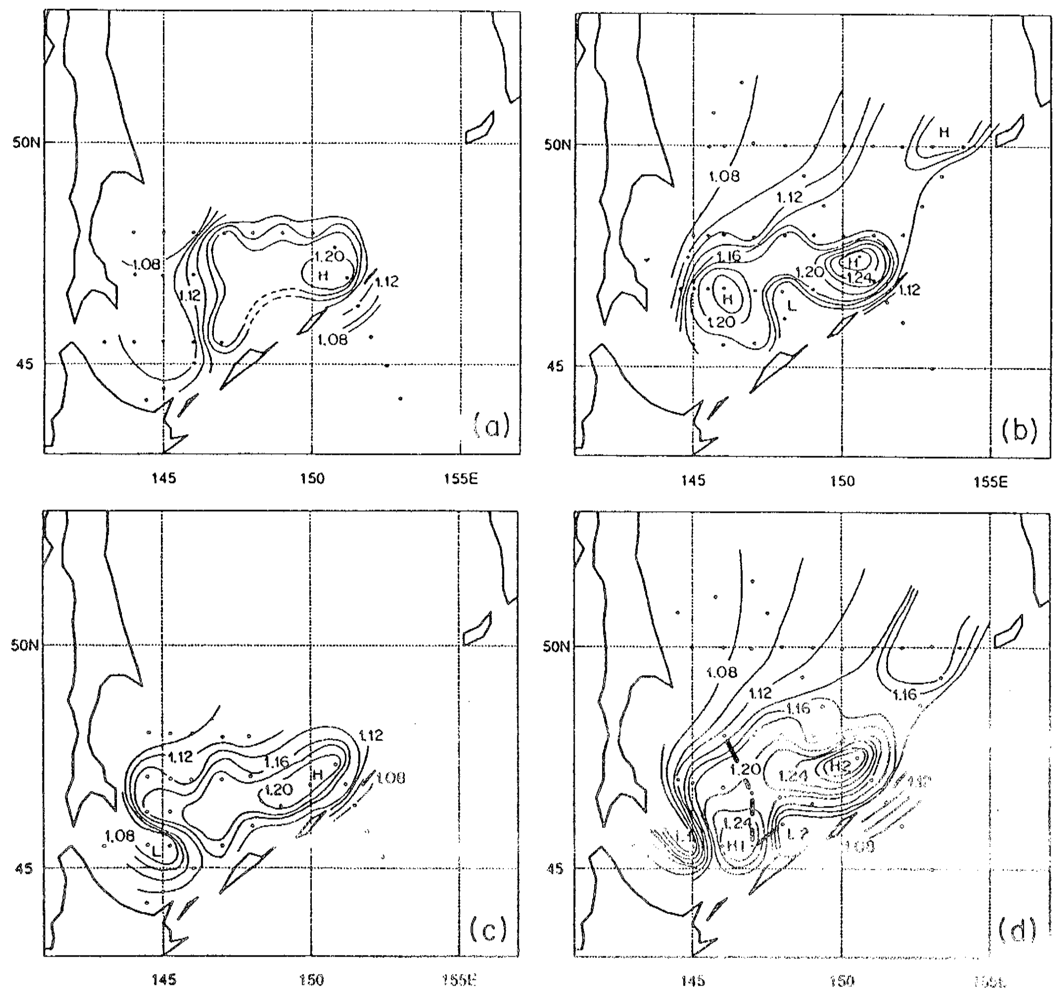


Fig. 2.3.15. Dynamic topography (0/1000 db) in the Kuril Basin for (a) June-July, 1977, (b) October, 1977, (c) July, 1978 and (d) November, 1978. The contour lines are in dynamic meters (Wakatsuchi and Martin, 1991).

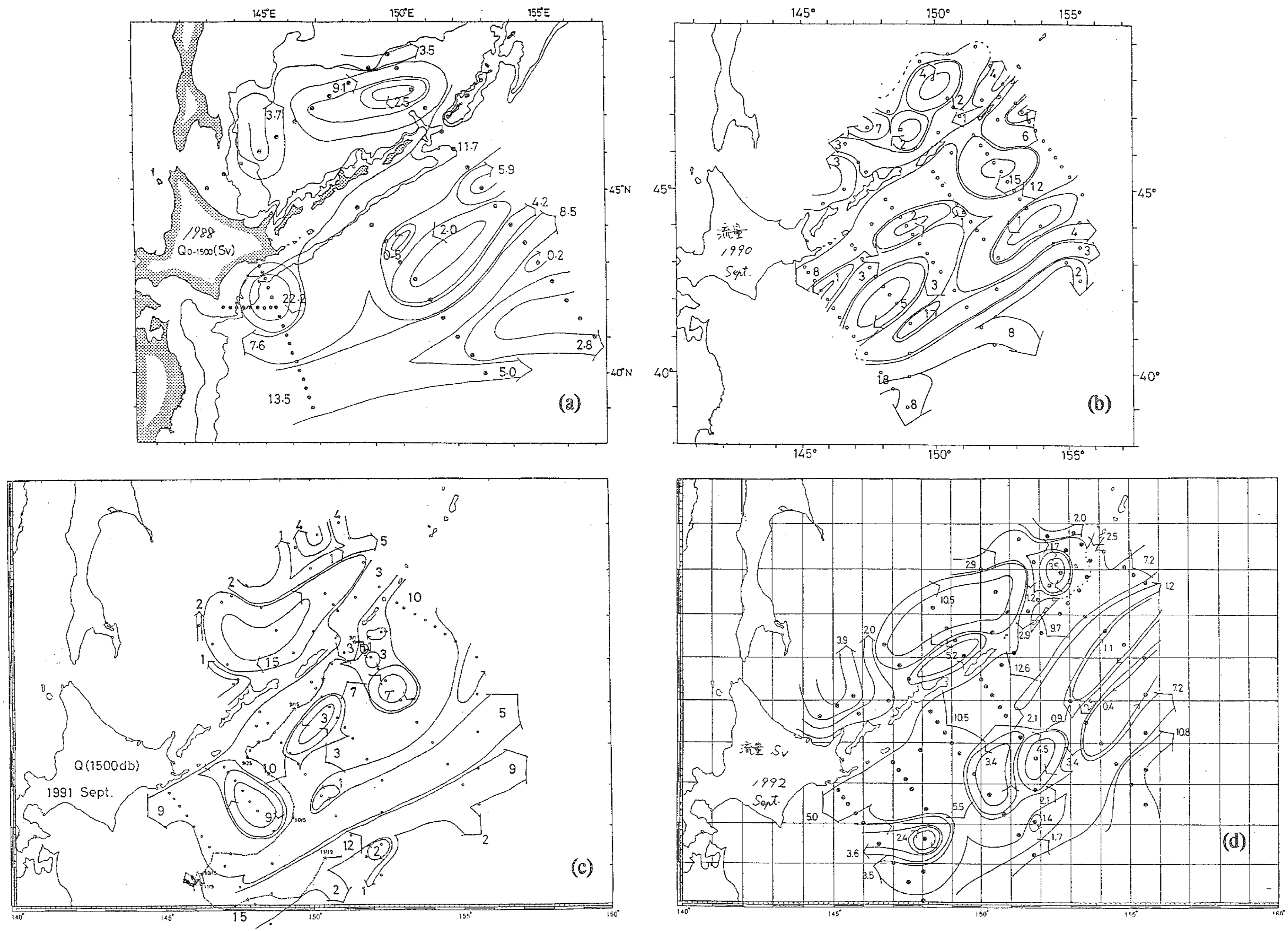


Fig. 2.3.16. Transport relative to 1500 dbar from the JFA Hokkaido surveys of (a) 1988, (b) 1990, (c) 1991, and (d) 1992. They show the anticyclonic circulation in the Kuril Basin gyre. Courtesy of Kawasaki and Kono.

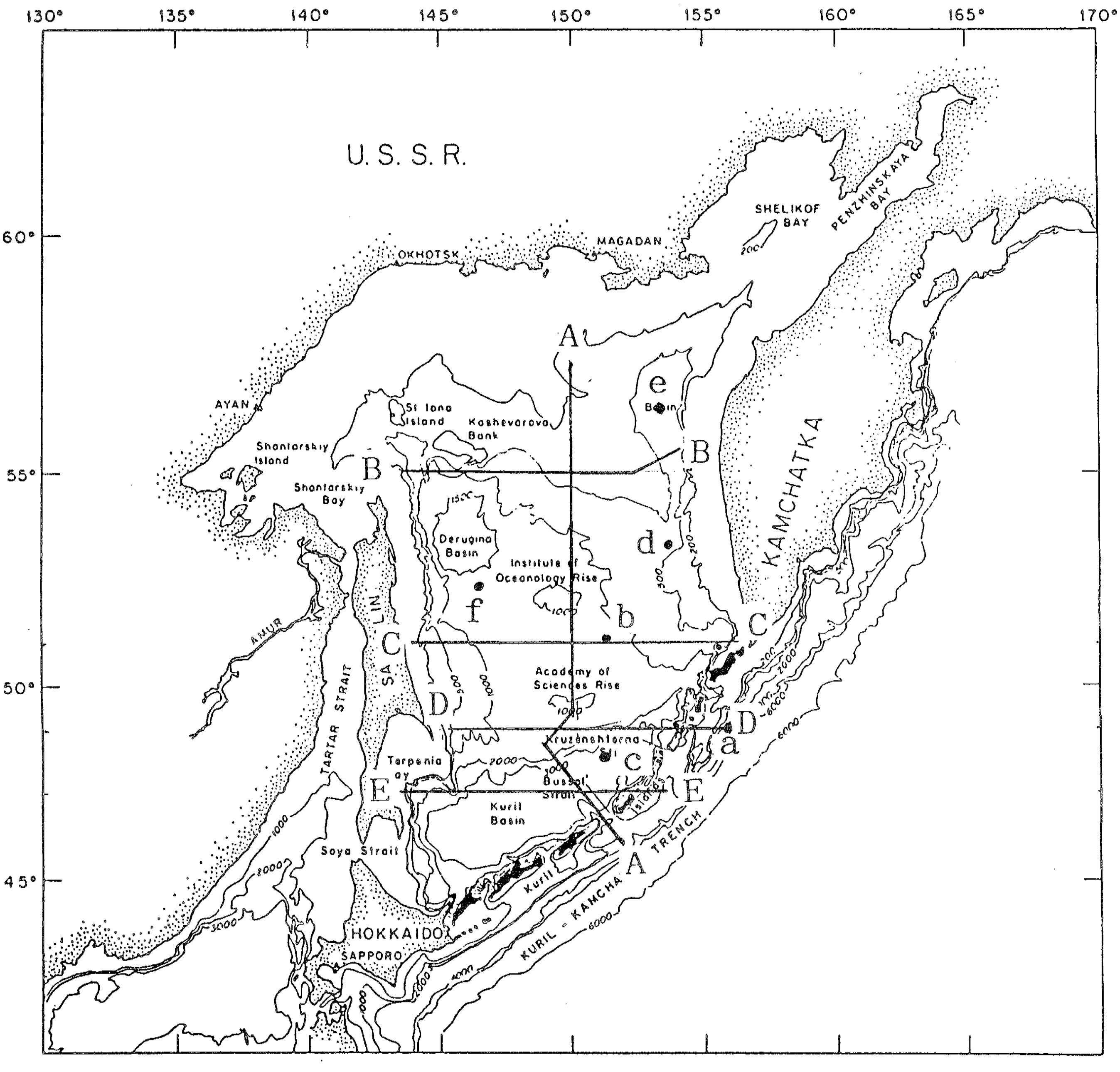


Fig. 2.3.17. Locations of the temperature and salinity sections shown in Fig. 2.3.18 and profiles shown in Fig. 2.3.21. (Kitani and Shimazaki, 1971).

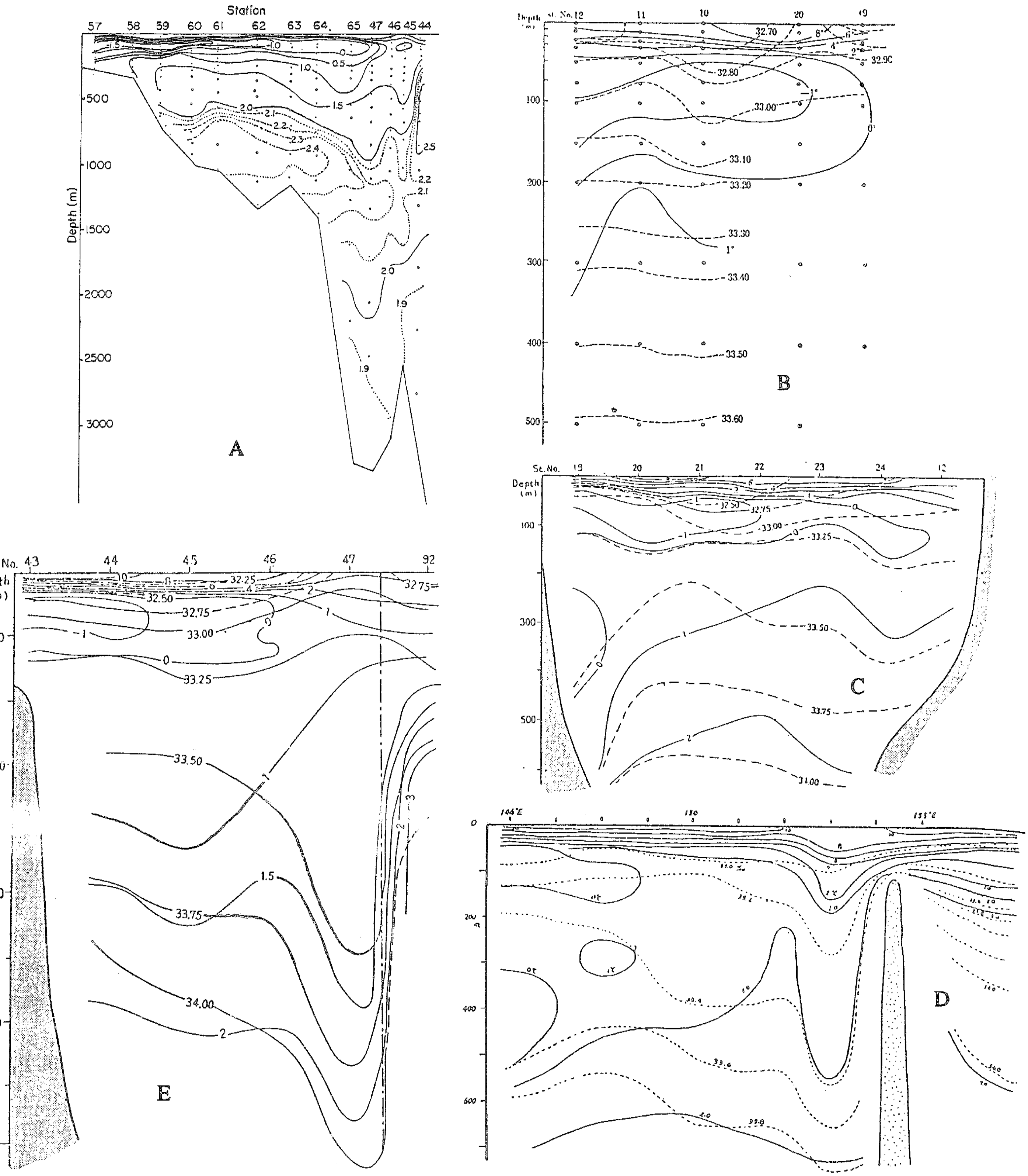


Fig. 2.3.18. Temperature (°C) and salinity sections along the lines shown in Fig. 2.3.17. (Note that observations deeper than 1000 m are shown only in A):

A: Temperature distribution along the meridional line A-A roughly along 150°E in June, 1967 (Kitani, 1973a)

B: Temperature and salinity roughly along 55°N in July-August, 1958 (Akiba et al., 1959)

C: Temperature and salinity roughly along 51°N in July-August, 1942 (Kajiura, 1949)

D: Temperature and salinity roughly along 49°N in August, 1941 (Tabata, 1952)

E: Temperature and salinity roughly along 47°N in July-August, 1952 (Kajiura, 1949). Vertical dotted and dashed line indicates the position of the Kuril Islands.

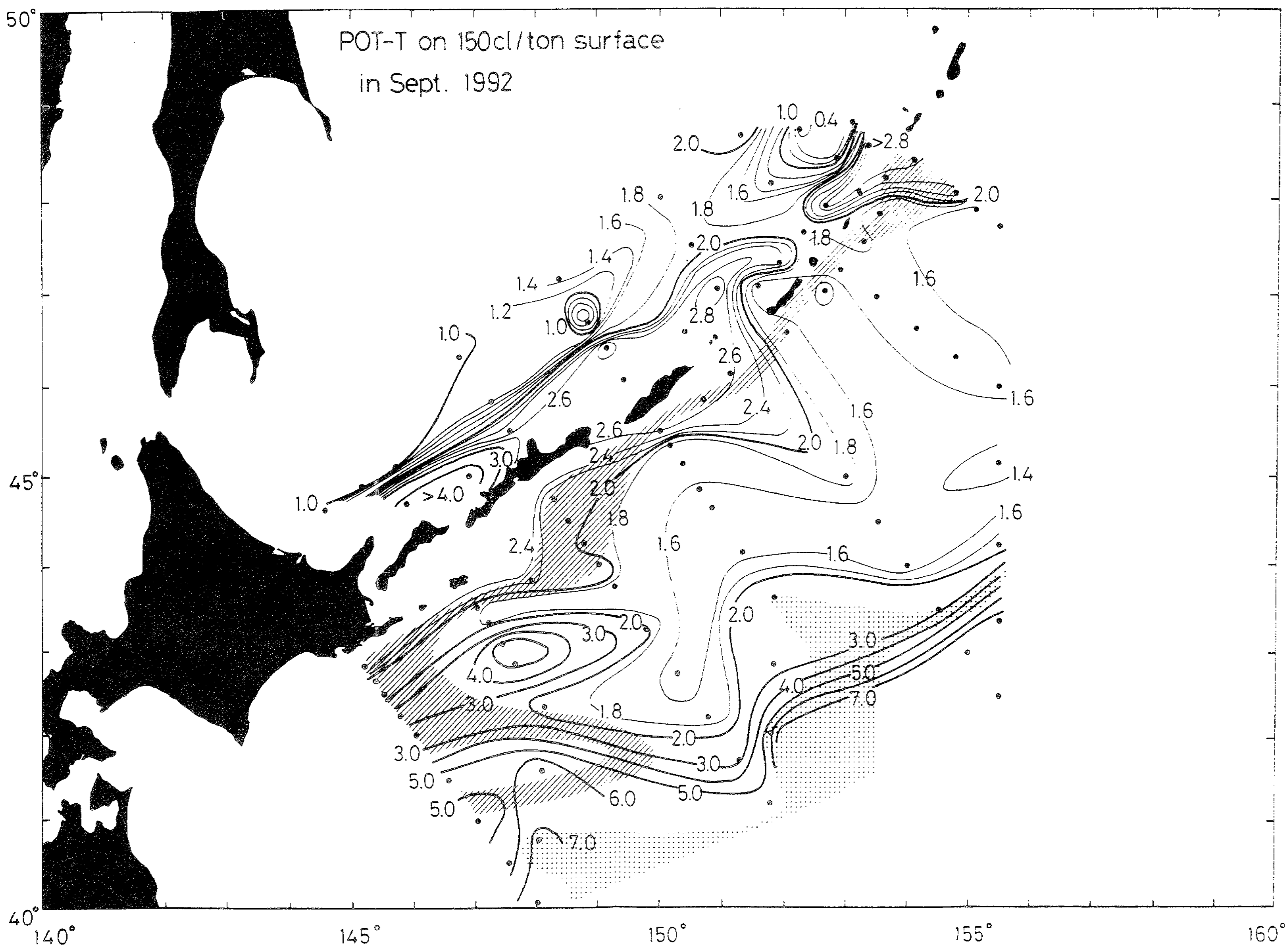


Fig. 2.3.19. Potential temperature at 26.65 σ_θ in September, 1992. (Kawasaki and Kono, 1993).

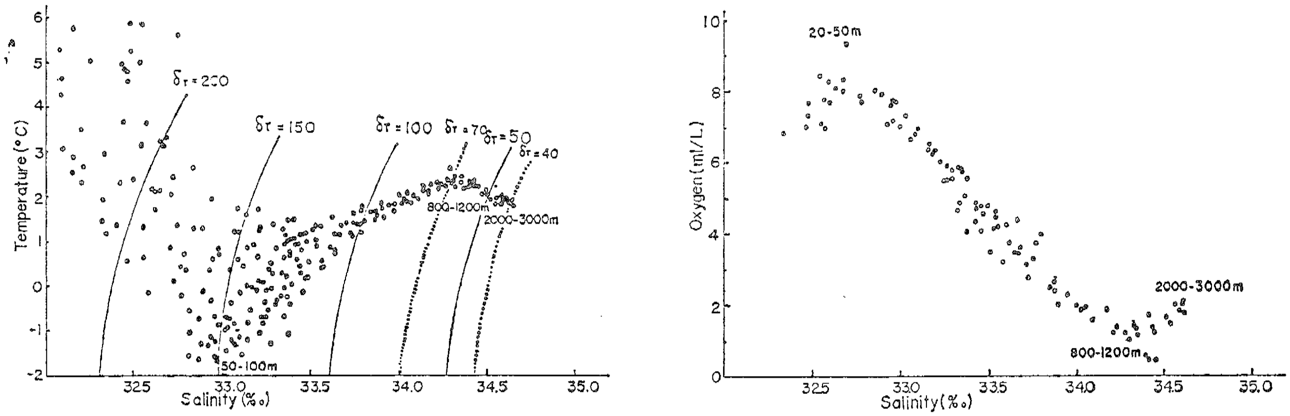


Fig. 2.3.20. T-S relations (upper figure) and O_2-S relations (lower figure) of the water in the deep southern Okhotsk Sea in summer. Salinity decreases monotonically from surface to bottom. (Kitani, 1973).

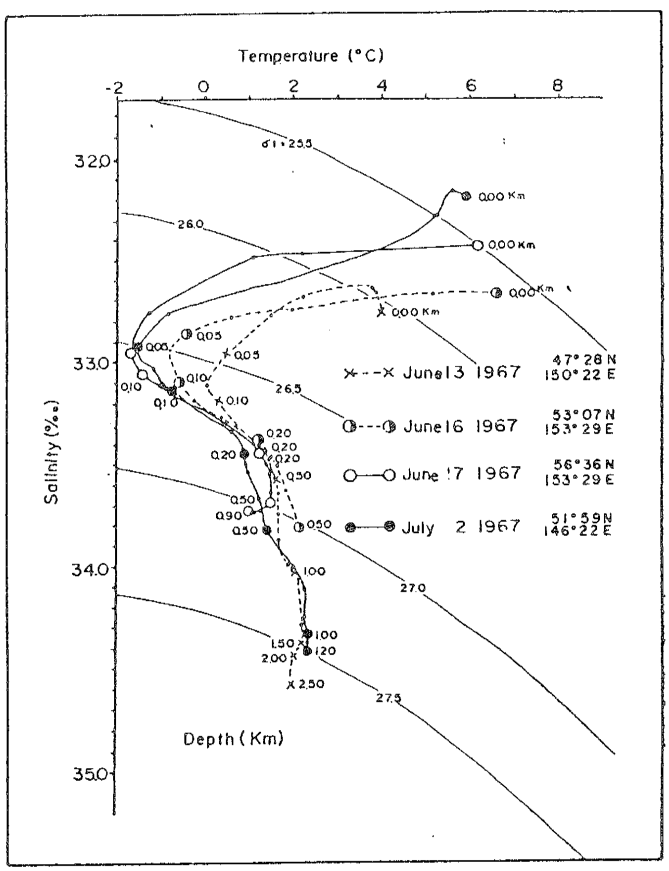


Fig. 2.3.21. T-S relations at various locations in the Okhotsk Sea (Yasuoka, 1968). The positions are shown in Fig. 2.3.17 labeled c through f.

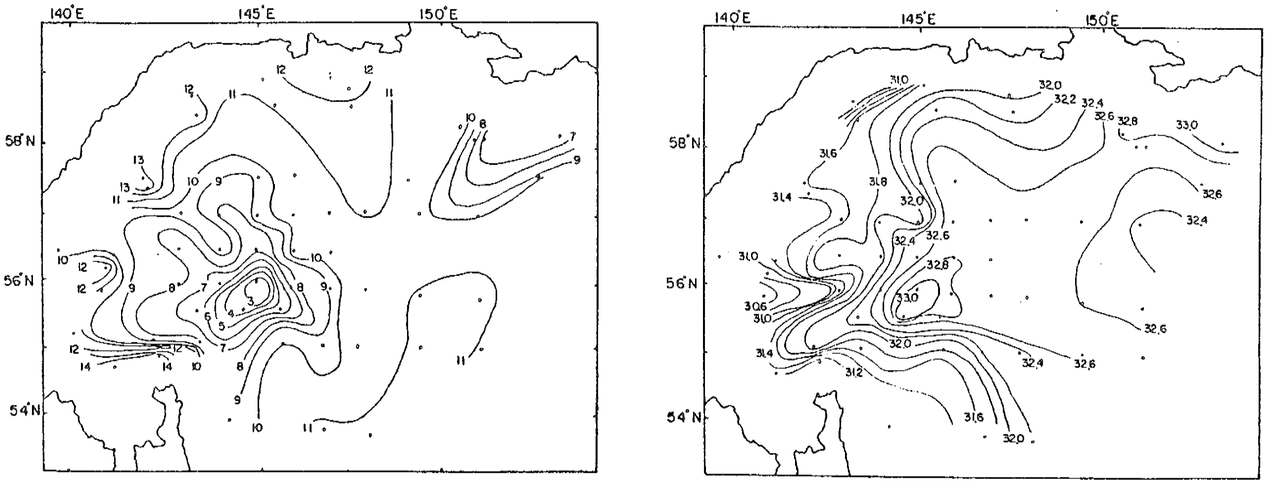


Fig. 2.3.22. Temperature (°C: left) and salinity (right) at the sea surface in September, 1970 (Kitani and Shimazaki, 1971).

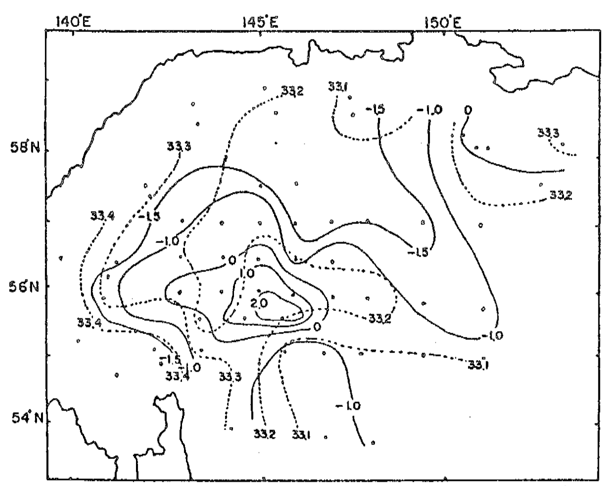


Fig. 2.3.23. Temperature (°C: solid) and salinity (dotted) at 100 m in September, 1970 (Kitani and Shimazaki, 1971).

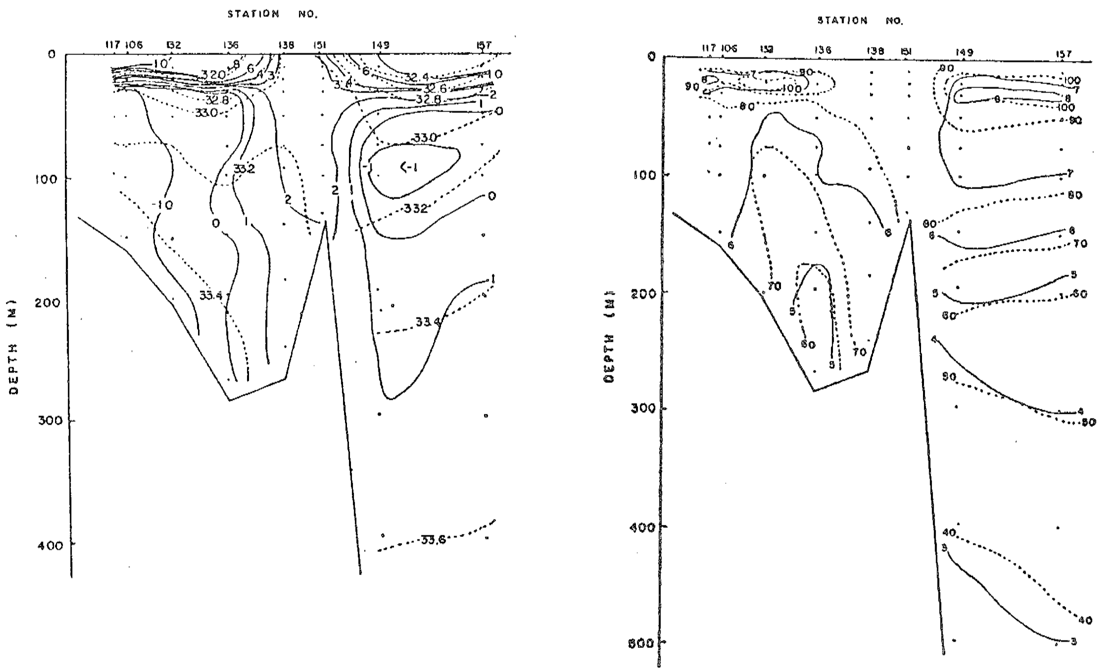


Fig. 2.3.24. Temperature (°C: solid) and salinity (dotted) (left figure) and dissolved oxygen content (ml/l: solid) and saturation (dotted) (right figure) for section C in Fig. 2.3.17 (Kitani and Shimazaki, 1971).

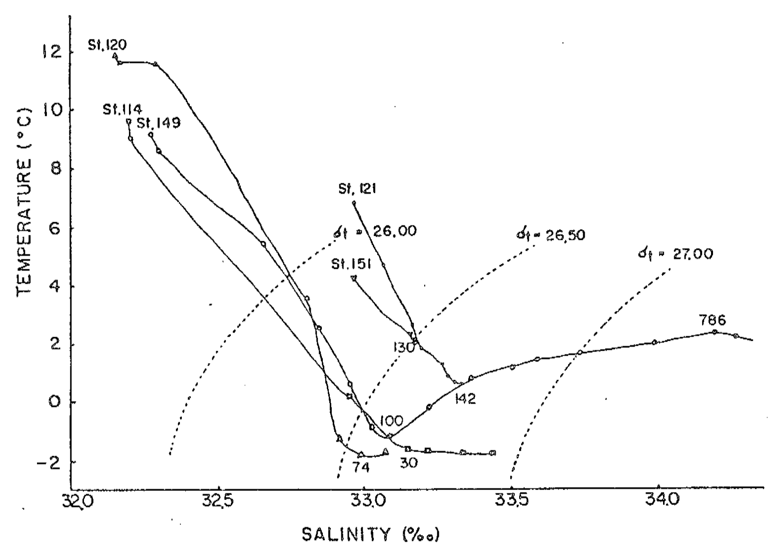


Fig. 2.3.25. Typical T-S curves observed in the northern part of the Okhotsk Sea (Kitani and Shimazaki, 1971). Station locations are shown in Fig. 2.3.17.

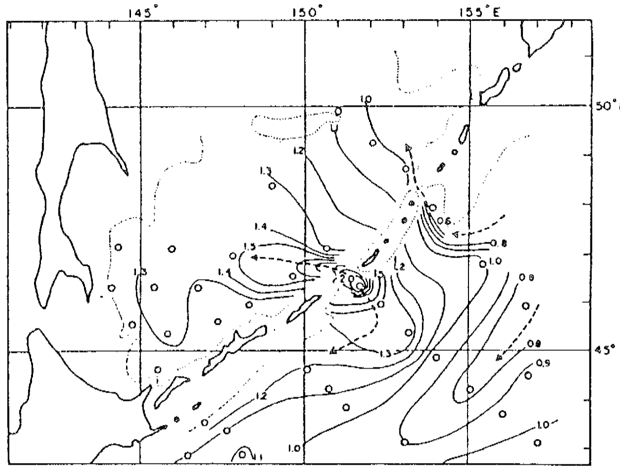


Fig. 2.3.26. Distribution of dissolved oxygen at 1,000 m in summer, 1965 (Yasuoka, 1968).

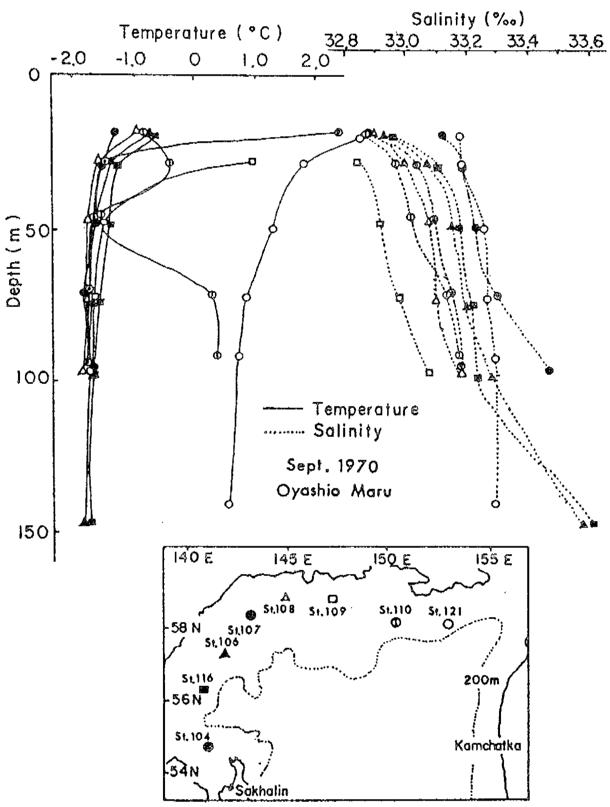


Fig. 2.3.27. Vertical profiles of temperature and salinity in the shelf region of the northern Okhotsk Sea. The symbols shown at data points indicate the observed positions shown in the lower map. (Kitani, 1973a).

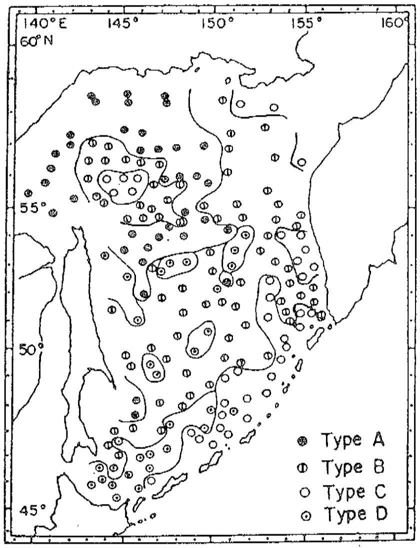


Fig. 2.3.28.

Horizontal distribution of water mass types defined in Kitani (1973a).

A': shelf water which is saline and dense near the bottom

A: water with a clear temperature minimum layer of tens of meters thickness, in which temperature and salinity are uniform

B: water with a fairly clear temperature minimum, but in which a homogeneous temperature and salinity layer is not apparent

C: vertically mixed water with weak vertical gradients both in temperature and salinity profiles

D: water with two temperature minima. Vertically mixed water appears over the Kashevarov Bank, over the eastern shelf region and off the Kamchatka Peninsula, and in the vicinity of the Kuril Islands

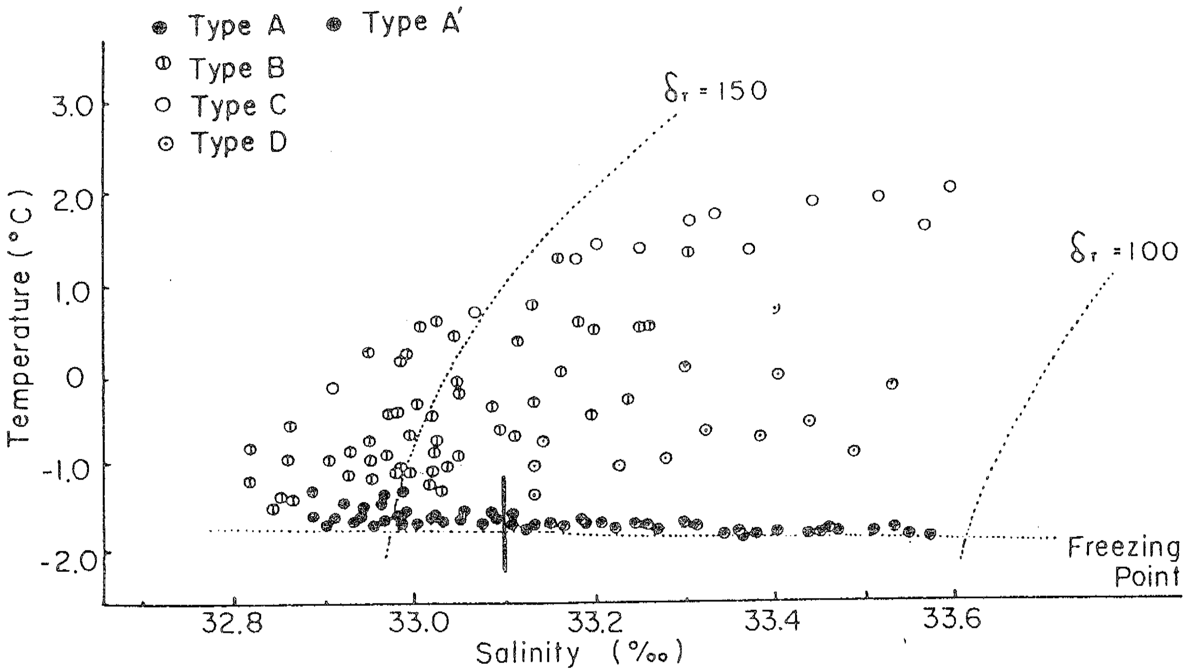


Fig. 2.3.29. Distribution of water types at the temperature minimum for each water mass type (Kitani, 1973a). Since the symbols used for Type A' and Type A are difficult to identify in the figure, the vertical bar at 33.1 indicates the boundary between these two types.

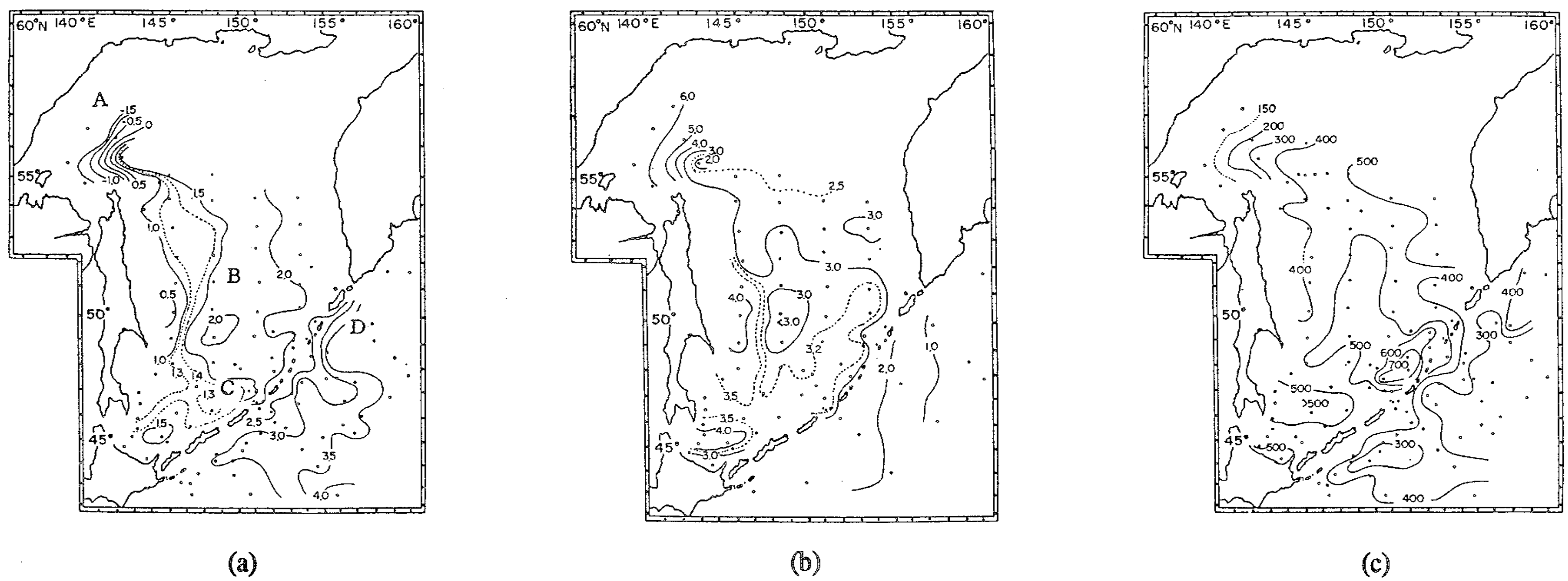


Fig. 2.3.30. Temperature (a: °C) and dissolved oxygen (b: ml/l) at thermosteric anomaly of 105 cl/t, and the depth (c: m) of the surface (Kitani, 1973a).

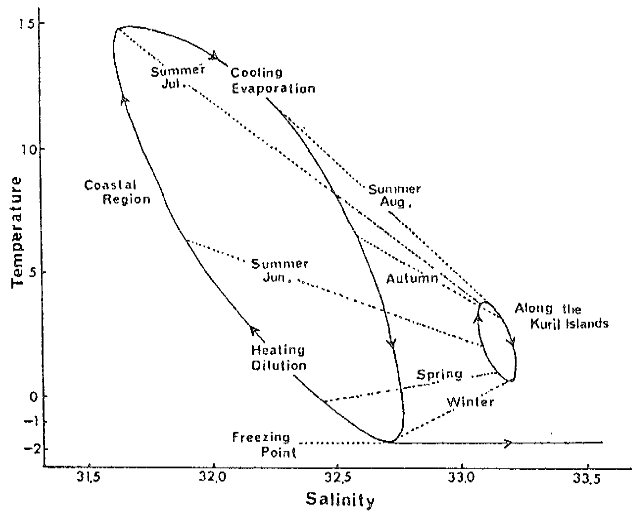


Fig. 2.3.31. Schematic representation of the seasonal variation of T-S relation of the surface water in the Okhotsk Sea (Kitani, 1973b).

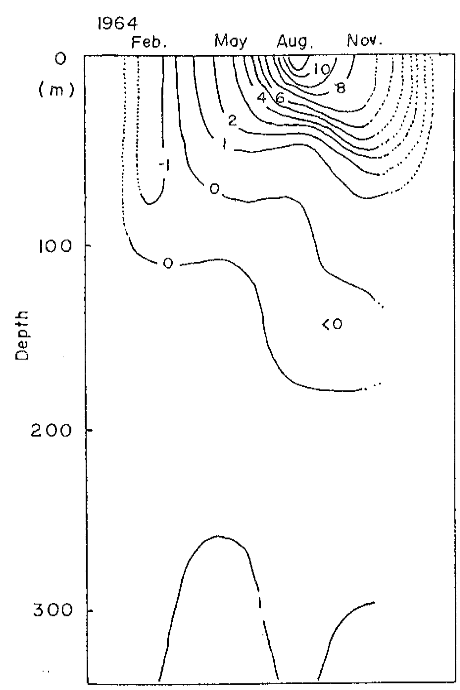


Fig. 2.3.32. Seasonal variation of the vertical temperature profile in the southern Okhotsk Sea in 1964 (Kitani, 1973b).

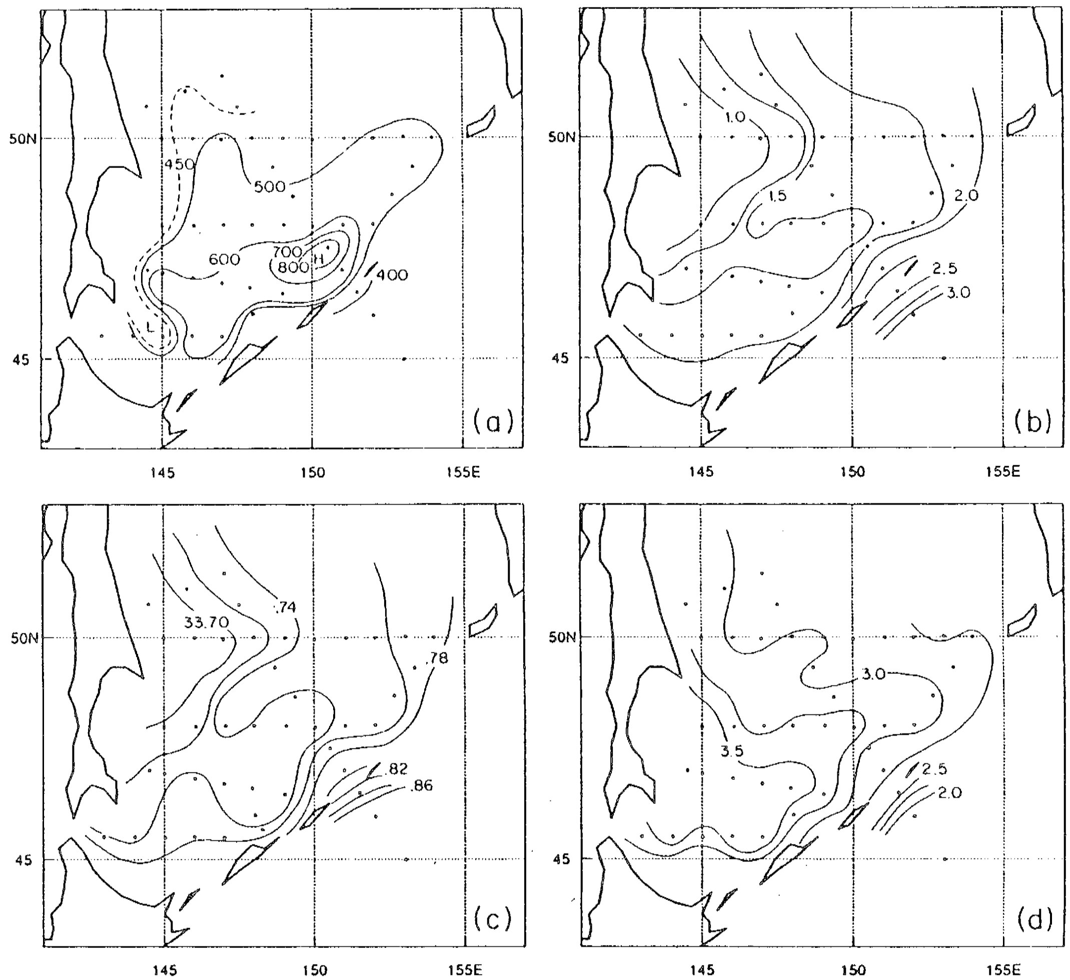


Fig. 2.3.33. (a) Depth (m), (b) temperature (°C), (c) salinity and (d) dissolved oxygen content (ml/l) at σ_θ of 27.02 (thermosteric anomaly of 105 cl/t) in November, 1978 (Wakatsuchi and Martin, 1991).

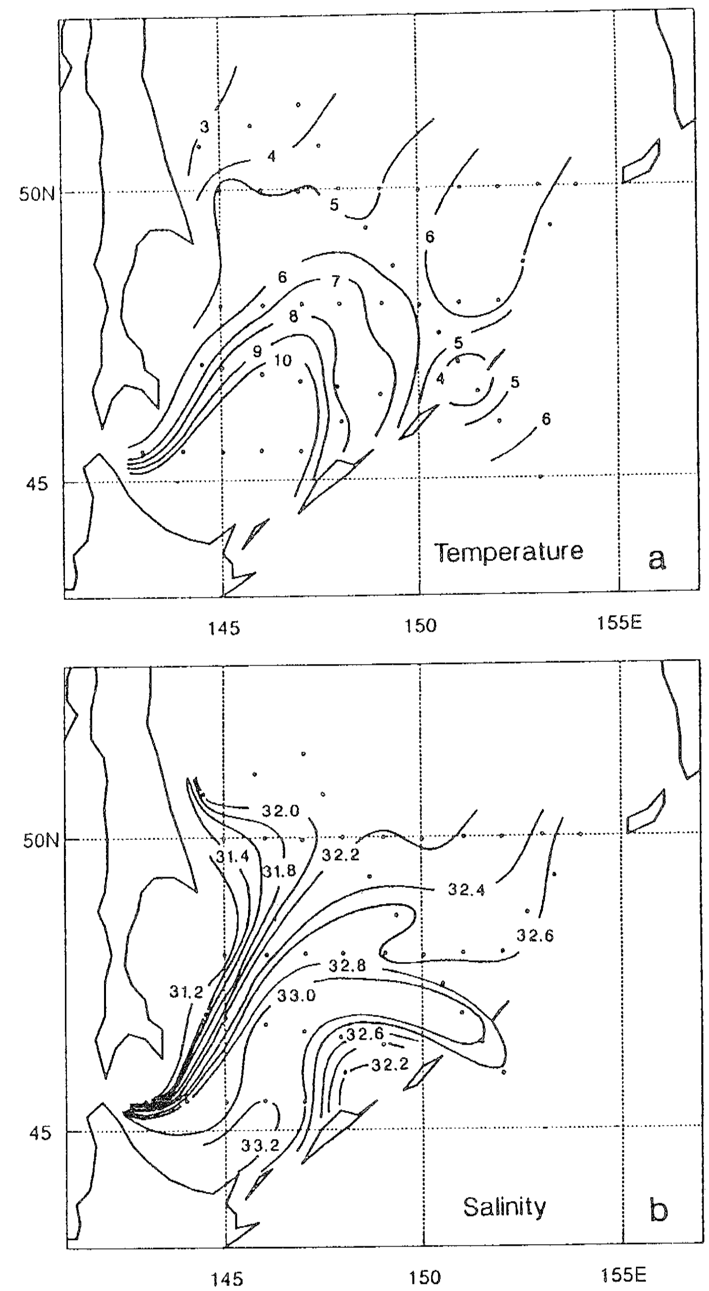


Fig. 2.3.34. Sea surface temperature (a: °C) and surface salinity (b) in the Kuril Basin Region in November 1978 (Wakatsuchi and Martin, 1991).

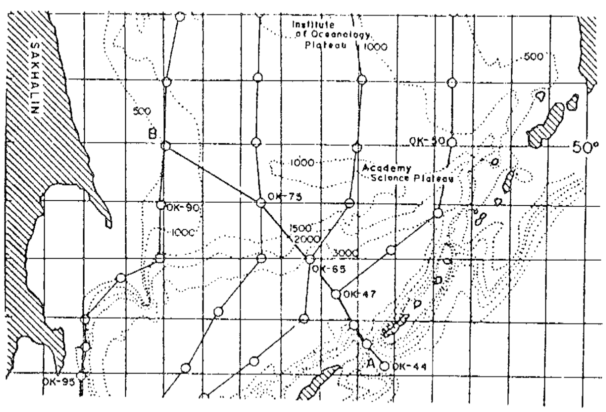
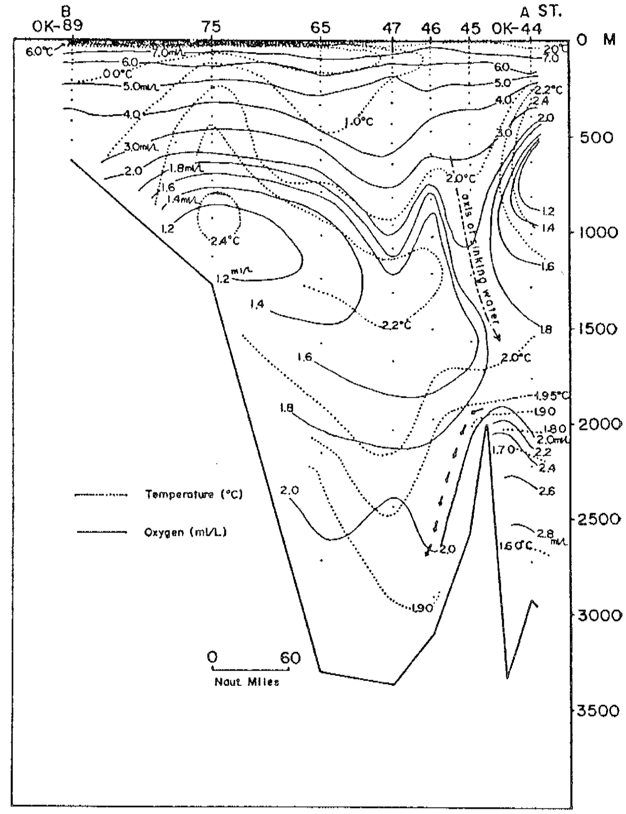


Fig. 2.3.35.

Temperature and salinity along the section passing through Bussol' Strait in the summer of 1967. The location of the section is shown in the left map as the A-B line (Yasuoka, 1968).



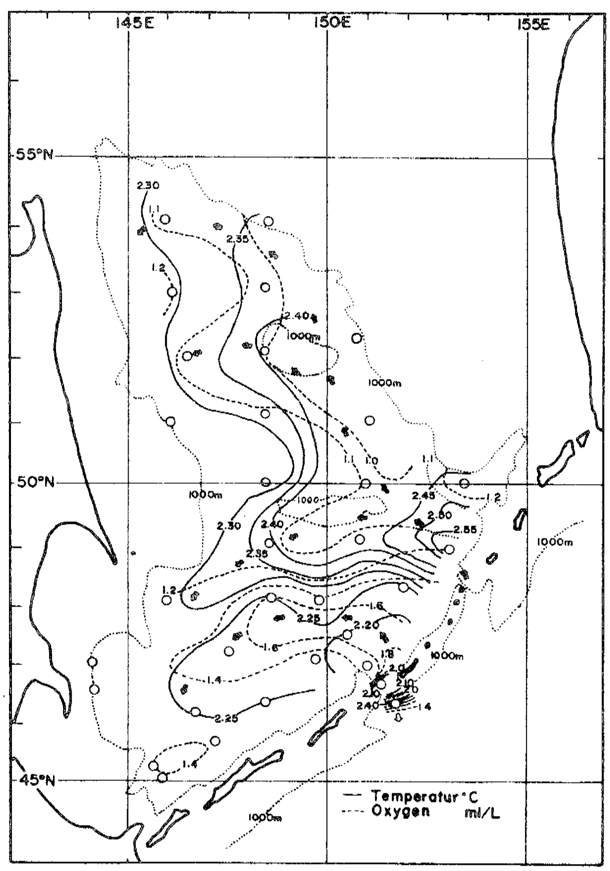


Fig. 2.3.36.

Temperature (°C) and dissolved oxygen (ml/l) on the σ_t = 27.4 surface in the summer of 1967 (Yasuoka, 1968). The arrows are the paths of water advection deduced from the distributions (Yasuoka, 1968).

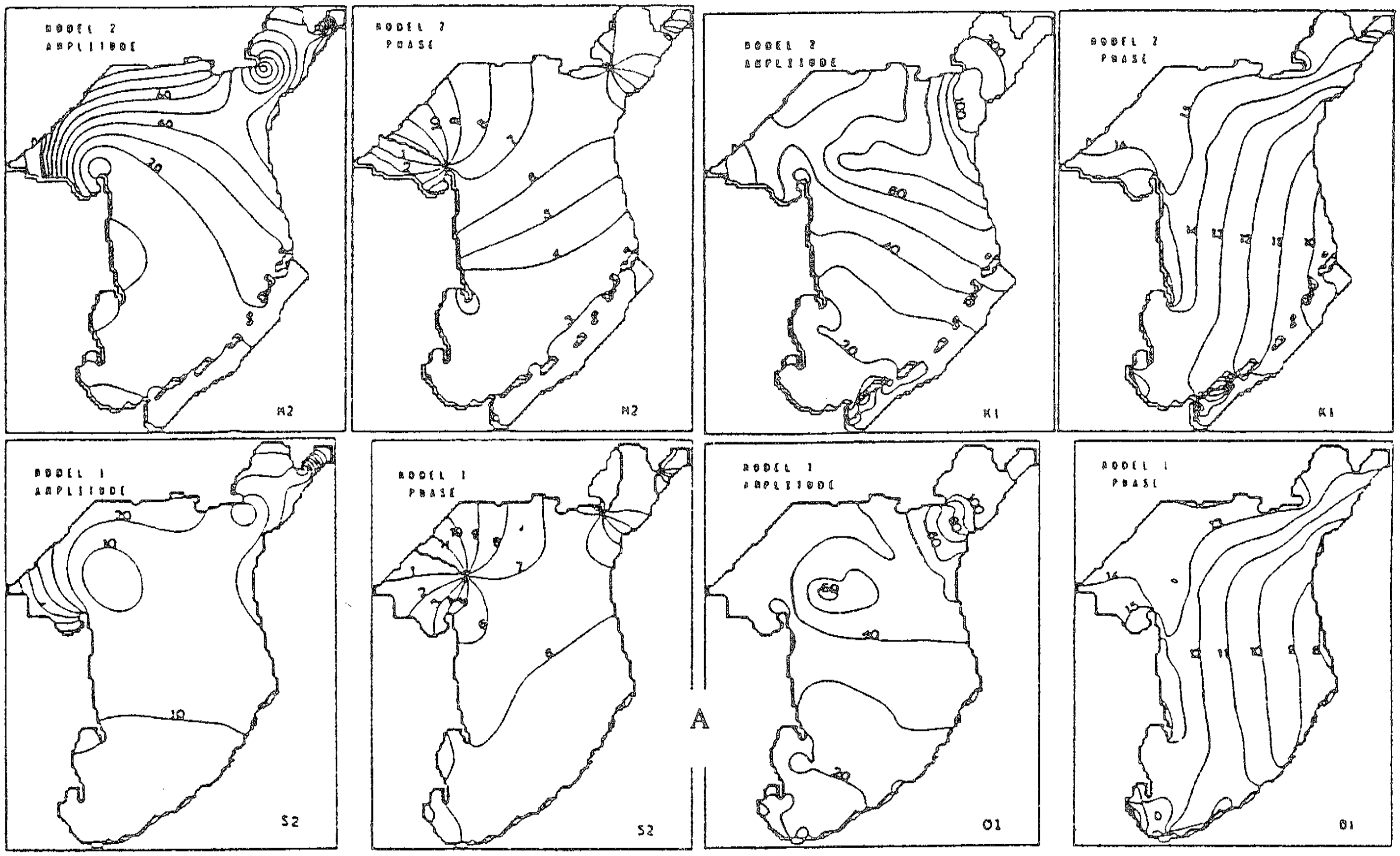


Fig. 2.3.37. (a) Calculated tidal amplitudes and phases, and (b) tidal ellipses for the different constituents of the tide (Suzuki and Kanari, 1986).

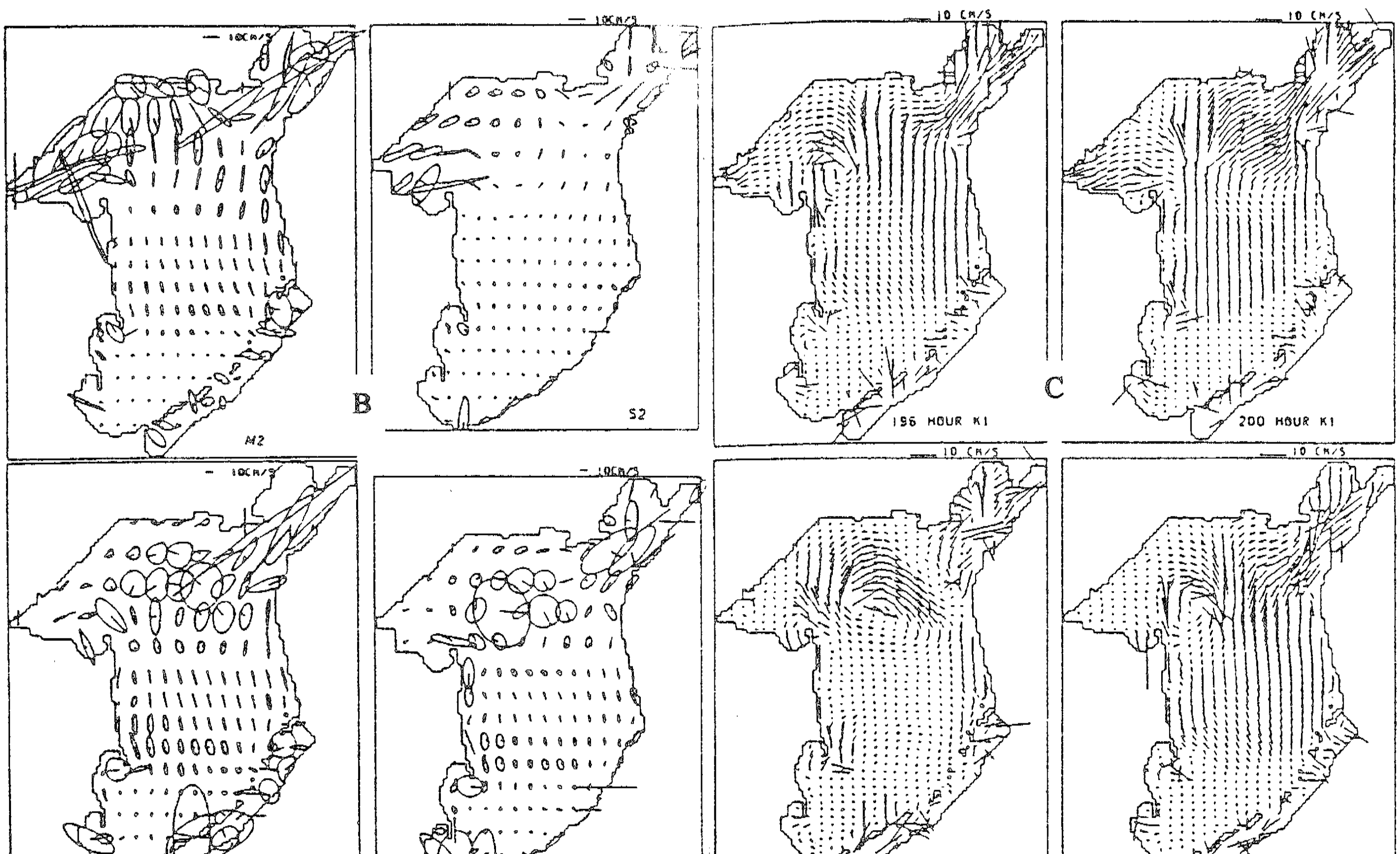


Fig. 2.3.37. (c) Currents at different phases of the tides (Suzuki and Kanari, 1986).

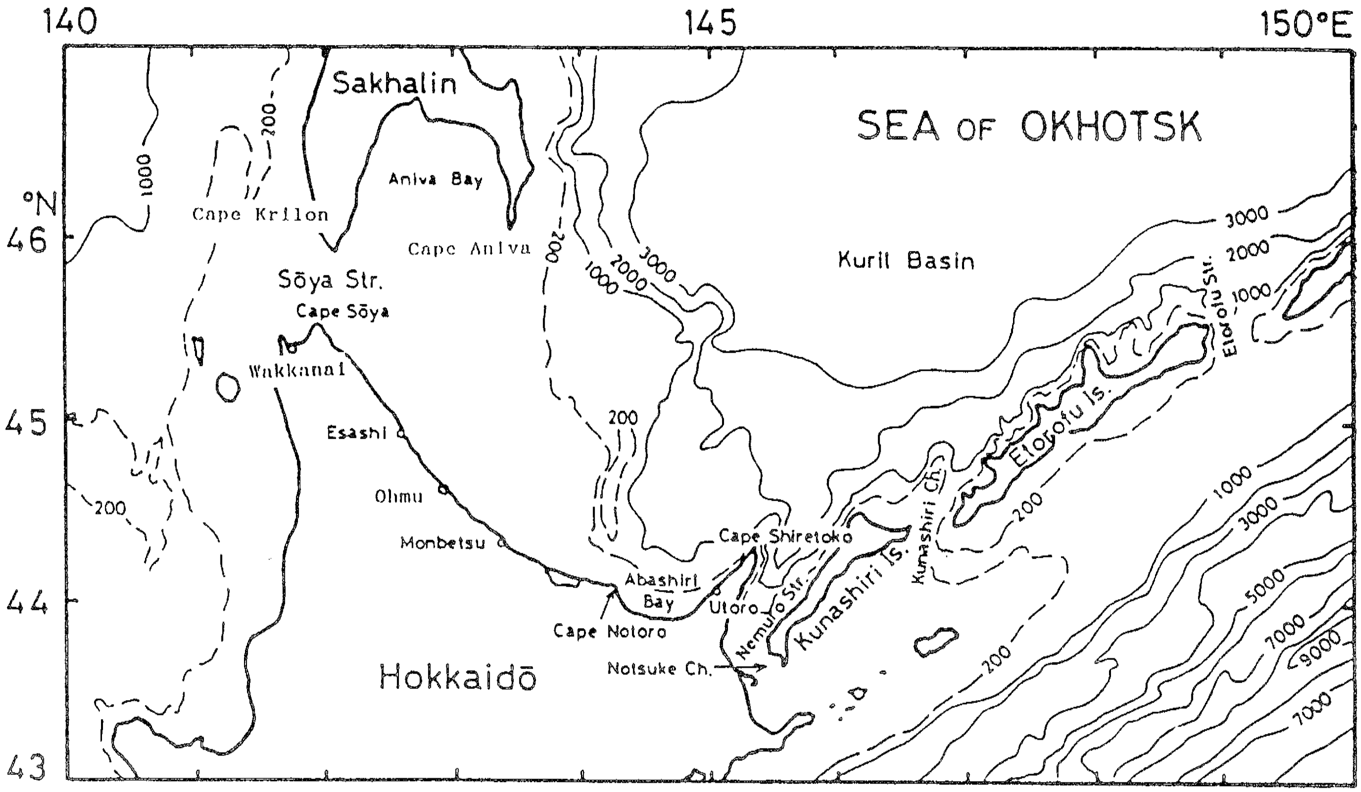


Fig. 2.4.1. Bathymetric chart (m) of the southern Okhotsk Sea (Takizawa, 1982).

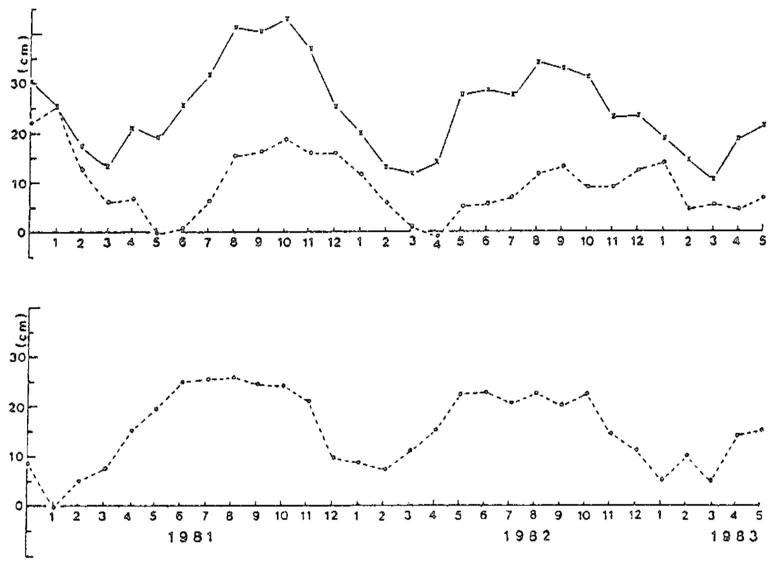


Fig. 2.4.2. Sea level variations (upper figure) at Wakkanai (solid) and at Abashiri (dashed), and the sea level difference (lower figure) between the two stations from December, 1980 to May, 1983. Sea levels are measured from the standard level at Tokyo Point (Nakamura et al., 1985).

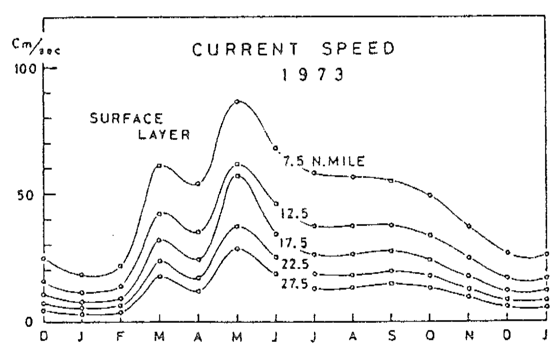


Fig. 2.4.3. Seasonal variations of the surface current off Mombetsu calculated from the sea level differences between Wakkanai, Mombetsu and Abashiri in 1973. The along shore current velocities are given for several distances from shore (numerals attached indicate the distance in miles) (Aota, 1975).

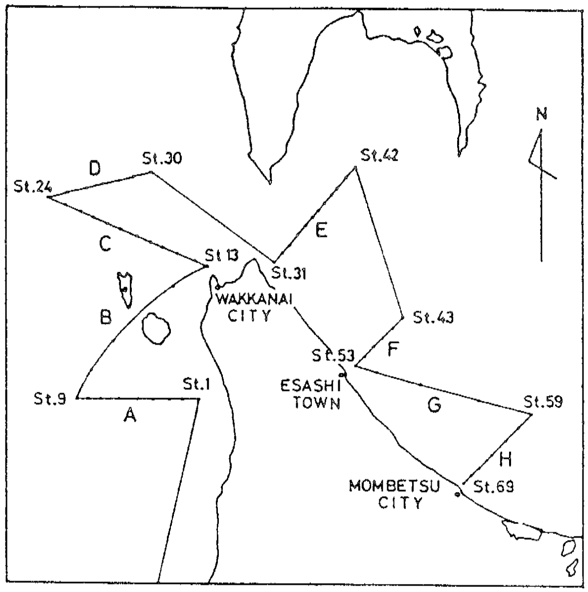


Fig. 2.4.4. Locations of observations on R/V Tansei-maru of the Ocean Research Institute, Univ. of Tokyo, 17-21 April, 1971 (Aota, 1971).

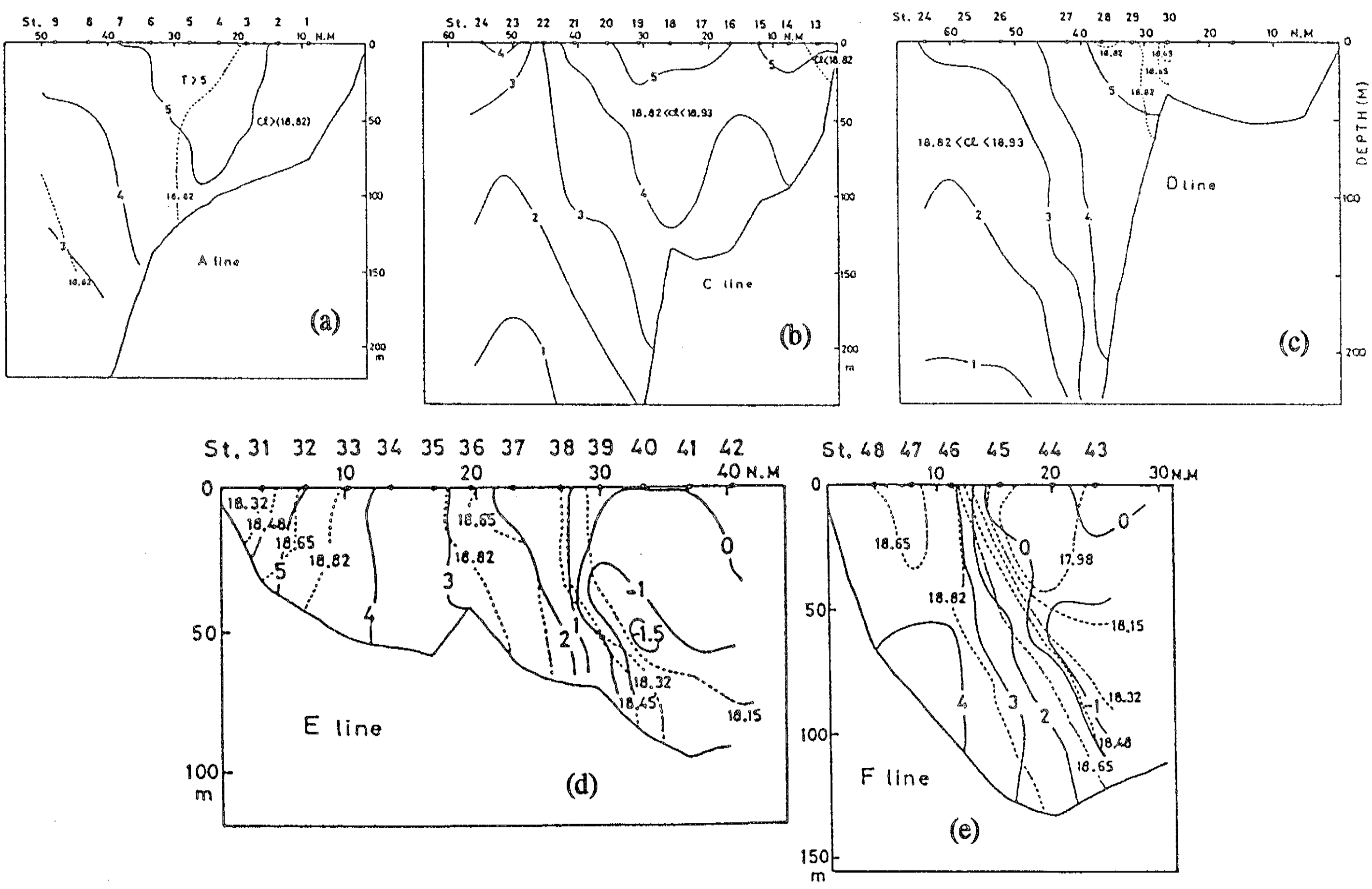


Fig. 2.4.5. Temperature (°C) and chlorinity (o/oo) distribution for sections along line A (a), line C (b), line D (c), line E (d), and line F (e). See Fig. 2.4.4 for the positions of these lines (Aota, 1971).

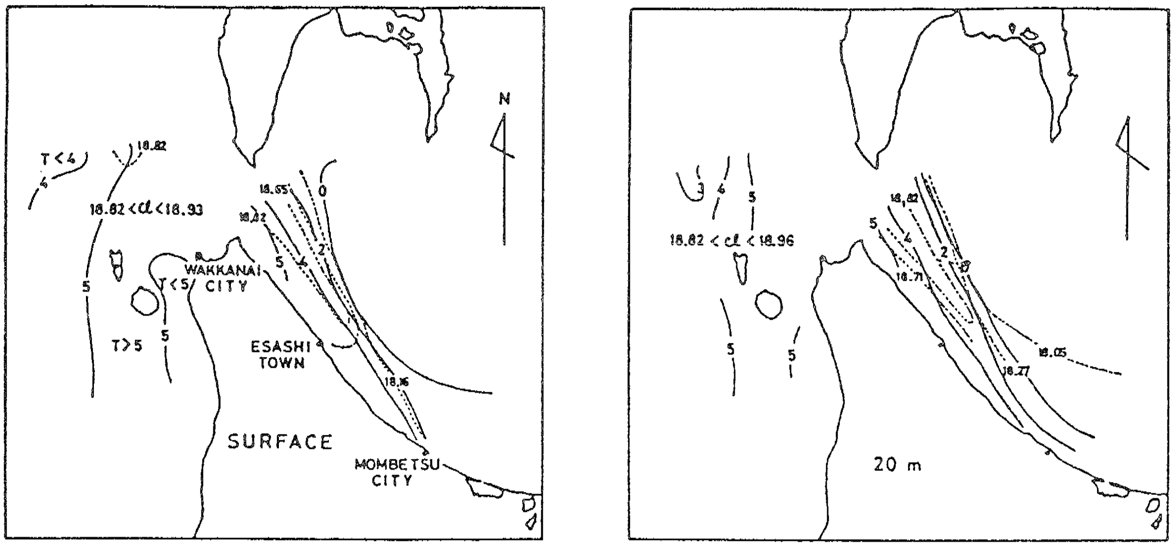


Fig. 2.4.6. Horizontal distributions of temperature (°C) and chlorinity (o/oo) on 17-21 April, 1971 (Aota, 1971).

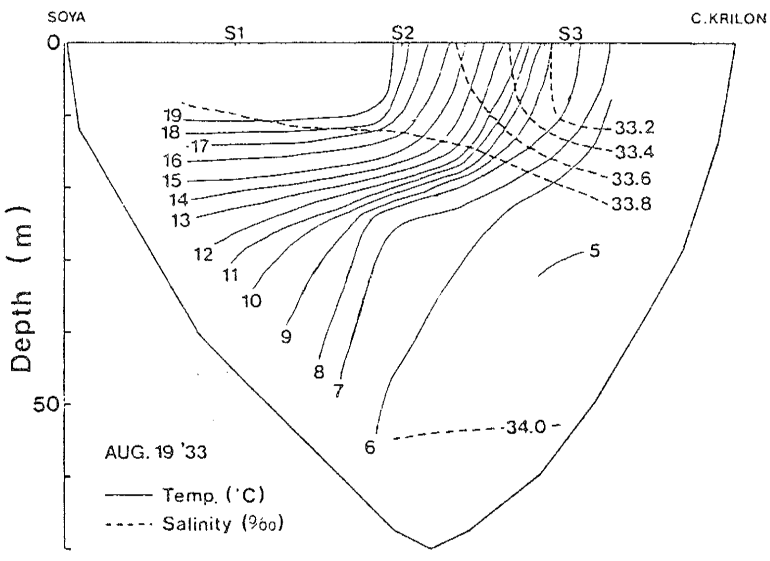


Fig. 2.4.7. Vertical sections of temperature (°C) and salinity (o/oo) in Soya Strait on 19 August, 1933 measured on R/V Tankai-maru (Aota et al., 1988). The line runs from Cape Soya to Cape Nishi-Notoro (Cape Krilion: the southernmost tip of Sakhalin), and the distance from Cap Soya is shown in abscissa.

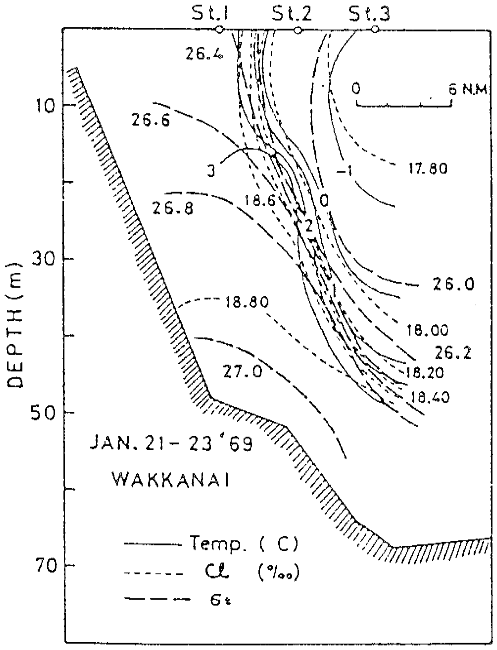


Fig. 2.4.8.

The temperature (°C) and chlorinity (o/oo) distributions from the section off Wakkanai on 21-23 January, 1969 (Aota, 1975).

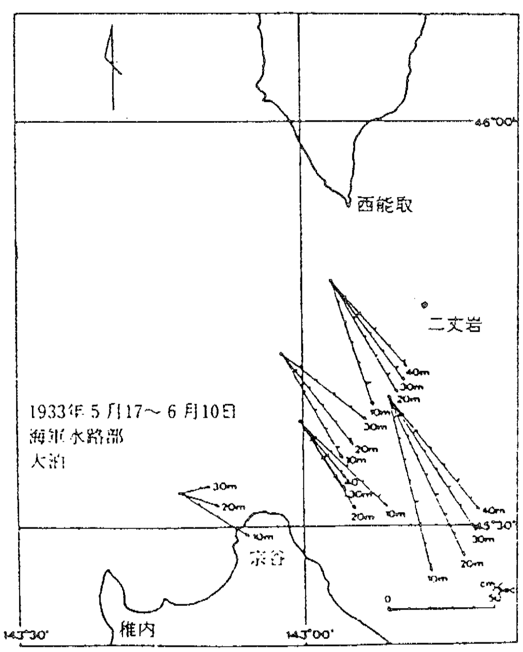


Fig. 2.4.9.

Current measurements over 24 hours using Ekman-Merz current meters in Soya Strait for 17 May - 10 June, 1933 on the survey ship Ohdomari of the Japanese Imperial Navy (Nakamura et al., 1985).

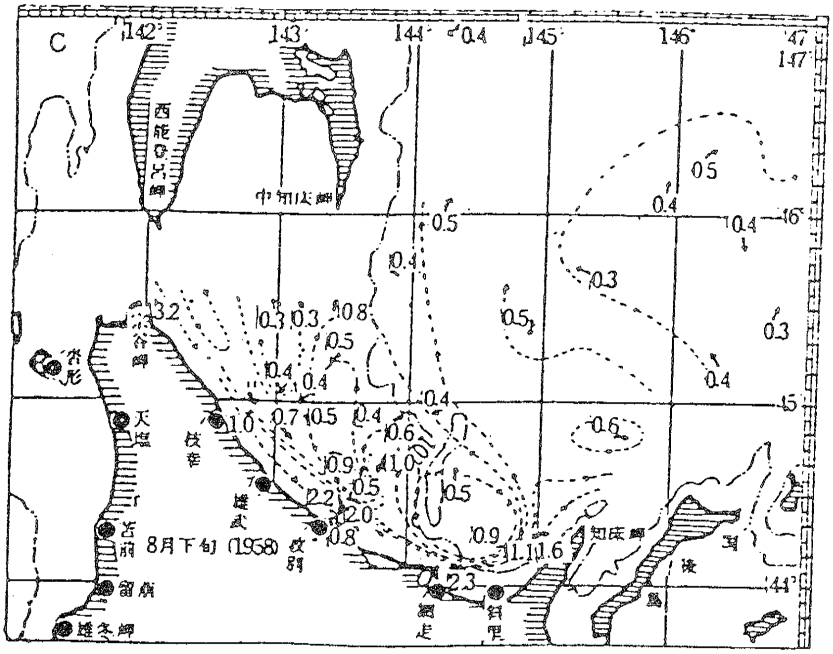


Fig. 2.4.10.

Currents measured by GEK in late August, 1958 (Wakao and Kojima, 1963). Numerals indicate current speed in knots.

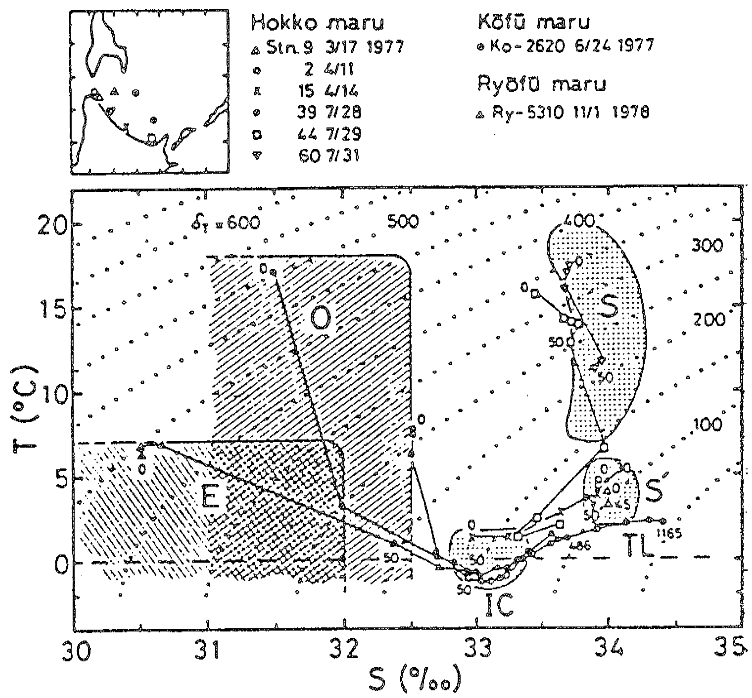


Fig. 2.4.11.

Typical T-S curves of the water masses in the southwestern Okhotsk Sea. The observation locations and dates are shown in the map and in the table in the upper column. T-S domains for typical masses are shown.

S: Soya Warm Water
S': Forerunner of the Soya Warm Water
IC: Intermediate Cold Water
TL: Transient Layer Water
O: Okhotsk Surface Water
E: East Sakhalin Current Water

Numbers attached to data points indicate depths in m (Takizawa, 1982).

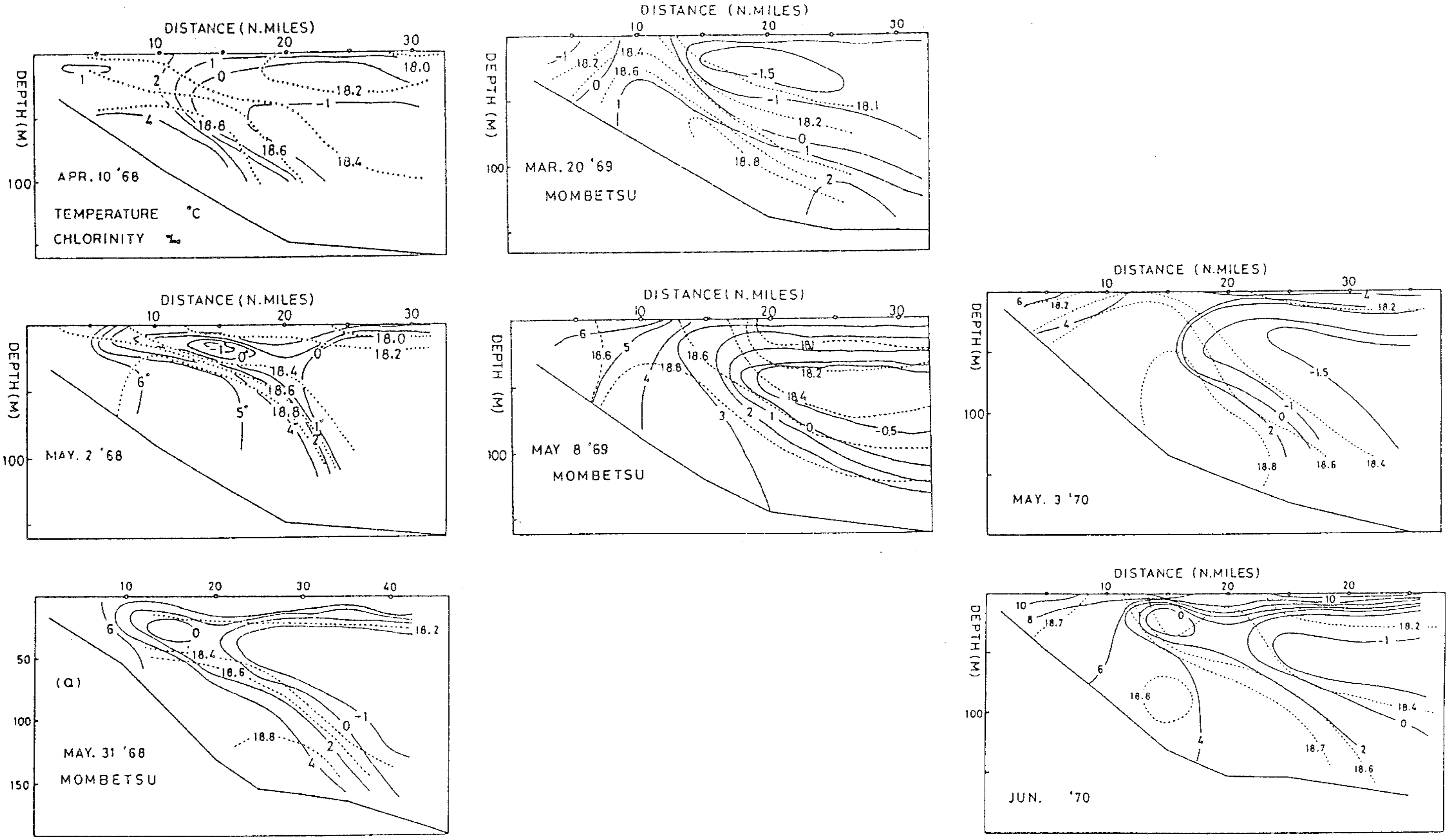


Fig. 2.4.12. Vertical sections of temperature (°C) and chlorinity (o/oo) off Mombetsu in March-May in the period from 1968 to 1970. The left, center and right columns are the observation years 1968, 1969 and 1970, respectively. Observation times are arranged roughly from top to bottom (Aota, 1975).

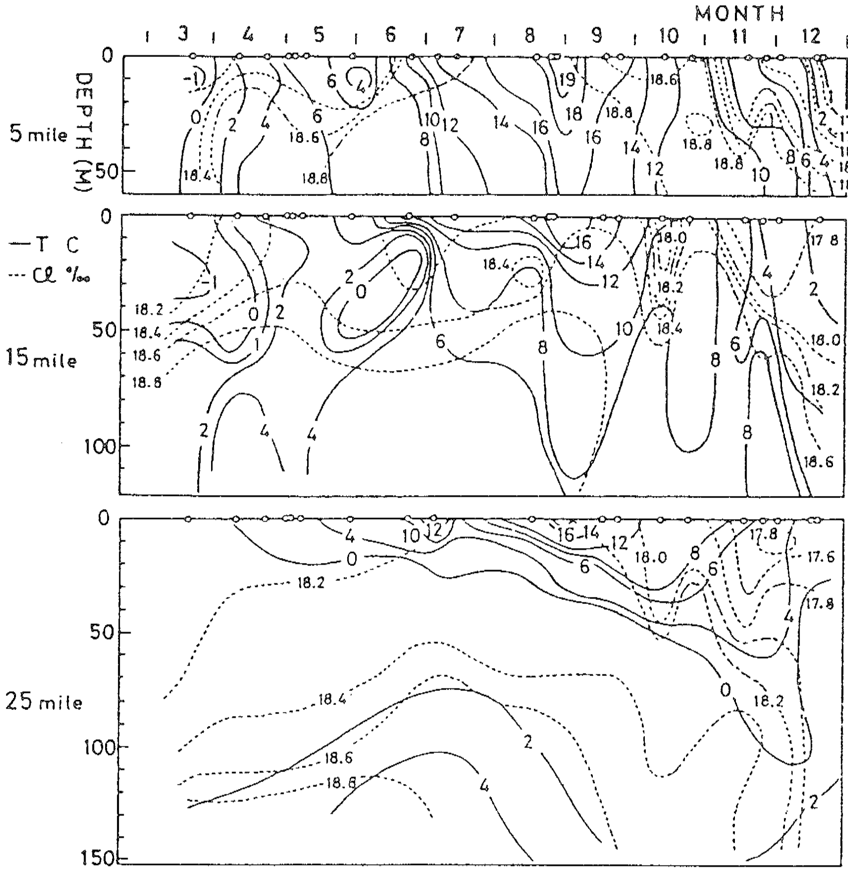


Fig. 2.4.13.

Seasonal variations of the vertical temperature and salinity profiles deduced from three years of observations. The upper figure is at the station 5 miles off Mombetsu, the middle figure at the station 15 miles, and the lower figure at the station at 25 miles, respectively (Aota, 1971).

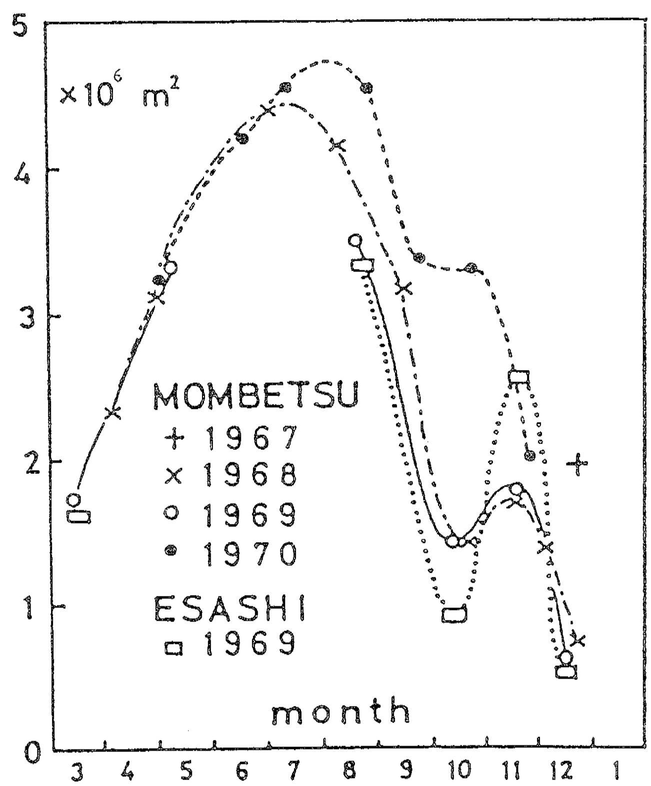


Fig. 2.4.14.

Seasonal variation of the cross-sectional area (km^2) of the Soya Current Water off Mombetsu and off Esashi (Aota, 1971). The symbols used are listed in the figure.

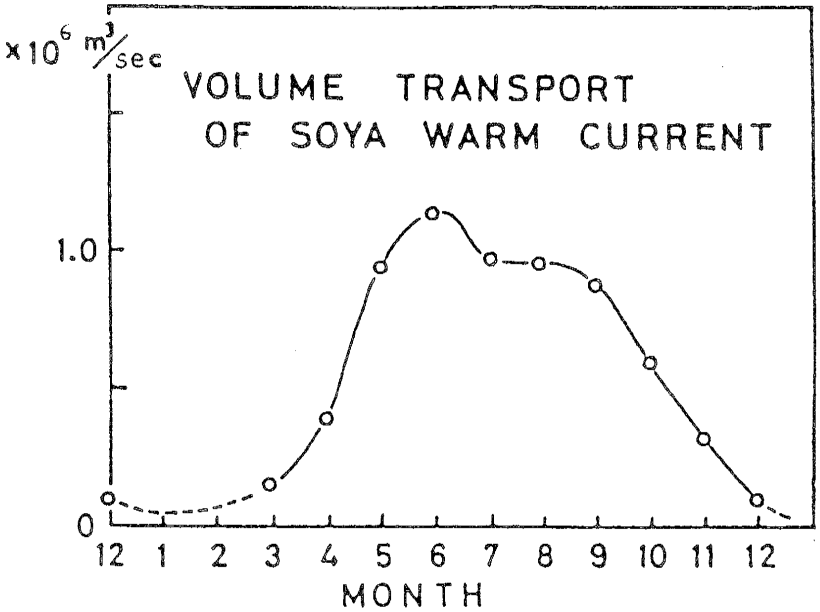


Fig. 2.4.15.

Seasonal variation of the volume transport of the Soya Current calculated from the cross-sectional area variation in Fig. 2.4.14 and from the velocity field variation deduced from the sea levels at Wakkanai, Mombetsu and Abashiri (Section 2.4.2) (Aota, 1975).

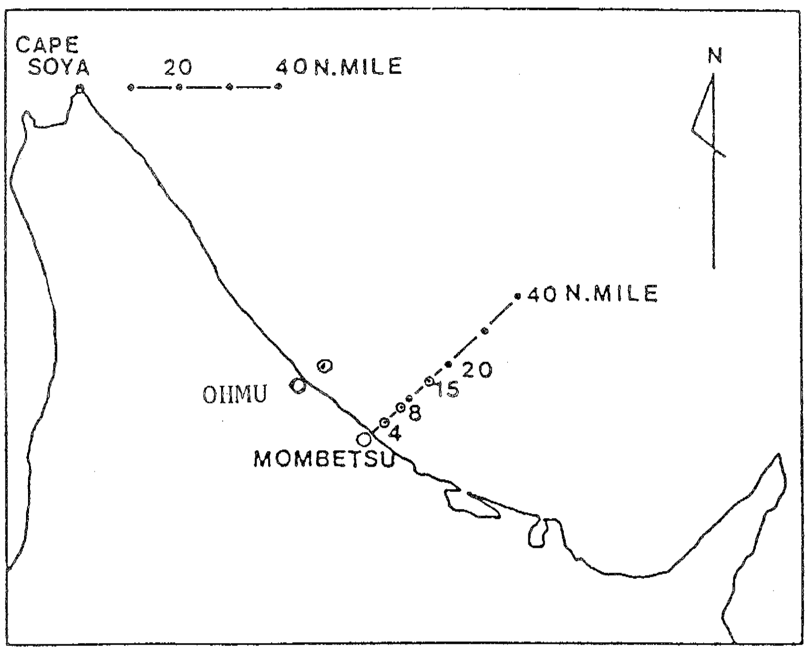


Fig. 2.4.16.

Locations of the moored current meter observations (open circles): at 25 m at the 4 mile and 8 mile stations in 1976-1977, at 25 m at the 4 mile station, at 25 m and 60 m at the 8 mile station and at 25 m at the 15 mile station in 1977-1978, and at 25 m at the 8 mile station in 1978-1979. In 1978-1979, measurement at 25 m at the 6 mile station of Ohmu was also carried out. Temperature and salinity distributions will be shown along the line to the northeast of Mombetsu. (Aota and Kawamura, 1978)

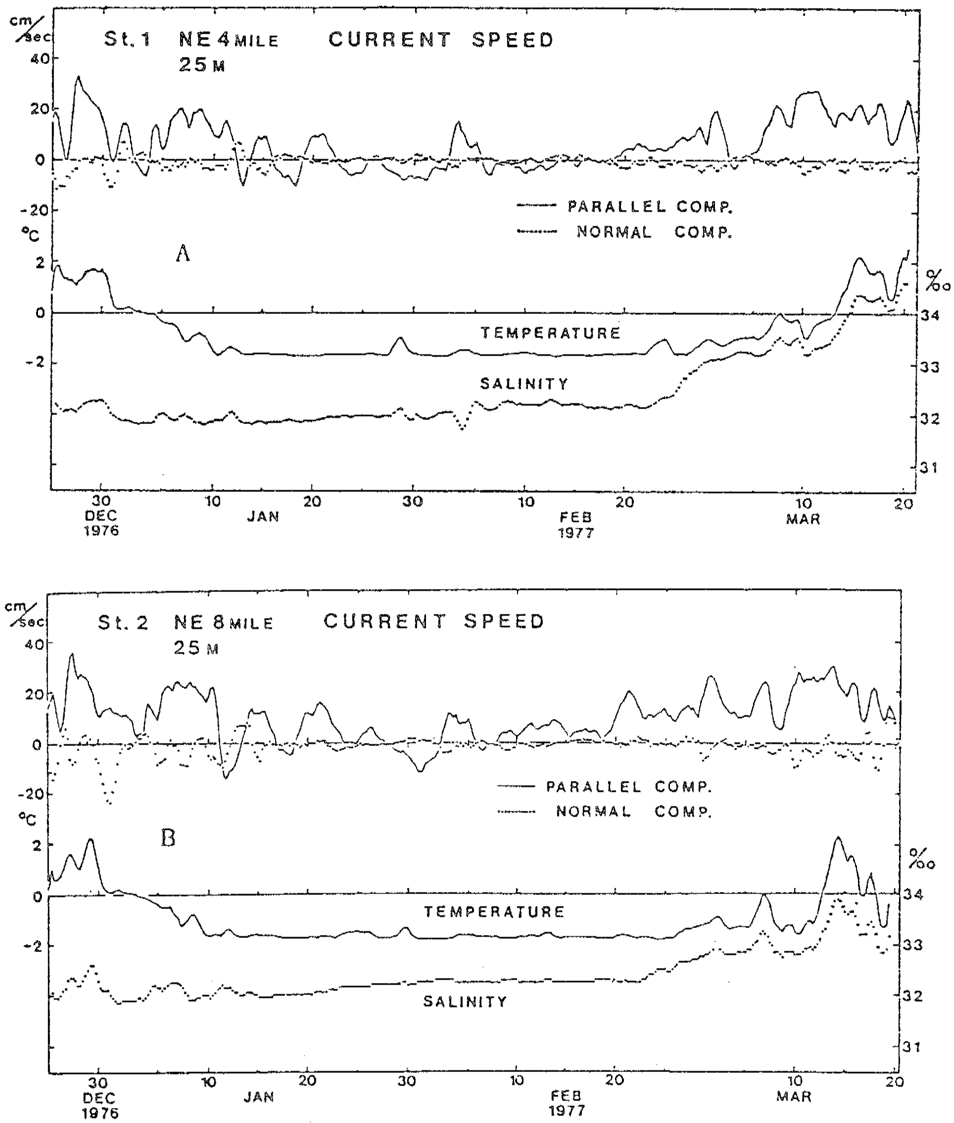


Fig. 2.4.17. Current components (24 hour running means) parallel and normal to the coast, and of temperature and salinity, off Mombetsu in winter of 1976-1977. Positive speed is southeastward and offshore. The upper figure is at 25 m at the 4 mile station, and the lower figure at 25 m at the 8 mile station. (Aota and Kawamura, 1978).

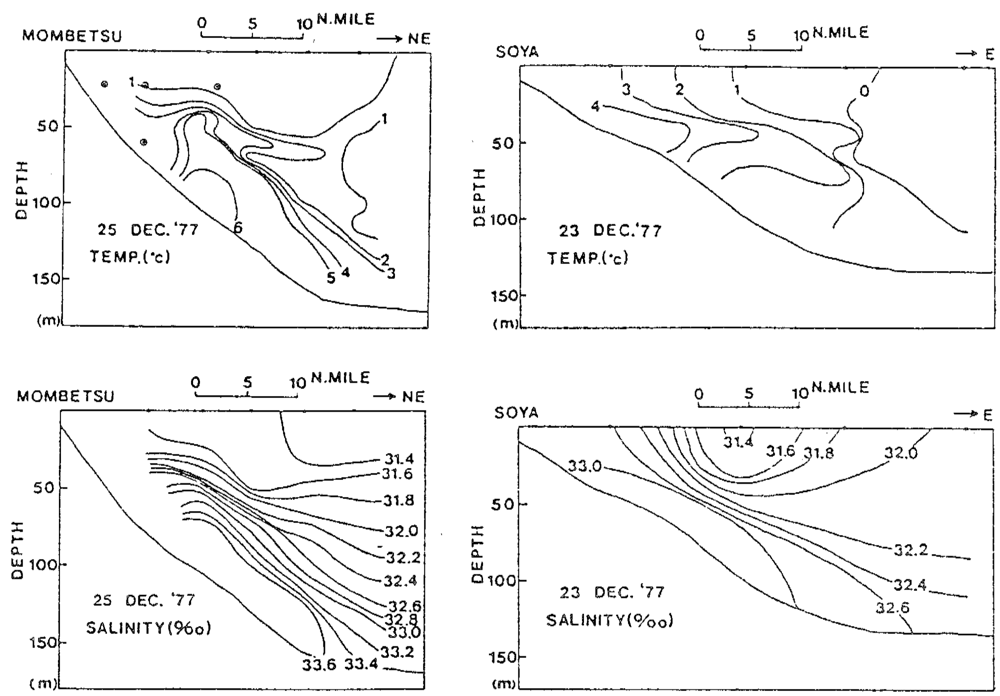


Fig. 2.4.18. Temperature and salinity sections along the line off Mombetsu (left) on 25 December and in Soya Strait (right) on 23 December, 1977. The positions of moored current meters in winter 1977-1978 are shown by white open circles in the upper and left figure (Aota and Kawamura, 1978).

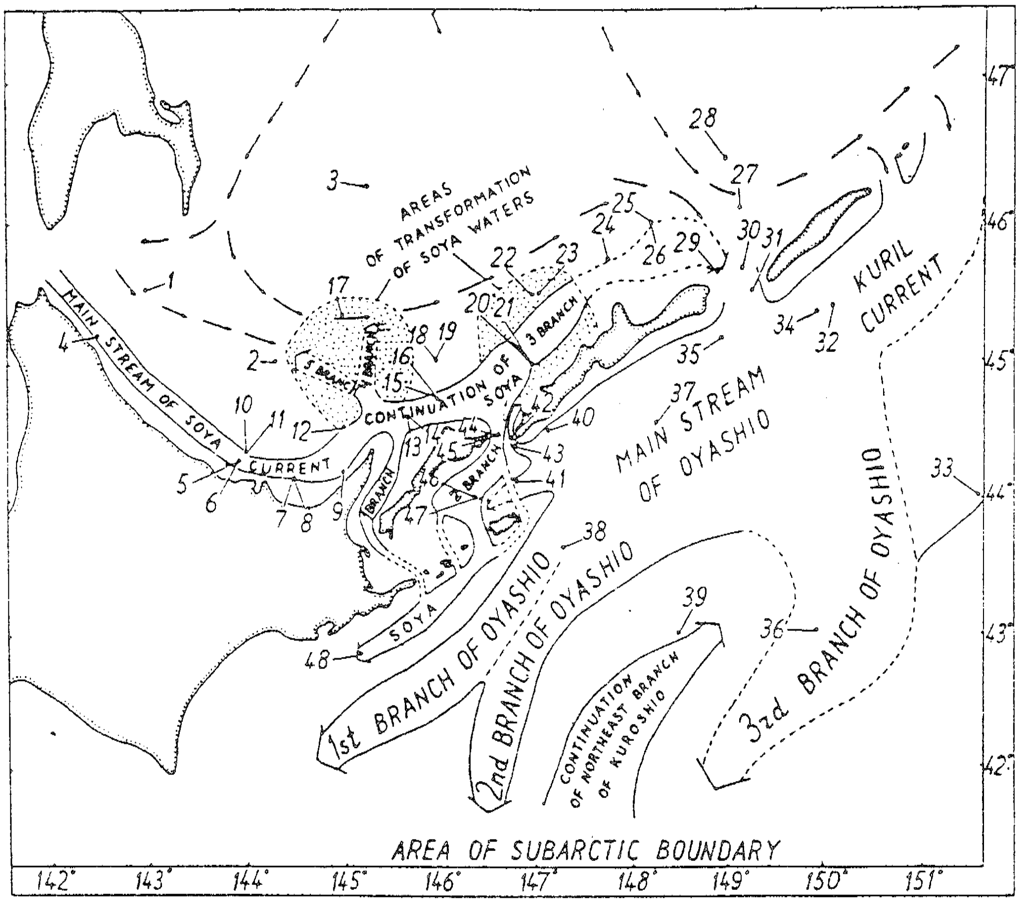
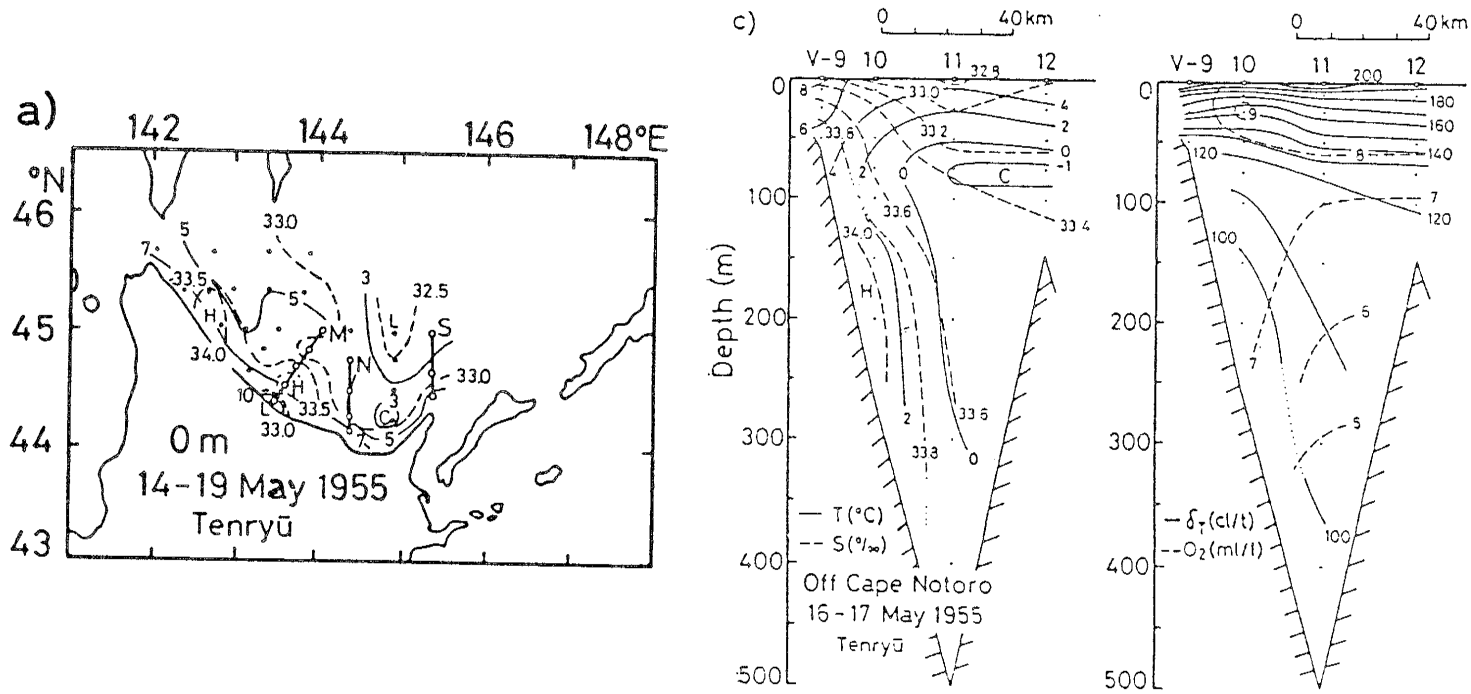
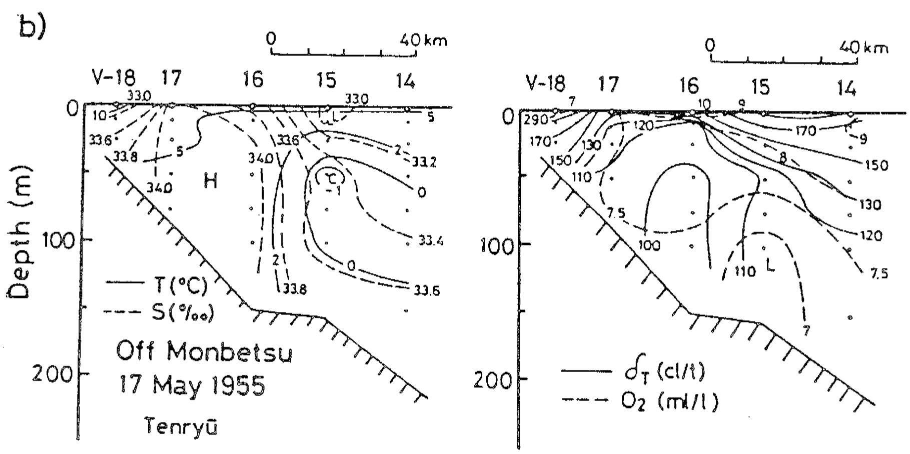


Fig. 2.4.19. Schematic of circulation of water masses in the southern Kuril area (Bobkov, 1993).





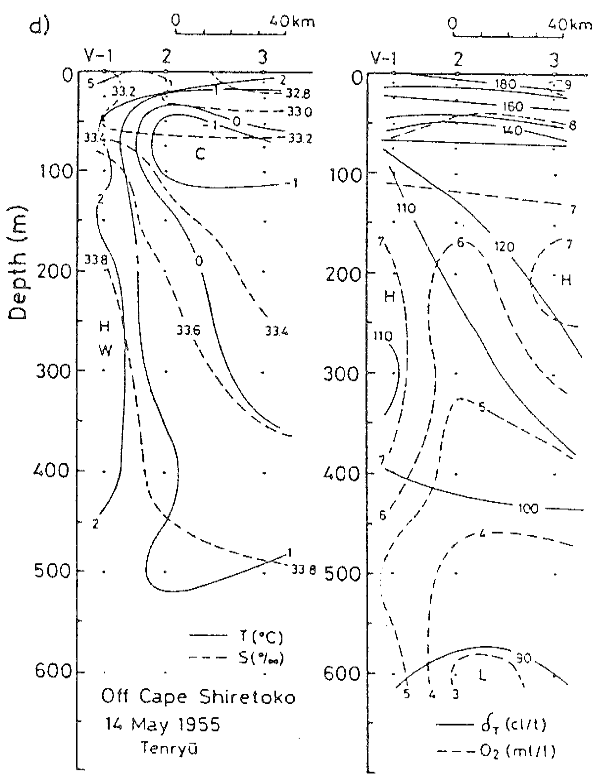


Fig. 2.4.20.

Oceanic conditions on 14-19 May, 1955 (Takizawa, 1982).

(a): The horizontal distribution of sea surface temperature (solid: °C) and salinity (dashed: o/oo)

(b): Temperature (solid: °C) and salinity (dashed: o/oo) sections (left figure), and thermosteric anomaly (solid: cl/t) and dissolved oxygen (dashed: ml/l) sections (right figure) along line M off Mombetsu

(c): The same as (b) except along line N off Cape Notoro

(d): The same as (b) except along line S off Cape Shiretoko

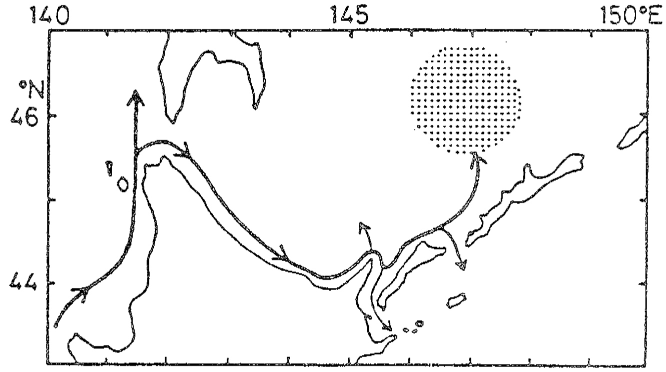


Fig. 2.4.21.

Schematic representation of the paths of the Soya Current. The shaded area indicates the area where the Soya Current Water eventually decays (Takizawa, 1982).

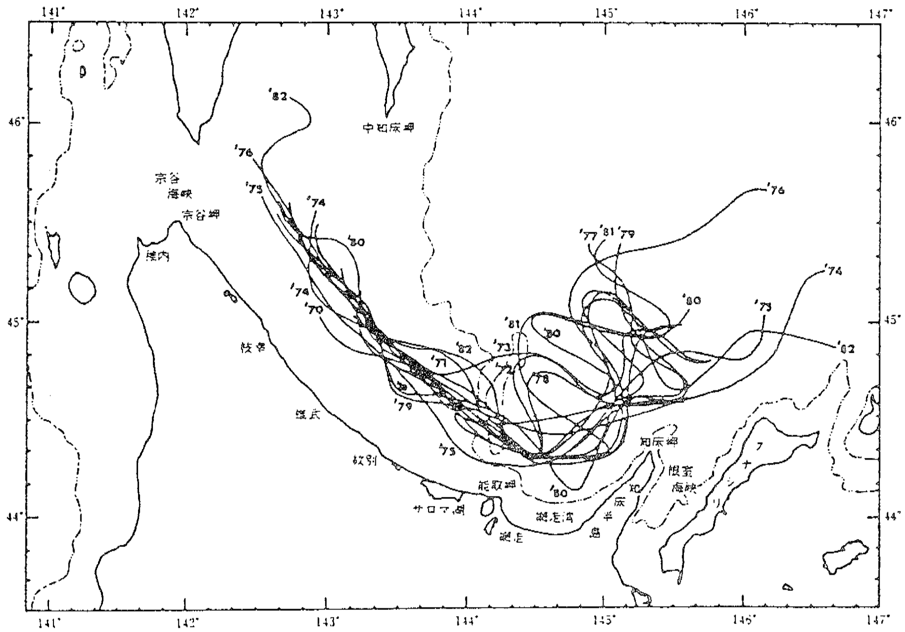


Fig. 2.4.22.

Variability of the 5°C isotherm position at 50 m depth. All positions measured in the period 1968 to 1982 are shown. This can be regarded as the southern boundary of the Dichothermal Water. Although there exists a narrow mixed water zone, the position also shows roughly the offshore boundary of the Soya Current Water (Nakamura et al., 1985).

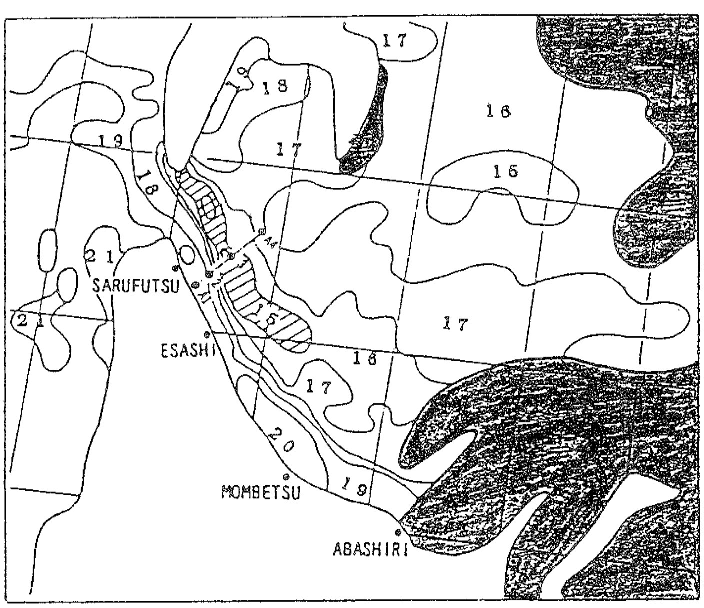


Fig. 2.4.23.

Sea surface temperature (°C) obtained by NOAA IR image in the southern Okhotsk Sea at 13:28 on 28 September, 1990. The cold water belt is indicated by hatching. The shaded area indicates no observation due to cloud cover. A1 through A4 indicate the position of hydrographic observations shown in Aota et al. (1991).

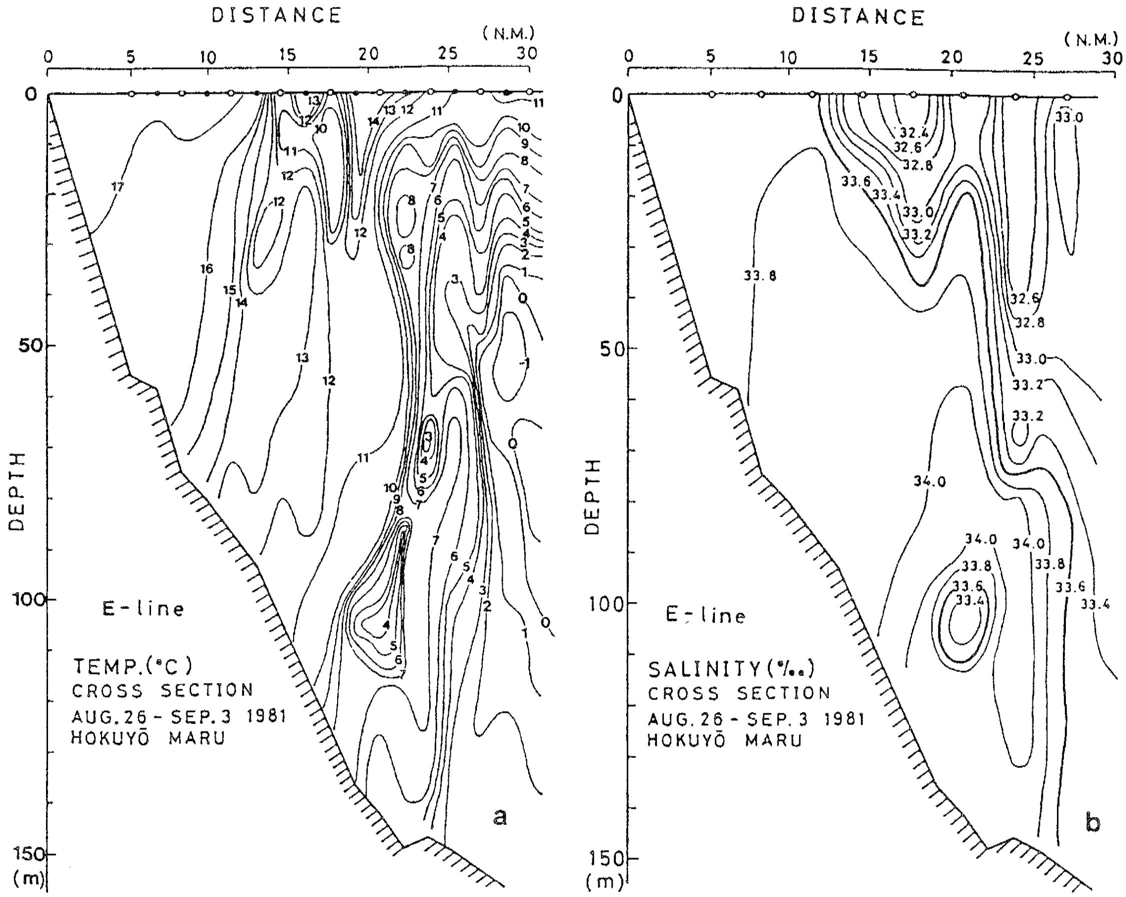


Fig. 2.4.24.

Vertical sections of temperature (°C: left figure) and salinity (o/oo: right figure) along the line extending northeast off Mombetsu on 26 August-3 September, 1981. White circles on the upper margin indicate the positions of CTD observations and black circles those of XBT observations (Motoi et al., 1982).

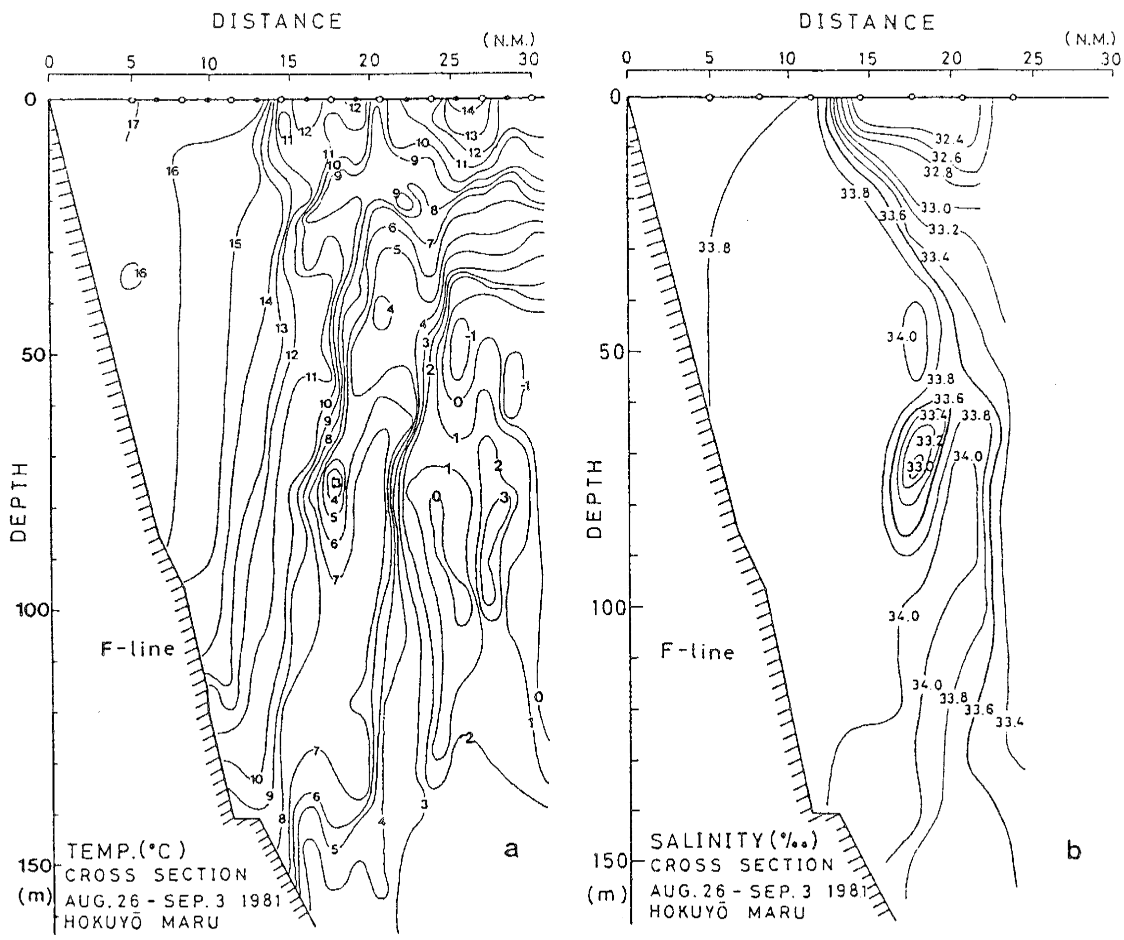


Fig. 2.4.25.

The same as in Fig. 2.4.24 except along the line 20 miles southeast of the line off Mombetsu (Motoi et al., 1982).

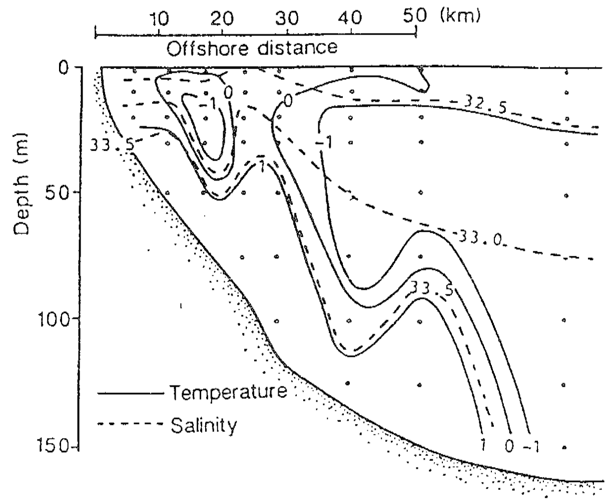


Fig. 2.4.26.

Temperature (°C) and salinity (o/oo) sections off Mombetsu in late April, 1984 (Wakatsuchi and Ohshima, 1990).

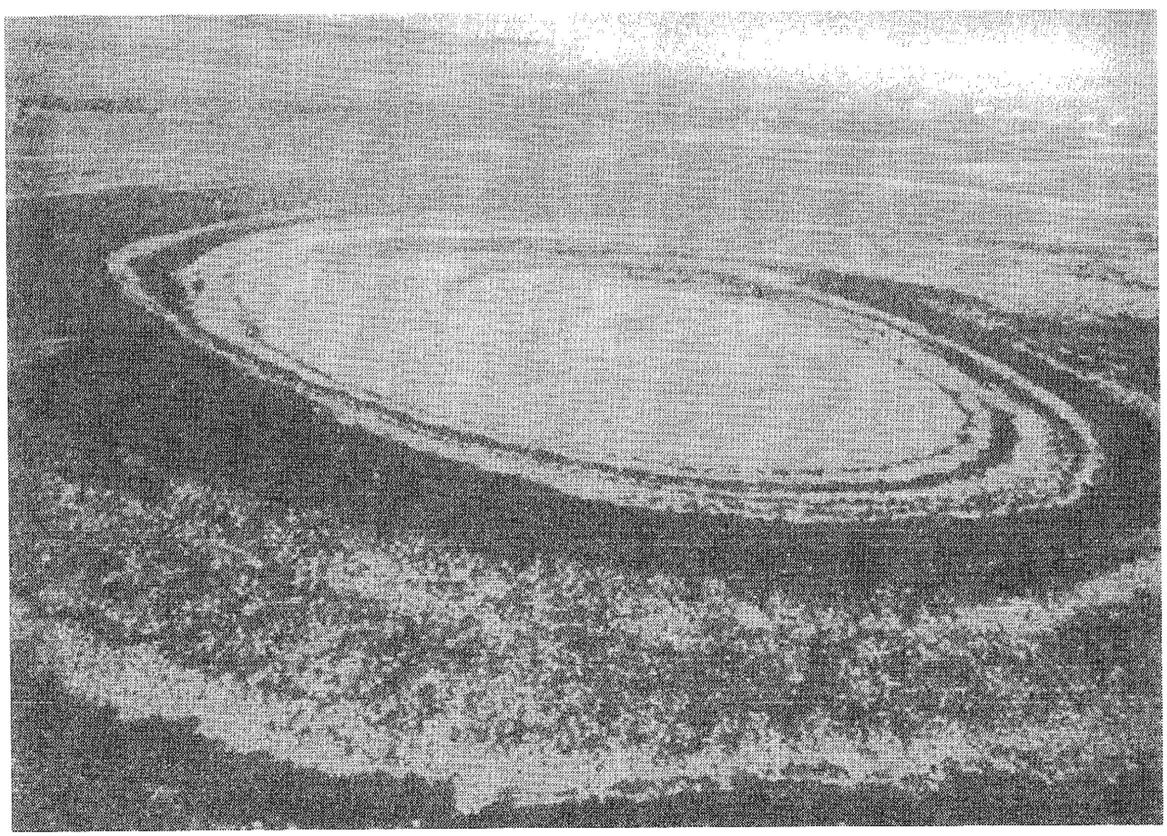


Fig. 2.4.27. A photograph of a cyclonic ice-ocean eddy observed off the coast of Esashi-Ohmu from an aircraft at altitude 1000 feet at 07:00 on 23 January, 1987. The eddy was about 20 km in diameter and was marked by ice belts composed of homogeneous sized ice floes with a diameter of about 10 m (Wakatsuchi and Ohshima, 1990).

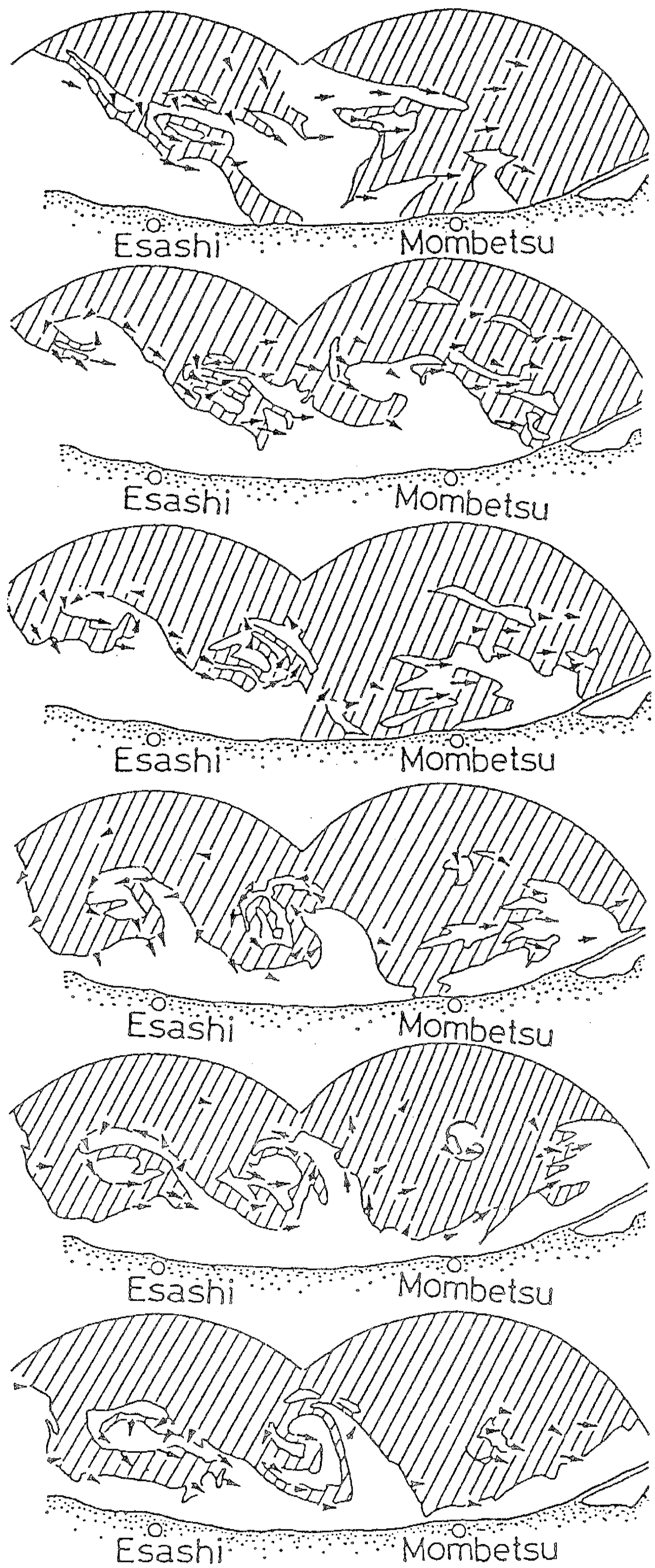


Fig. 2.4.28.

Evolution of the backward breaking wave pattern in the ice edge observed by the sea ice radar network from 0:00 on 14 April, 1984 to 12:00 on 16 April, 1984: left figures show the radar images and right figures are sketches of pack-ice area with arrows which indicate the moving direction of ice floes (Wakatsuchi and Ohshima, 1990).

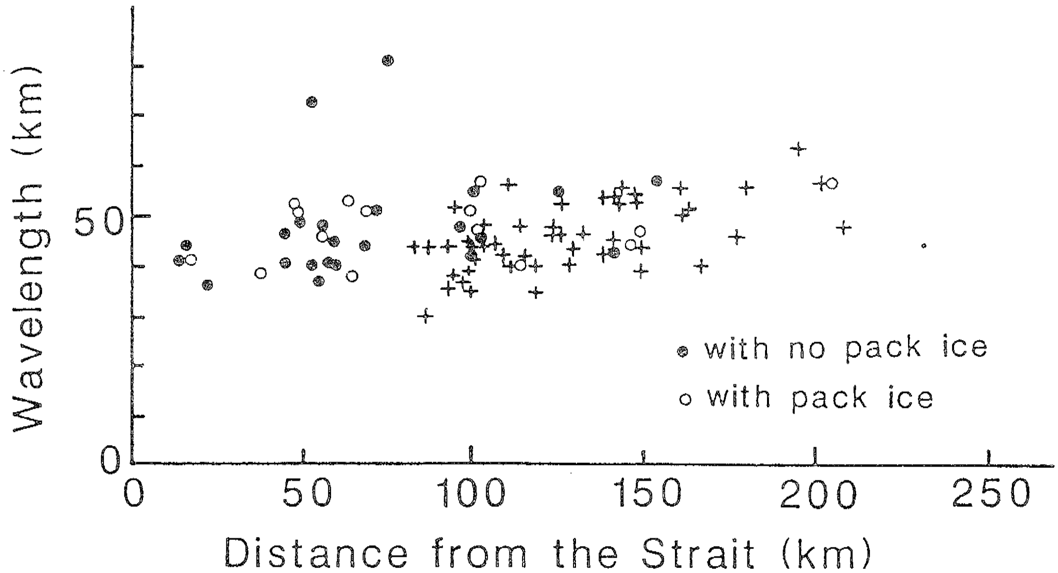


Fig. 2.4.29. Wavelengths of the frontal waves as a function of distance from Soya Strait. Data (+) are based on the records of radar images collected during the years 1969-1988. Data (black and white circles) are based on the NOAA IR images in the spring (March through May): black circles indicate that no sea ice exists and white circles that sea ice exists (Wakatsuchi and Ohshima, 1990).

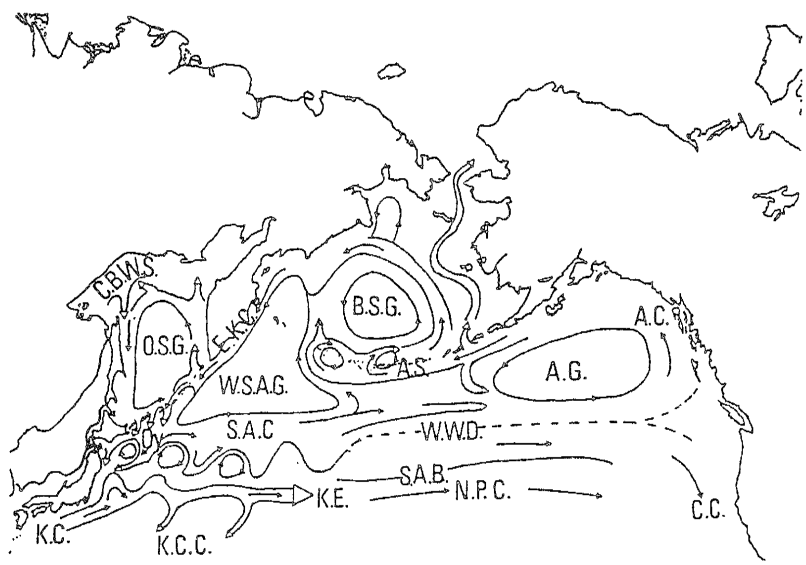


Fig. 2.5.1. Schematic of the subarctic gyre in the North Pacific (Ohtani, 1991).

KC: Kuroshio	KCC: Kuroshio Counter current
KE: Kuroshio Extension	NPC: North Pacific Current
CC: California Current	SAB and Oy: Subarctic boundary and Oyashio
SAC: Subarctic current	WWD: West Wind Drift
AC: Alaska current	AG: Alaskan gyre
AS: Alaskan Stream	EKC: East Kamchatka Current
WSAG: Western subarctic gyre	OSG: Okhotsk gyre
CBWS: cold saline bottom water	

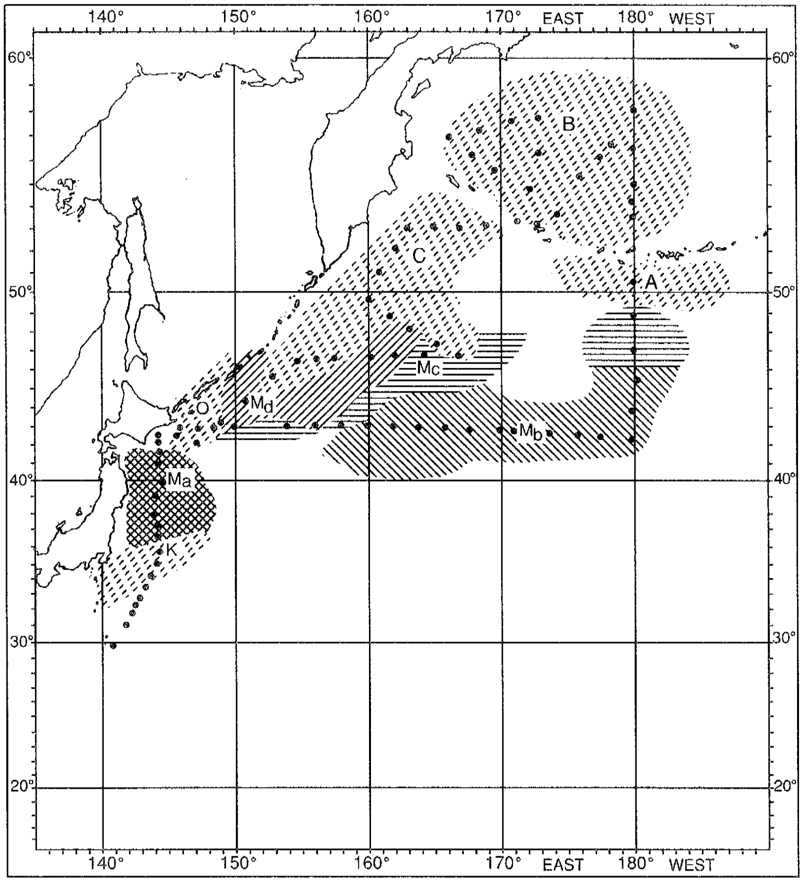


Fig. 2.5.2.

Hirano's (1957) classification of waters in the western subarctic gyre.

K: Kuroshio Water

O: Oyashio water (Okhotsk water in Hirano's classification)

B: Bering water, C: central water of the western subarctic region

A: water from Gulf of Alaska

Ma and Mb: mixed water between the Kuroshio and Oyashio waters off the Sanriku coast and along the subarctic boundary, respectively

Mc: mixed water between the central water

Mb, Md: mixed water between the central water and the Oyashio water

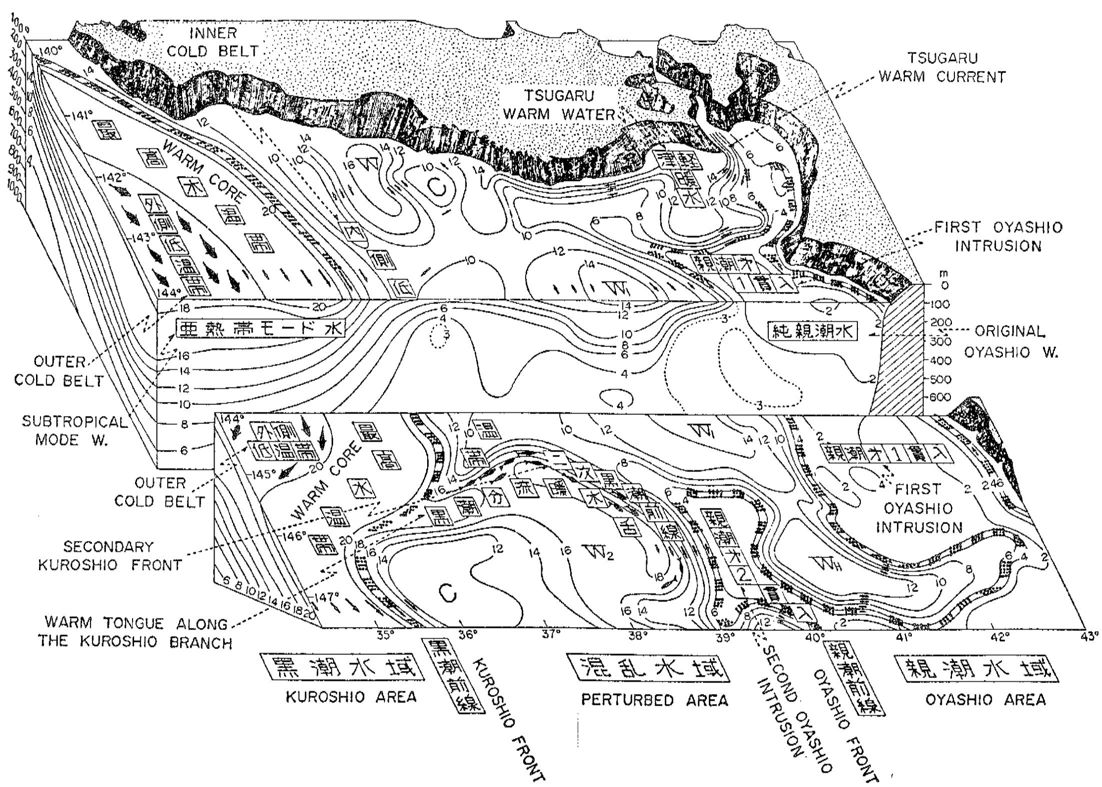


Fig. 2.5.3.

Schematic of circulation and water masses in the Mixed Water Region from Kawai (1972).

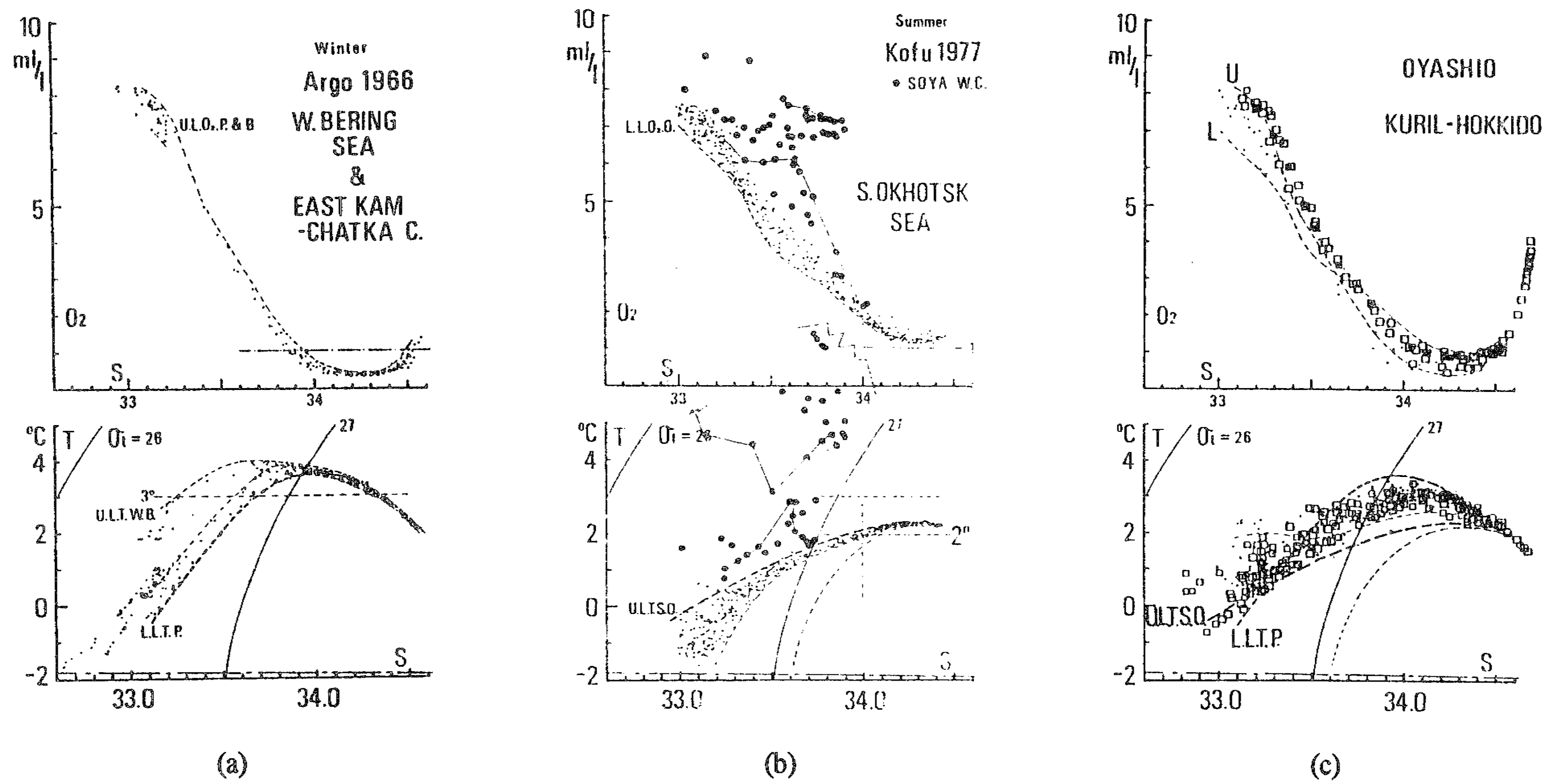


Fig. 2.5.4. (a) T-S relation in the East Kamchatka Current and western Bering Sea. L.L.T.P.: lower limit of temperature in the Pacific waters. U.L.T.W.B.: upper limit of temperature in the western Bering Sea
(b) T-S relations in the southern Okhotsk Sea. U.L.T.S.O.: upper limit of temperature in the southern Okhotsk Sea
(c) T-S in the Oyashio, showing that its properties lie between the East Kamchatka Current (which is warmer) and Okhotsk Sea properties.(which is colder). "Argo" stations are those used in Figs. 2.5.6 and 2.5.7 (Ohtani, 1989).

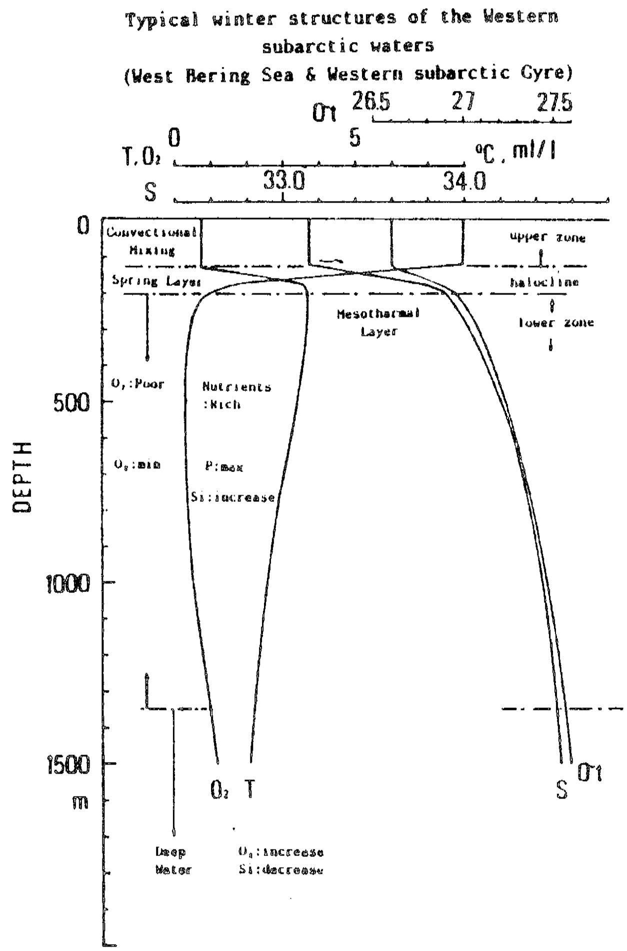


Fig. 2.5.5. Typical winter structure of the western subarctic waters. (Ohtani, 1989).

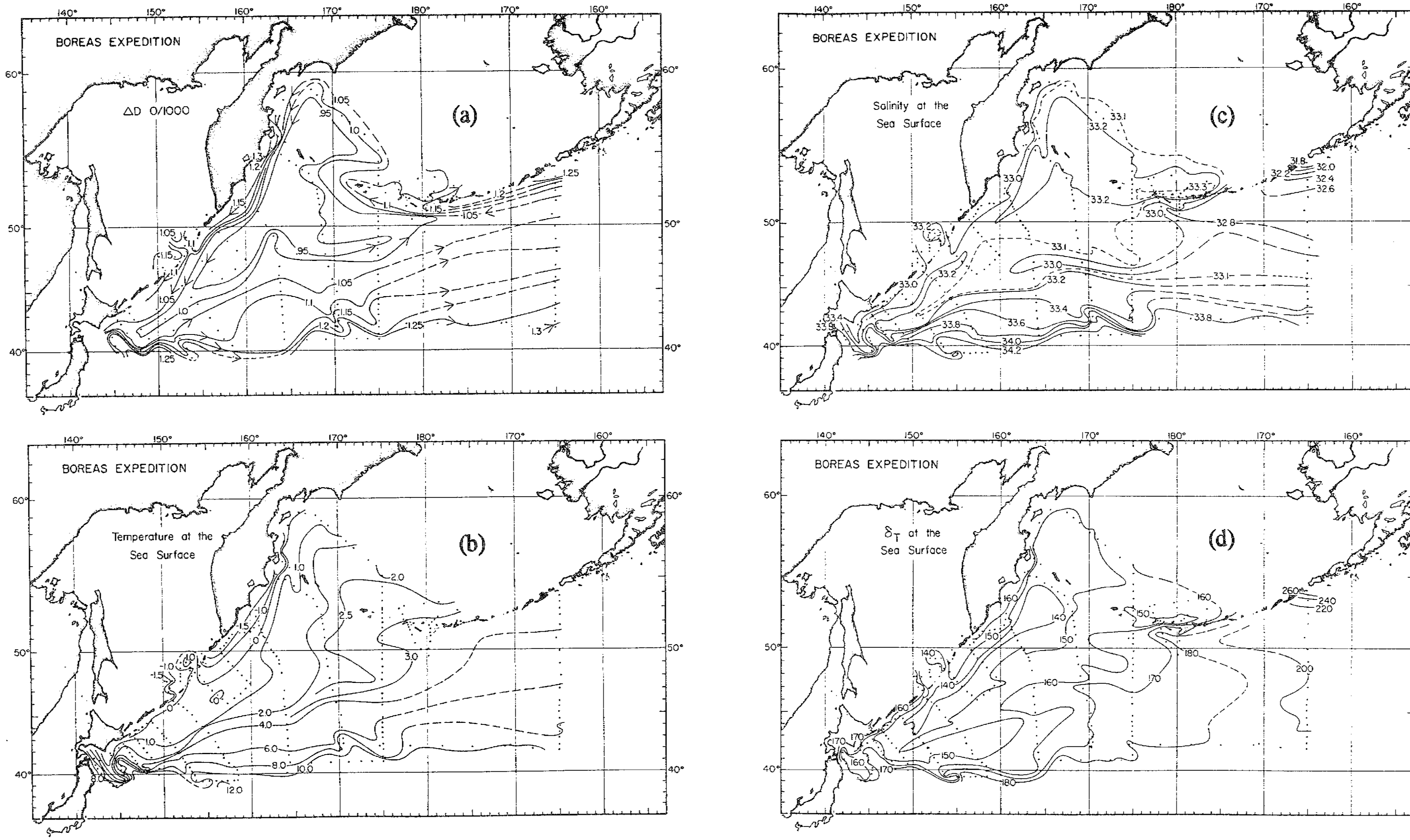


Fig. 2.5.6. (a) Geopotential anomaly at the sea surface with respect to 1000 dbar
(b) Temperature (°C) at the sea surface
(c) Salinity at the sea surface
(d) Thermosteric anomaly at the sea surface (Reid, 1972).

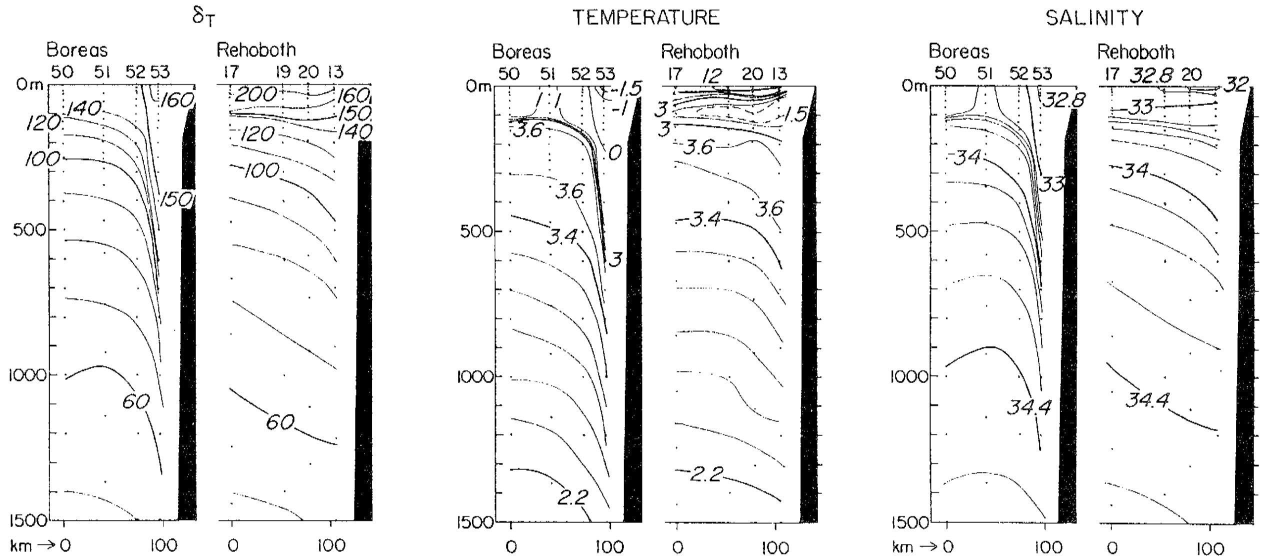


Fig. 2.5.7. Vertical sections of temperature just south of Kamchatka Strait: (left - winter; right - summer), from Reid (1972).

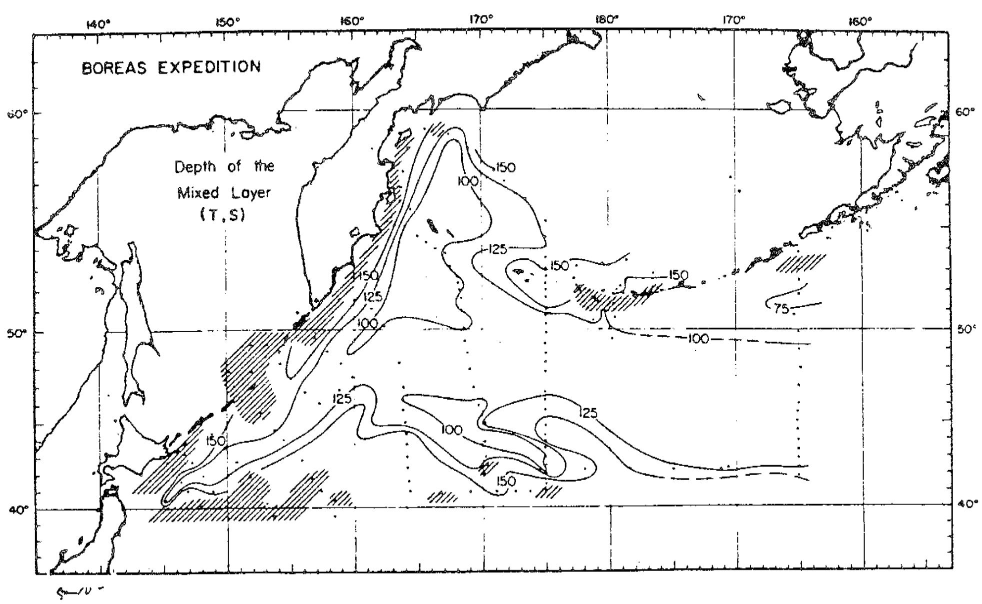
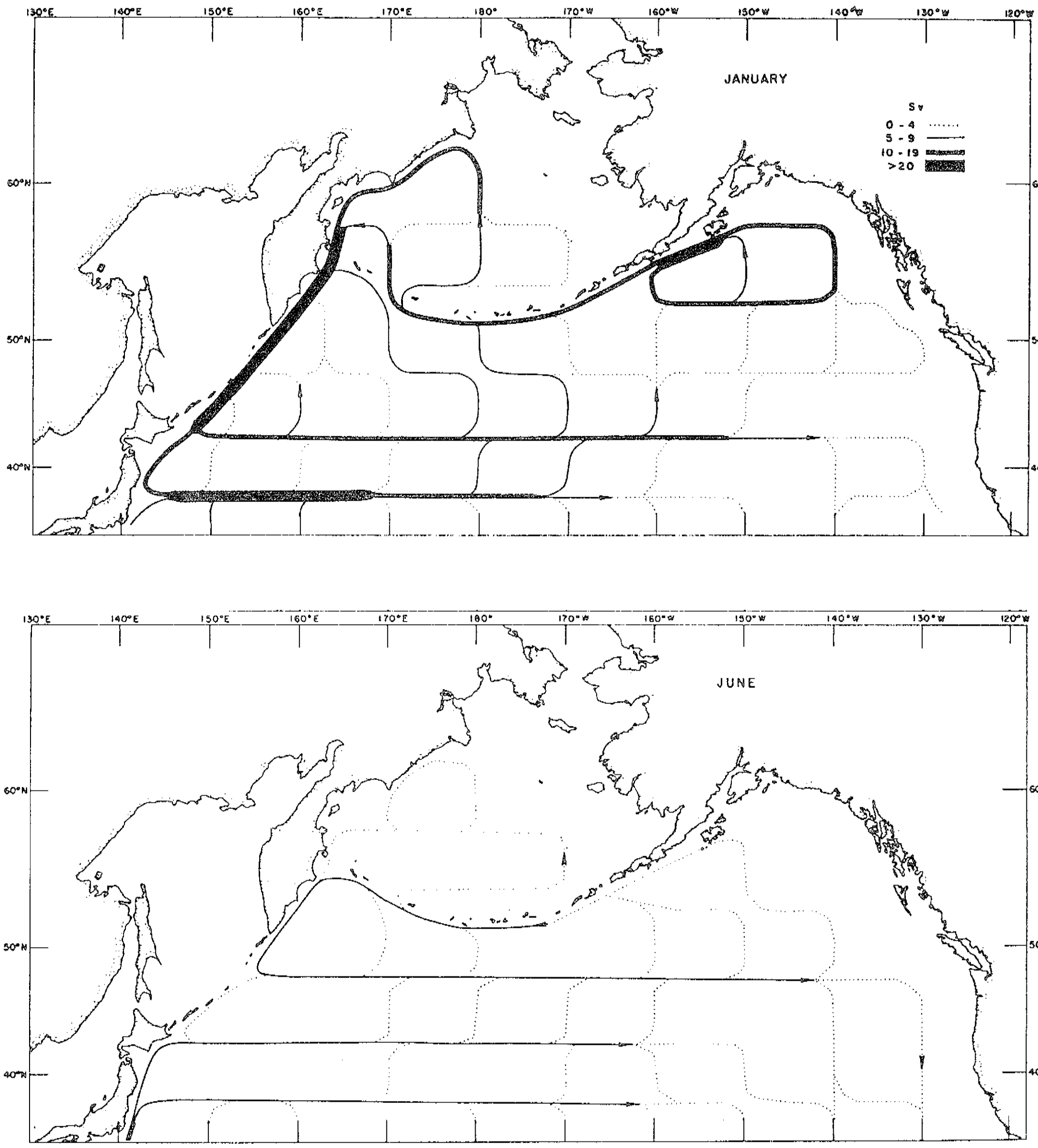


Fig. 2.5.8. Mixed layer depth estimated from the saturation ratio of dissolved oxygen (Reid, 1982).



(a)

(b)

Fig. 2.5.9. Monthly mean integrated Sverdrup transport (Sv), 1960-1969, for (a) January and (b) June (Favorite et al., 1976).

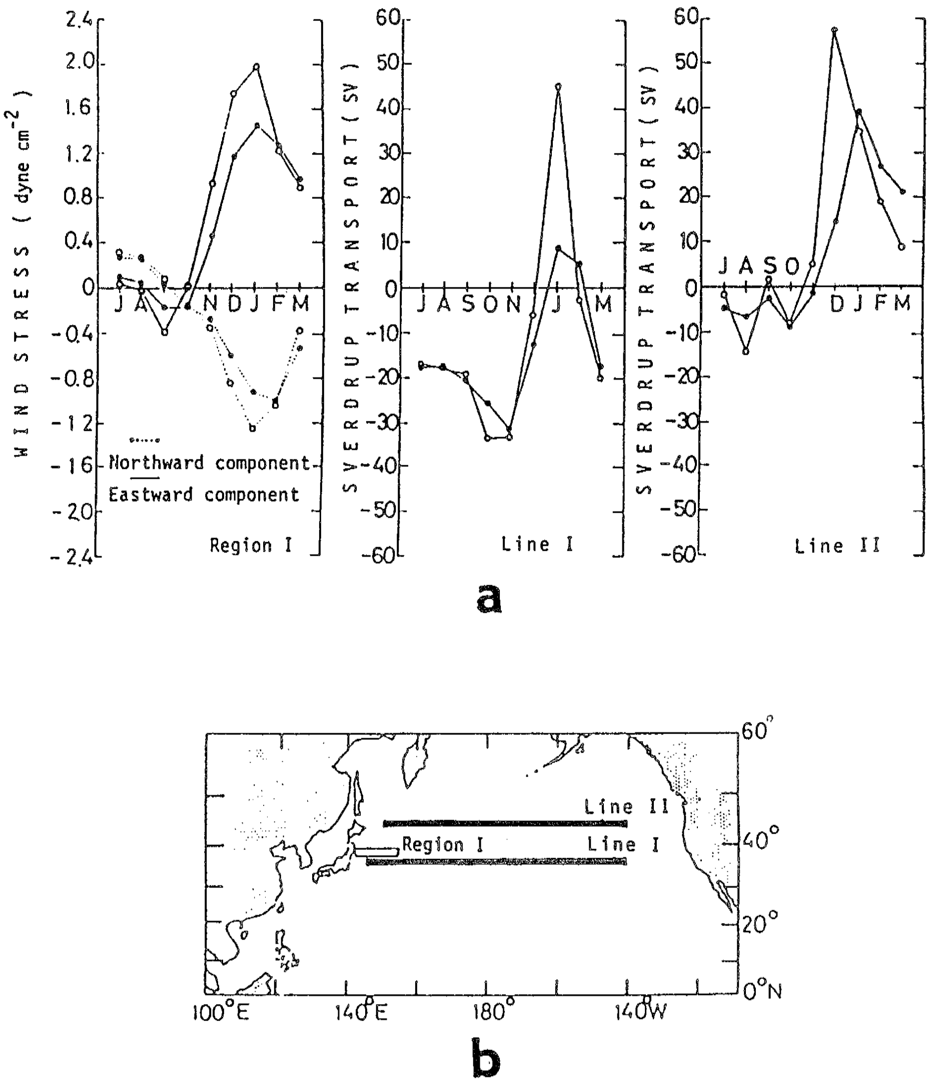


Fig. 2.5.10. (a) Monthly mean wind stress and Sverdrup transport along the two lines in (b). Open circles are for the years of anomalous southward intrusion (Fig. 2.5.25) and solid circles are for all other years during 1961 - 1983 (Sekine, 1988).

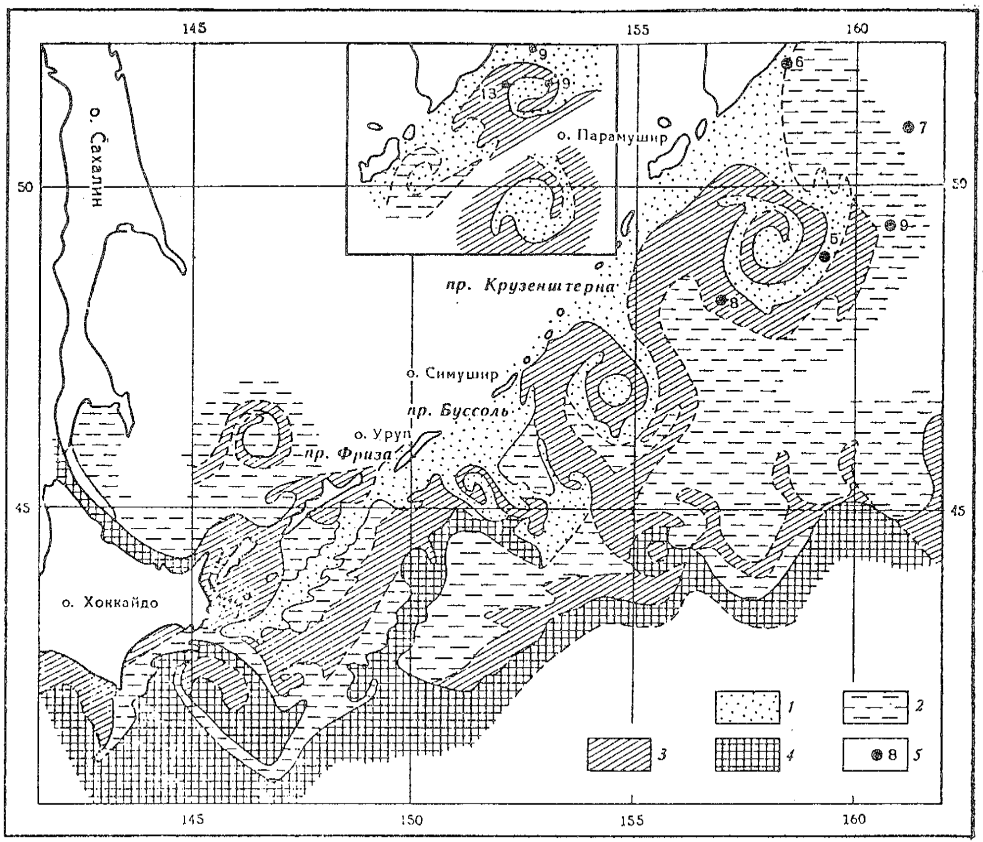


Fig. 2.5.11. Eddies in the East Kamchatka Current and Oyashio, from infrared images from NOAA satellites for 29 September-2 October, 1980. The small panel at the top is for September 21-22, 1981. For the key in the lower right corner:

1 - cold currents
2 - subarctic waters and transformed waters of the cold currents
3 - transformed waters of warm currents
4 - branches of the warm currents
5 - location of CTD casts (Bulatov and Lobanov, 1983).

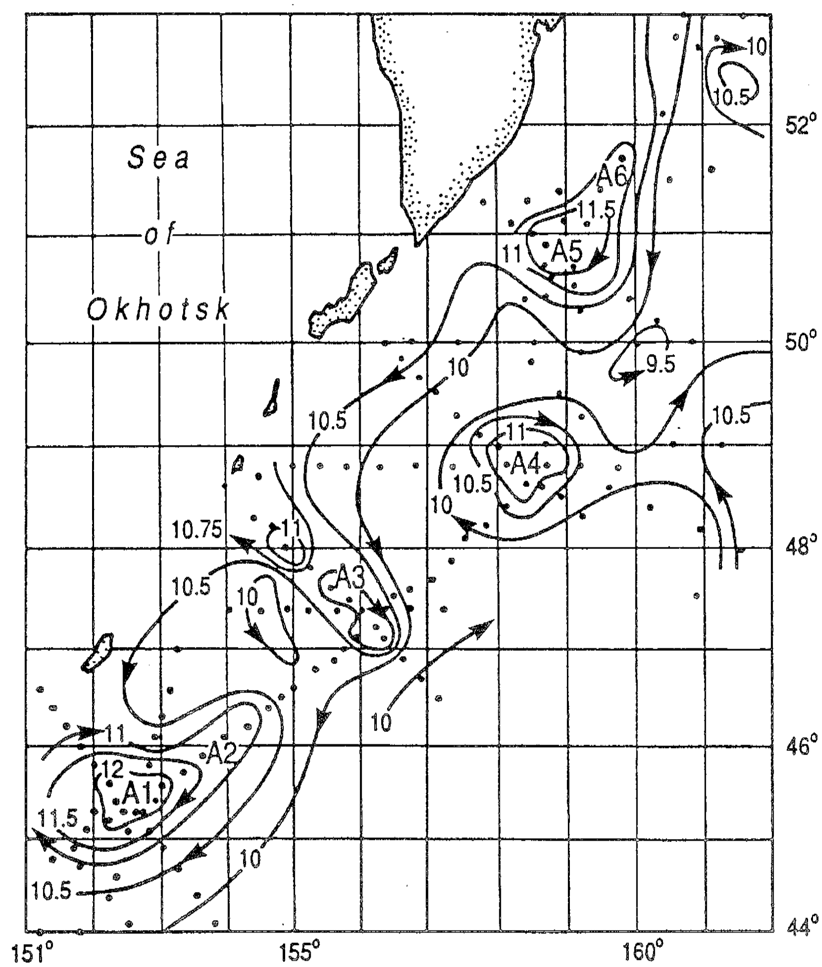
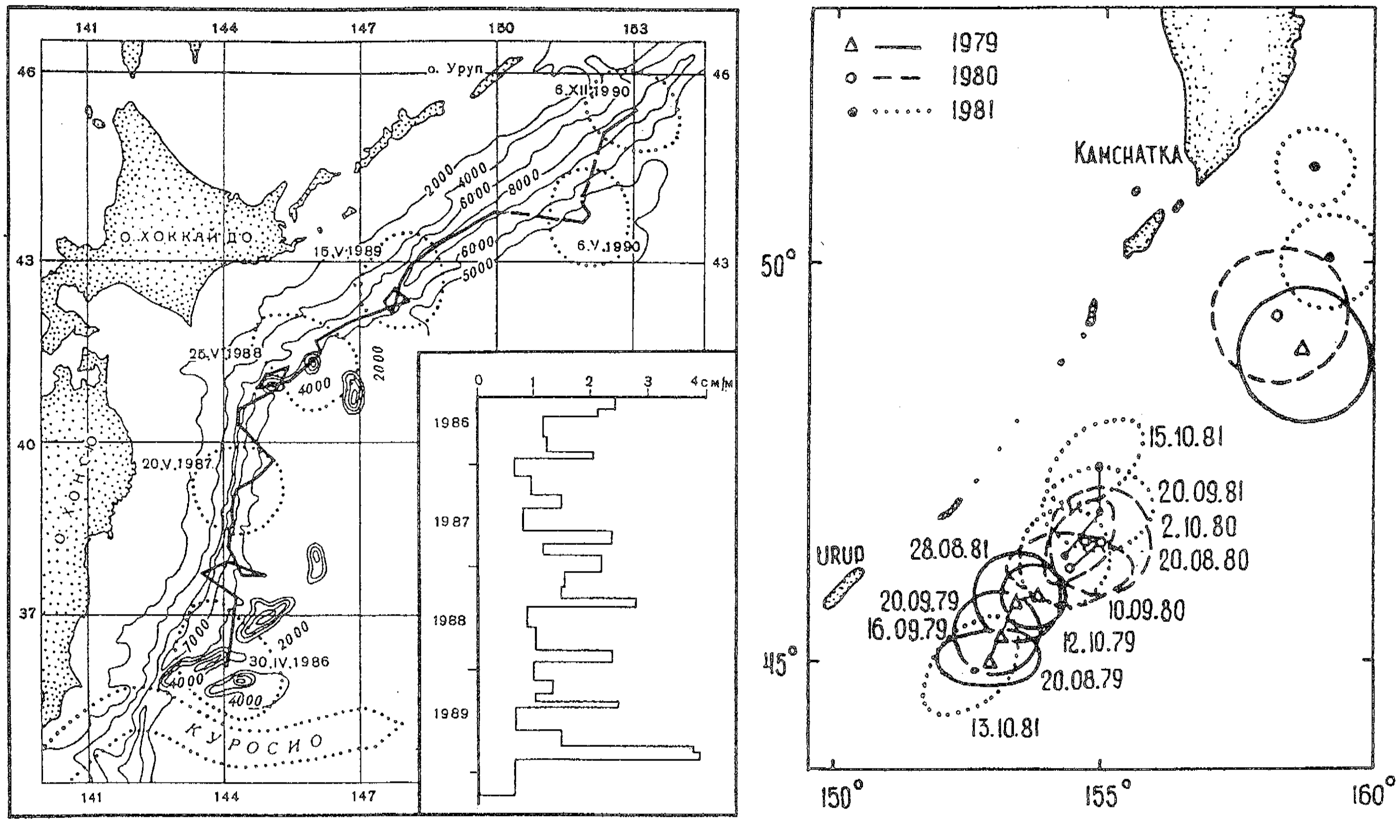


Fig. 2.5.12. Dynamic height at the sea surface relative to 1000 dbar in fall, 1990, showing Kuril eddies (Rogachev et al., 1993).



(a)

(b)

Fig. 2.5.13. (a) Track of Kuroshio warm core ring 86B (A3), based on satellite photographs and ship data. The insert panel is the translation velocity of the eddy (Lobanov et al., 1991).
(b) Tracks of several Kuril eddies, moving northeastward at 2-6 cm/sec (Lobanov and Bulatov, 1993).

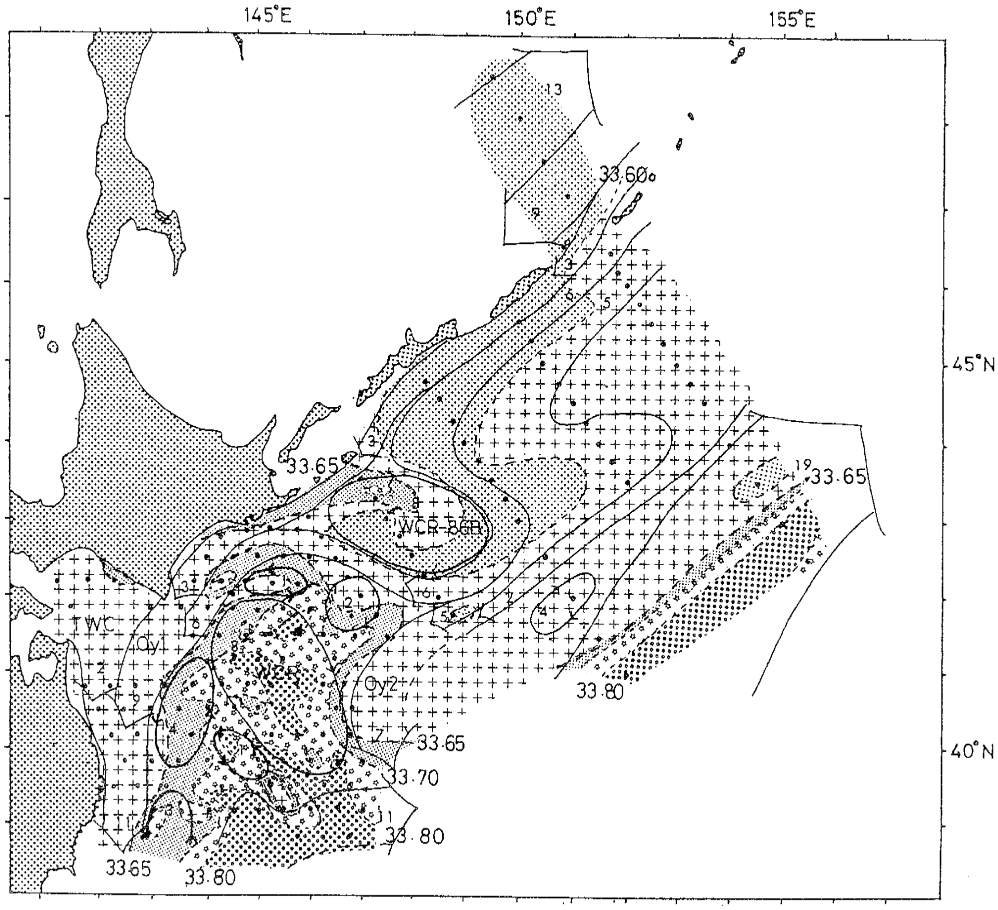


Fig. 2.5.14. Volume transports relative to 1500 dbar and salinity at 120 cl/ton in September, 1989 (Kawasaki et al., 1991).

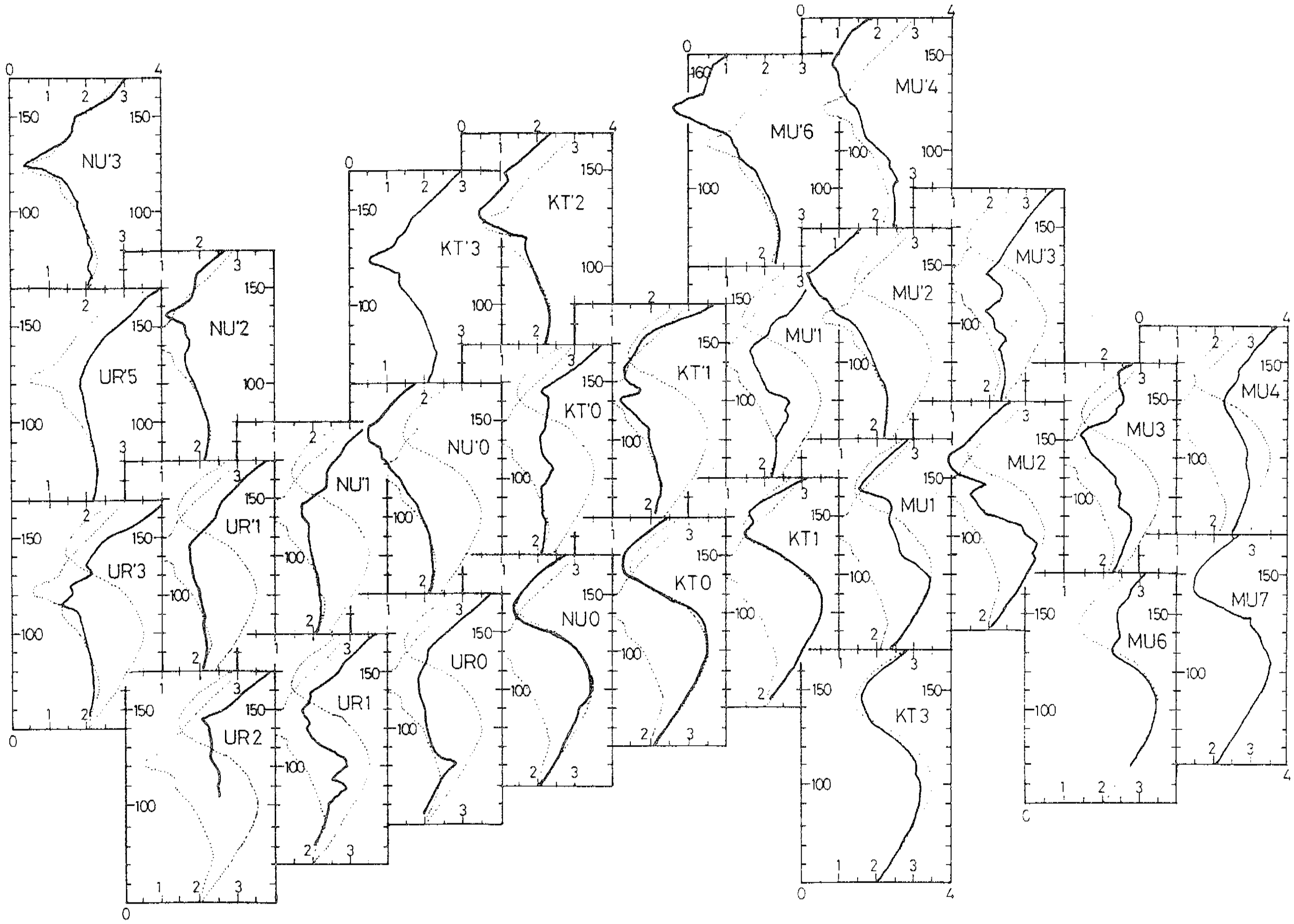
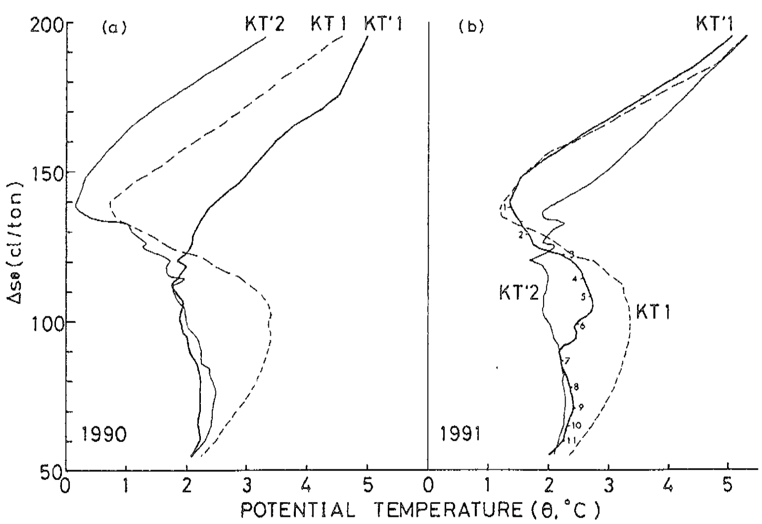


Fig. 2.5.15.

(a) Potential temperature as a function of specific volume anomaly around the Kuril Islands. The light dashed curves are reference profiles from the East Kamchatka Current (MU7) and the Okhotsk Sea (KT'3) (Kawasaki and Kono, 1993b).



(b) Individual comparison of waters from the East Kamchatka Current (KT1), the Okhotsk Sea (KT'2), and the mixed water around the Kuril Islands (KT'1) from Kawasaki and Kono (1992).

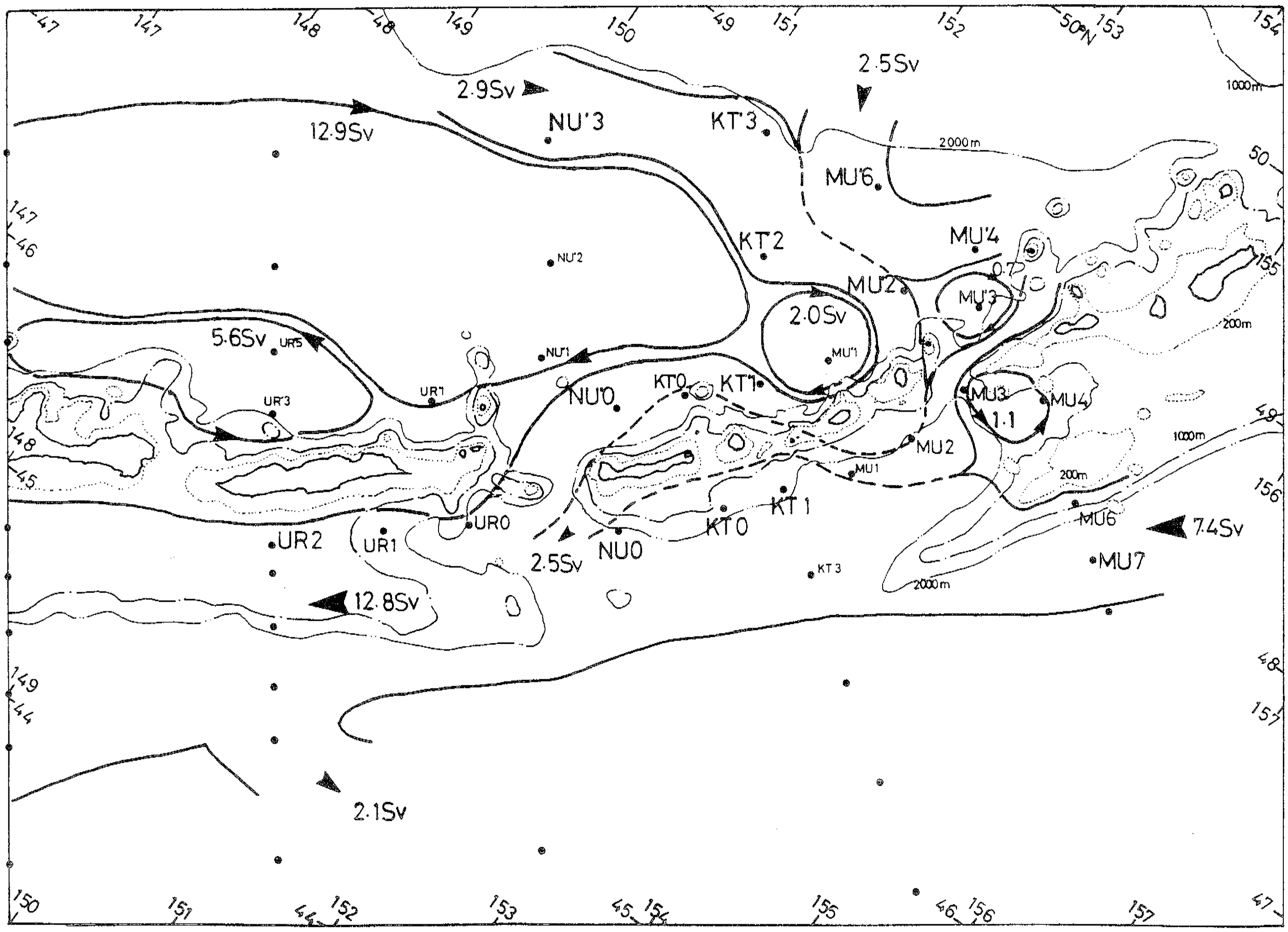


Fig. 2.5.15 (c) Station locations for the preceding.

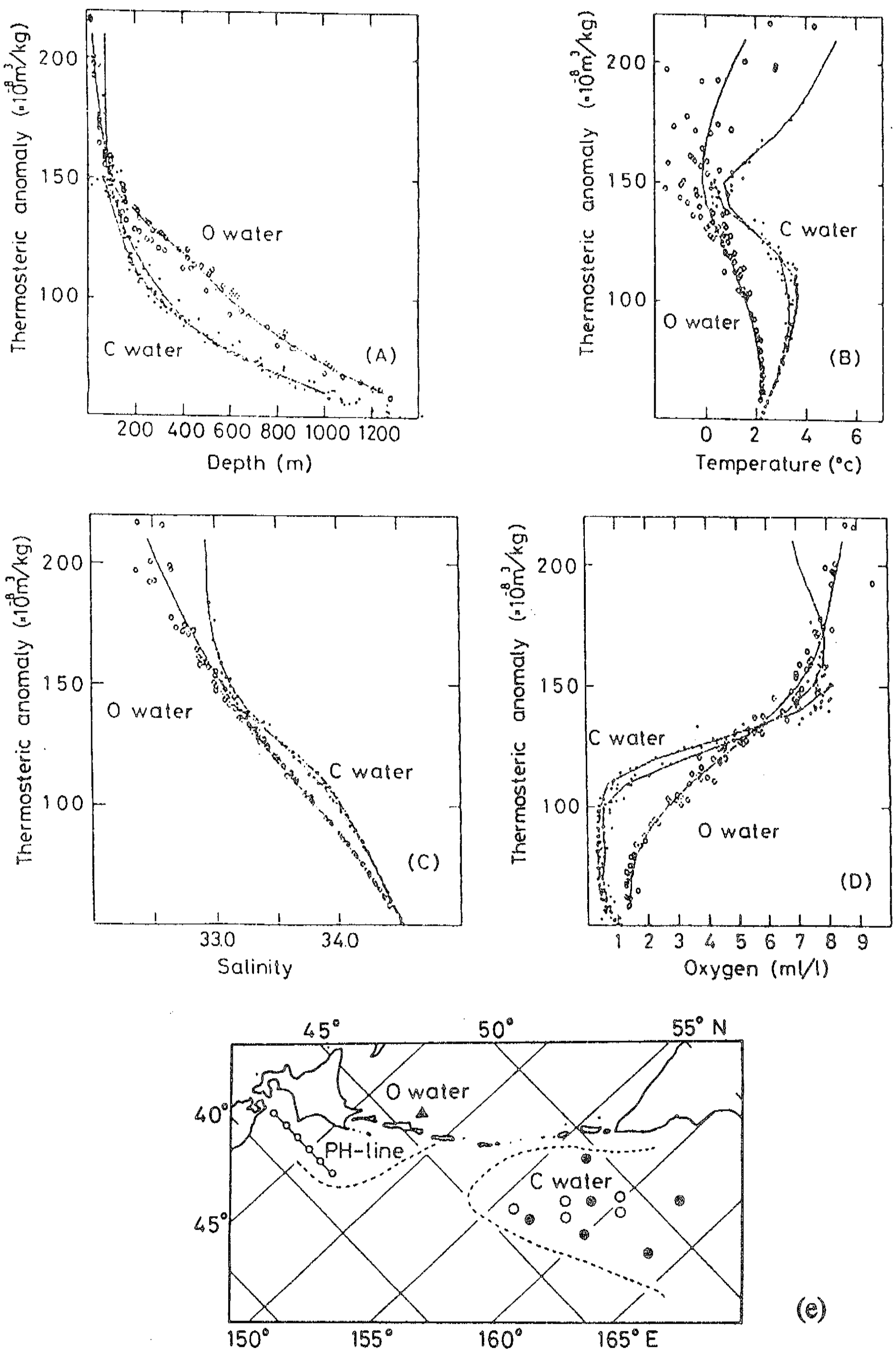


Fig. 2.5.16. Okhotsk and Central (East Kamchatka Current) waters: (a) - (d) properties, (e) location of stations (Ishikawa, 1988).

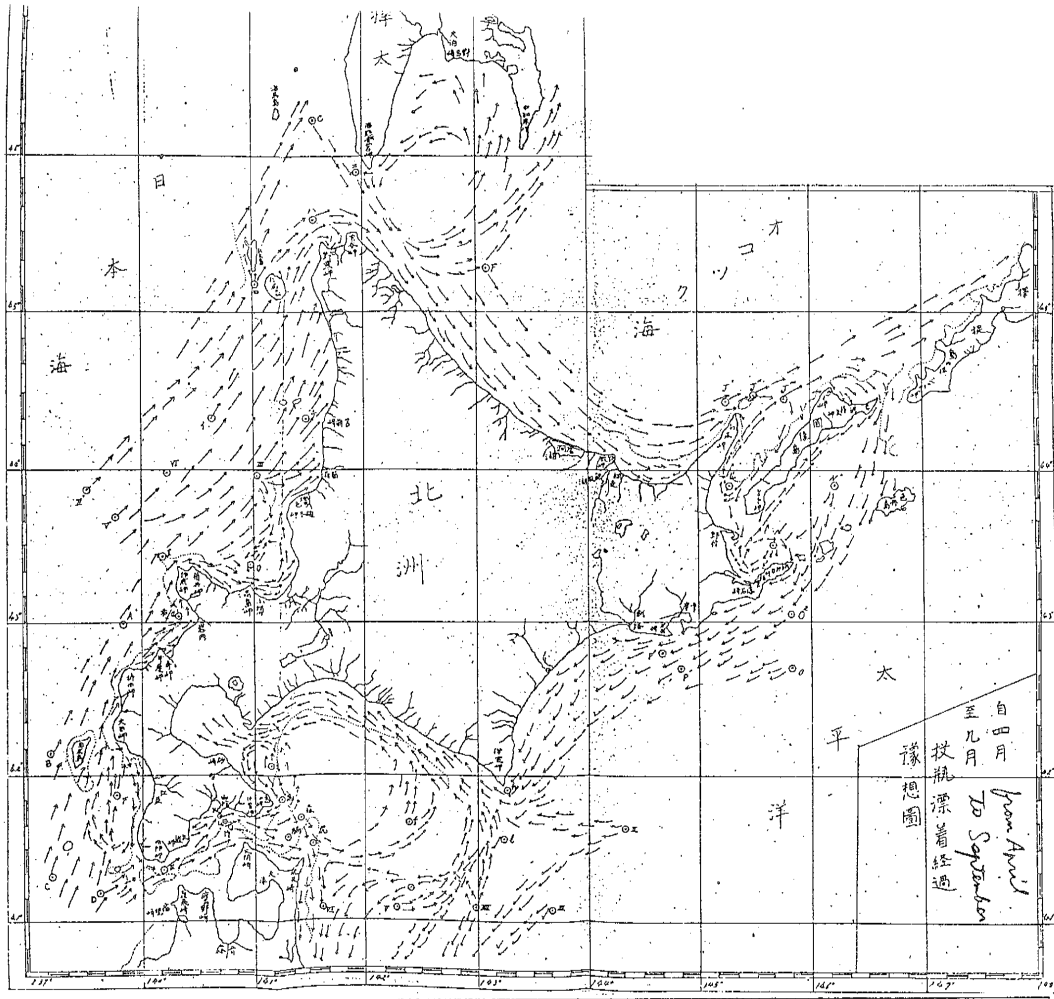


Fig. 2.5.17. (a)

Results from drift bottle releases in 1914 (Kajiyama, 1936). The small circles show the locations of regular releases (approximately 50 at each site). The arrows show the inferred currents based on the recoveries. A total of 4960 were released and 771 recovered.

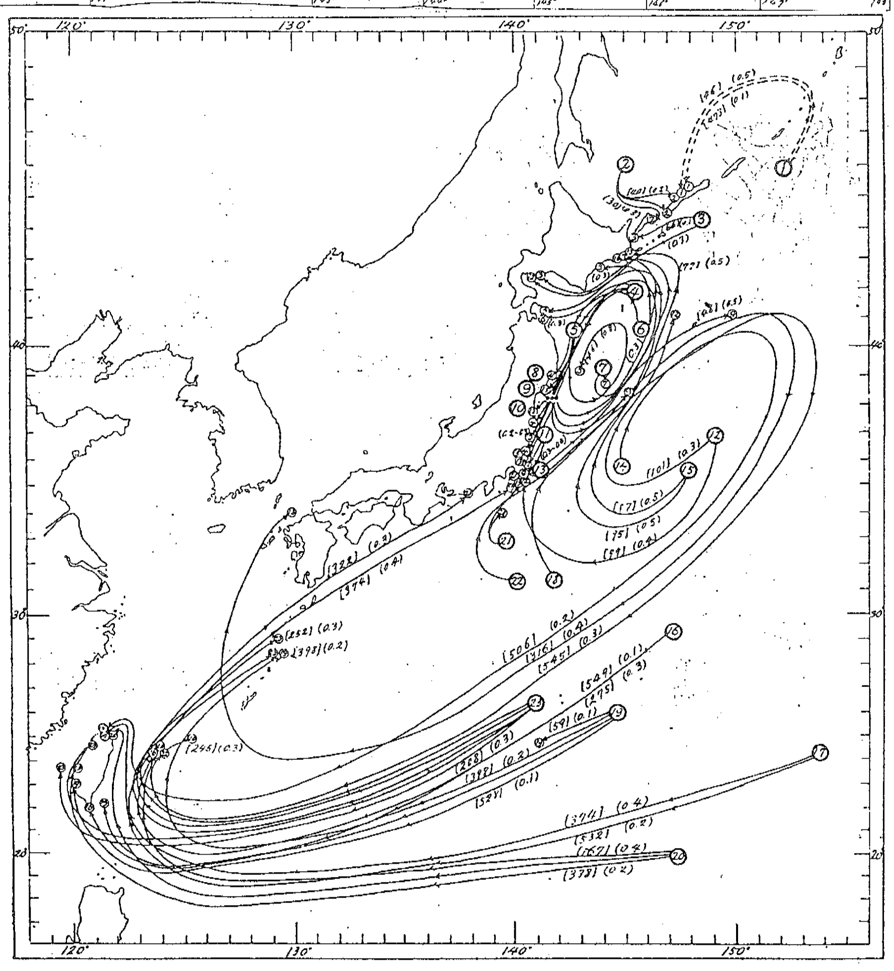


Fig. 2.5.17 (b)

Results from drift bottle releases in 1933 (Uda, 1936). In the boxes are shown the number of bottles released and recovered.

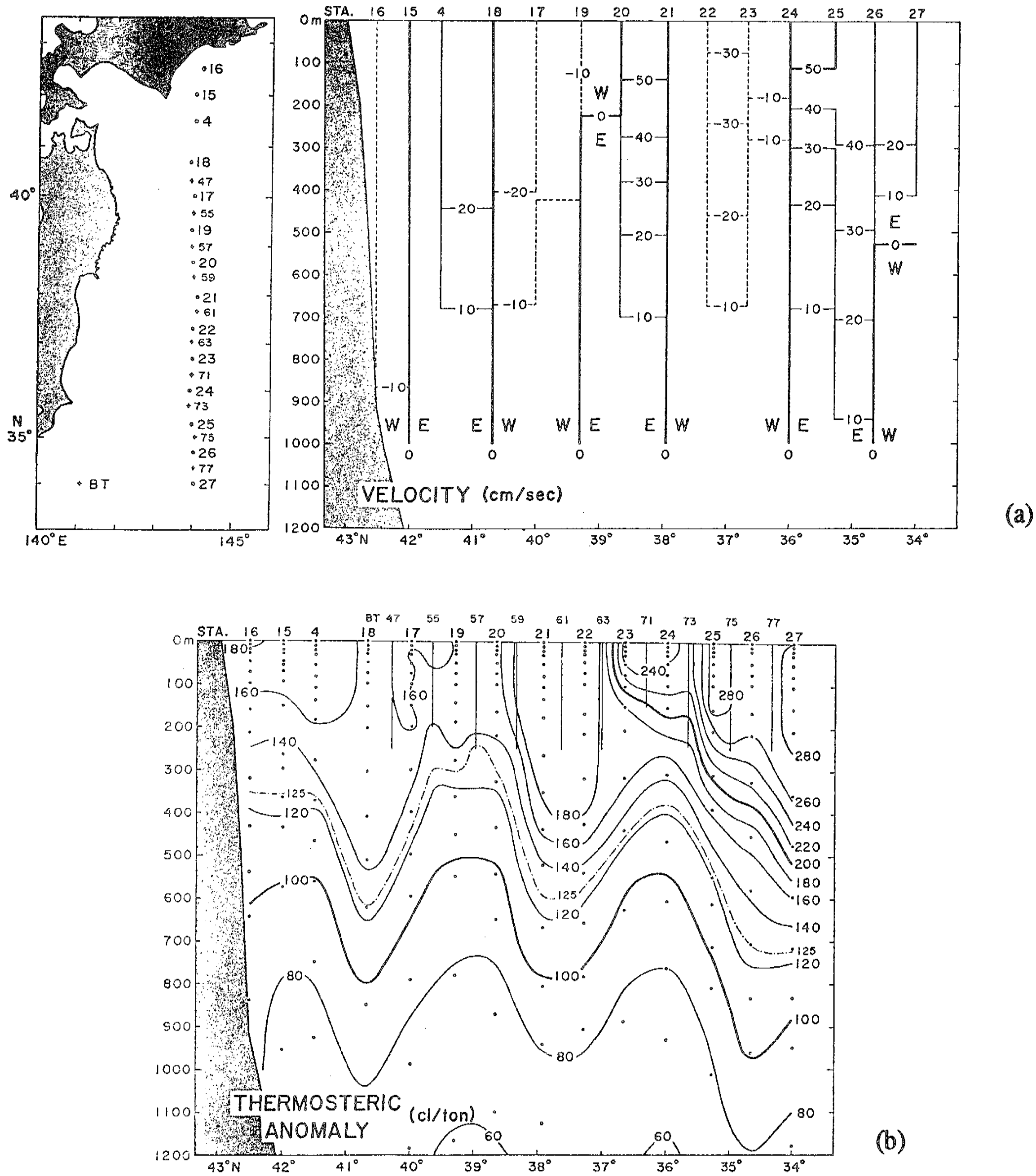


Fig. 2.5.18. (a) Geostrophic velocity relative to 1000 dbar, from the 144°E section across the Oyashio and Kuroshio Extension, February 1967.
(b) Thermosteric anomaly for the same section (Kawai, 1972).

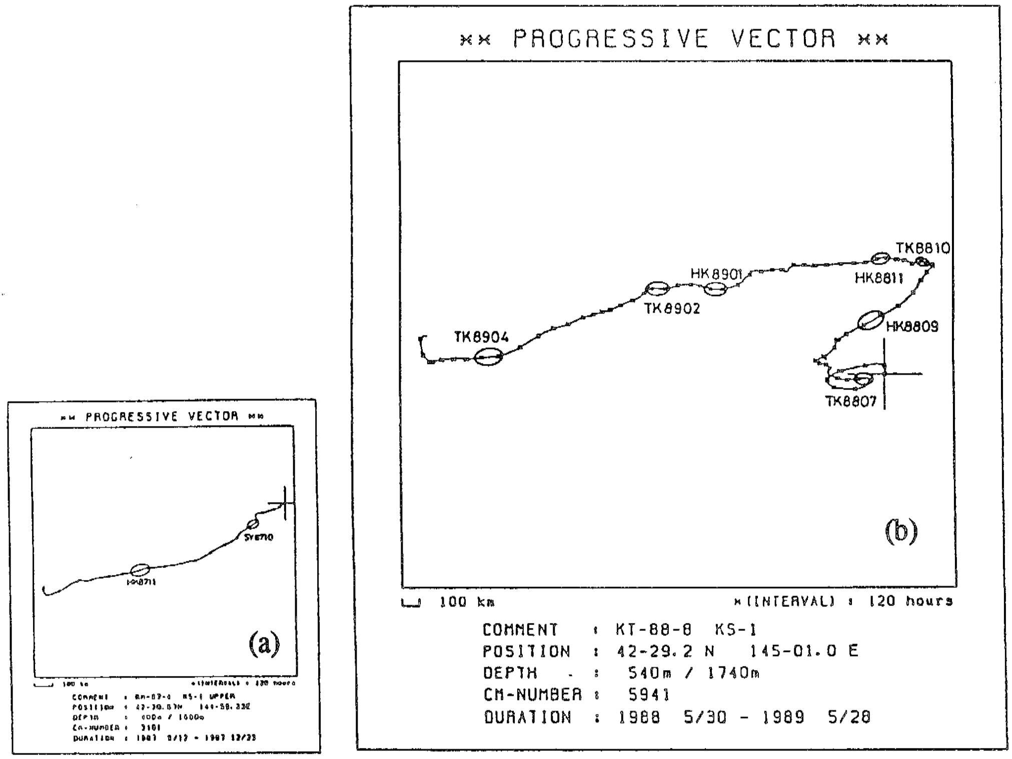
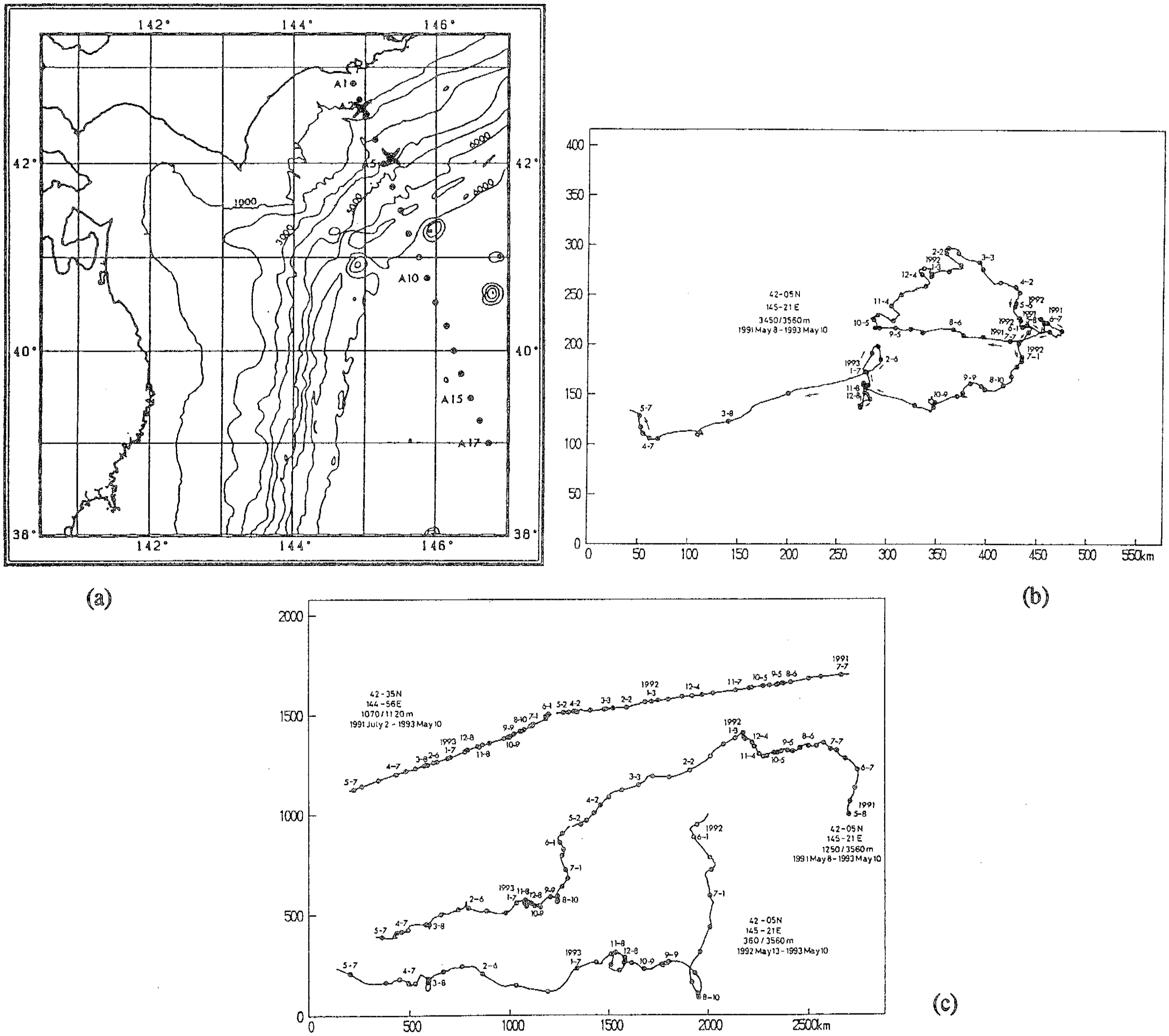


Fig. 2.5.19. Progressive vector diagrams from a current meter deployed at about 500 m in water of about 1700 m depth along the Akkeshi-line in 1987-1989:
(a) at 480 m in 1680 m depth in 1987 and
(b) at 540m in 1740 m depth for 1988-1989 (Kawasaki and Kono, 1992 paper 28).



(a) (b) (c)

Fig. 2.5.20. (a) Current meter mooring locations since 1991 (large x's) and routine hydrographic station locations (solid circles) along the Akkeshi-line. Progressive vector diagrams from (b) the bottom current meter on the 3500 m mooring and (c) the near-surface and mid-depth current meters on the 3500 m mooring and the bottom current meter on the 1100 m mooring. (Kawasaki and Kono, 1993c).

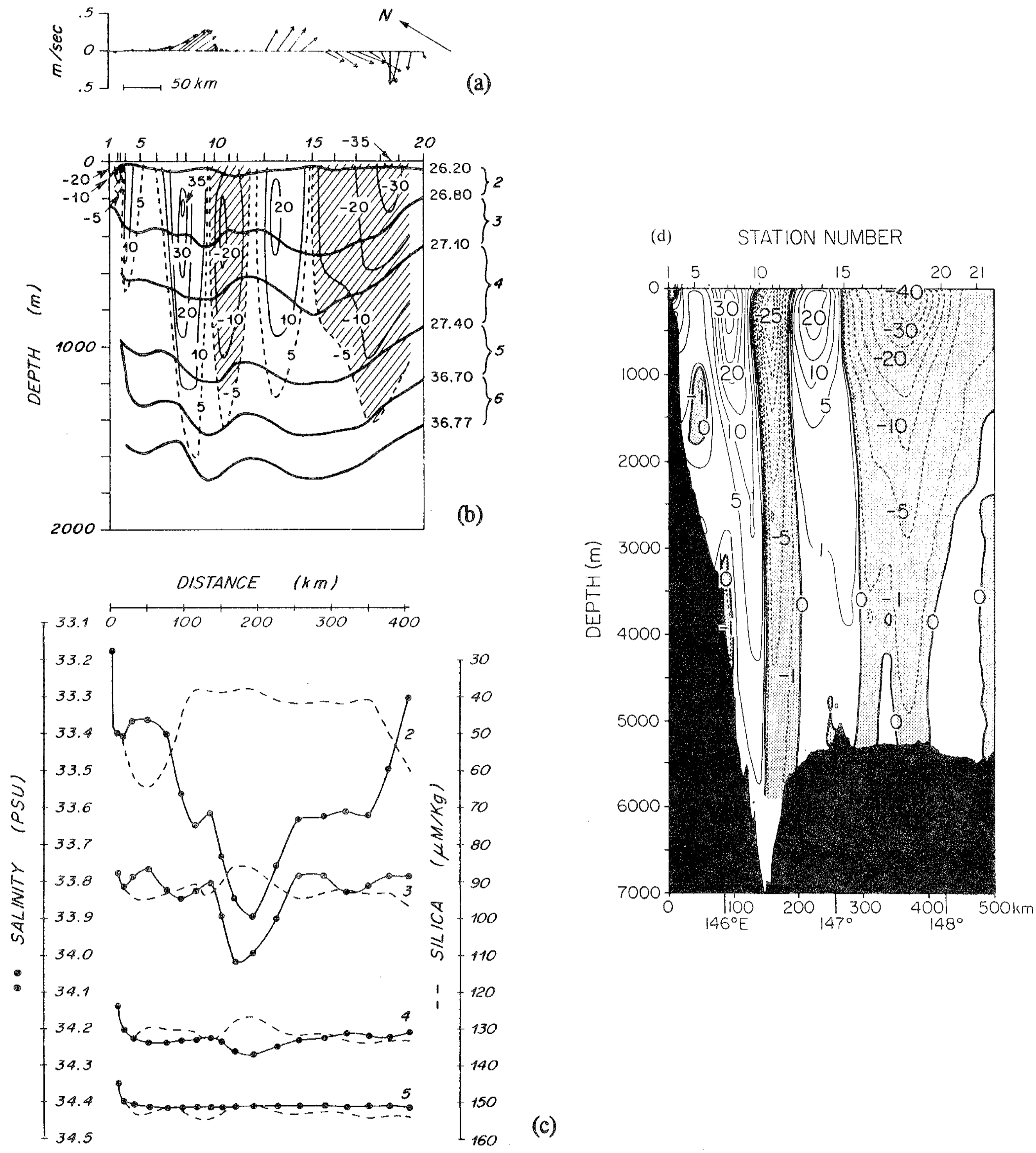
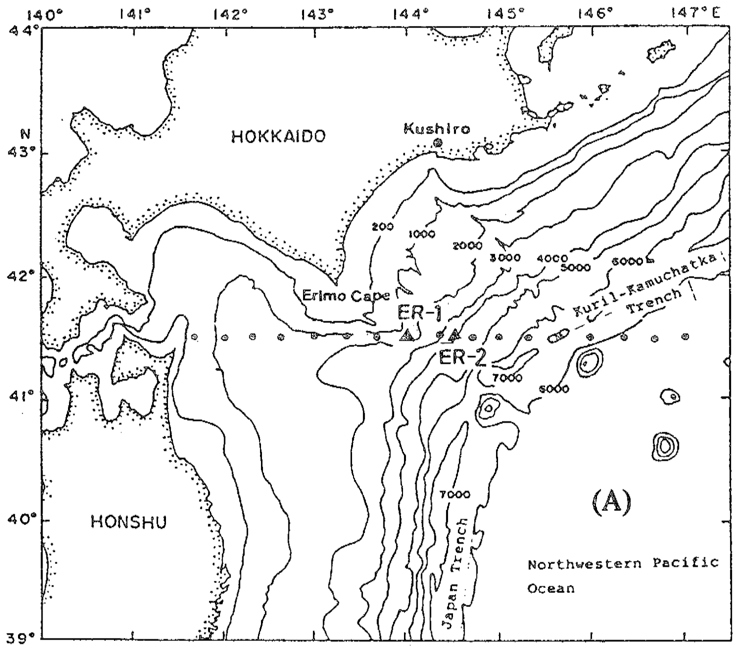
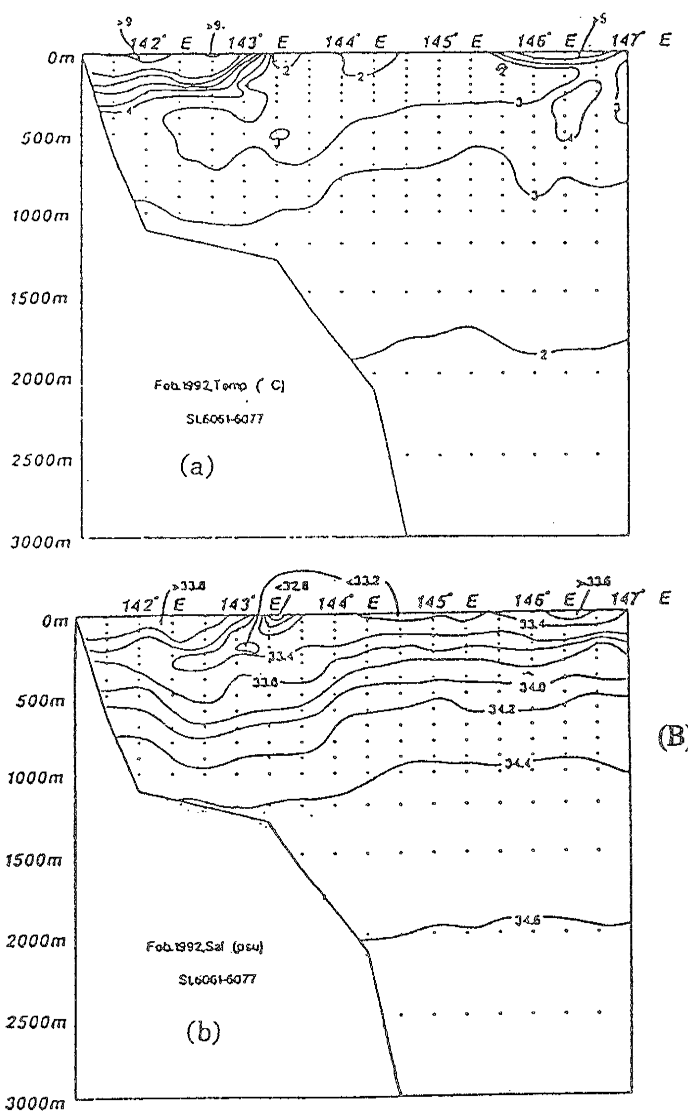


Fig. 2.5.21. Geostrophic velocities relative to the ocean bottom along nearly the same section as shown in Fig. 2.5.20a, in summer, 1985 (Talley et al., 1991).





(B)

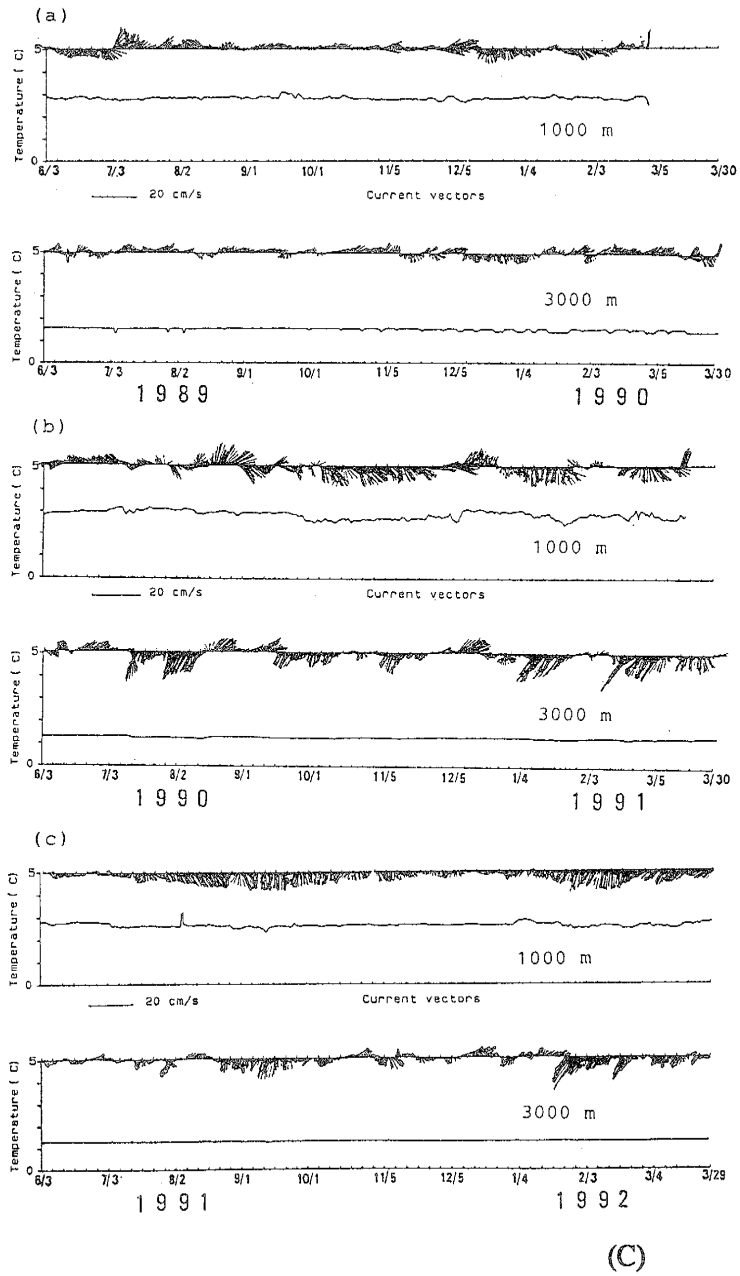


Fig. 2.5.22. The 41°30'N line:

(A) hydrographic station locations (filled circles) which have been repeated many times over many years and current meter locations (triangles) for 1989-1992;

(B) typical hydrographic section along 41°30'N, this one for February 1992 (Uehara and Miyake, 1993);

(C) stick diagrams for the two current meters at about 1000m and 3000m at ER-2, where the water depth is about 3500m. The first intrusion of the Oyashio often flows across these mooring sites (Miyake et al., 1993).

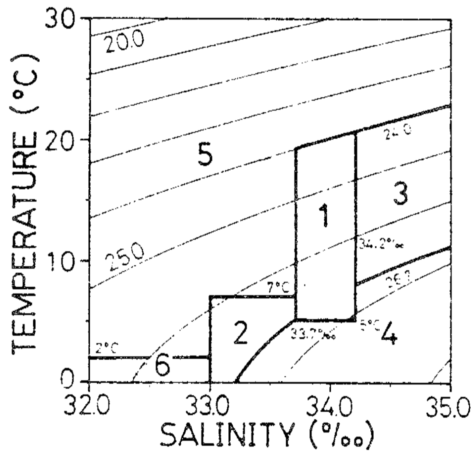


Fig. 2.5.23.

Water property classification in the Mixed Water Region.
1. Tsugaru Warm Current water (TW)
2. Oyashio water (OW)
3. Kuroshio water (KW)
4. cold lower-layer water (CL)
5. surface-layer water (SW)
6. Coastal Oyashio Water (CO)
(Hanawa and Mitsudera, 1986).

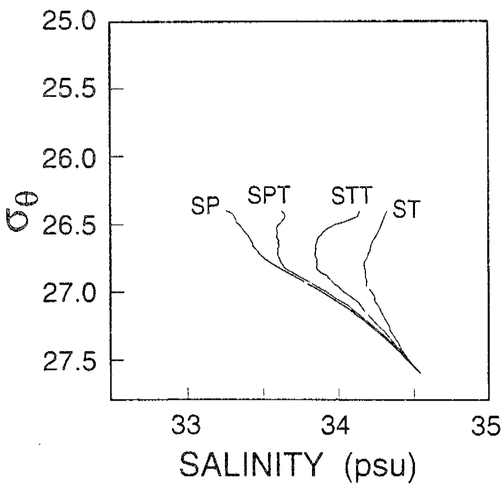


Fig. 2.5.24.

Average potential density-salinity relations in the Mixed Water Region, based on 278 CTD profiles from spring, 1989.

ST: subtropical; SP: subpolar (Oyashio)
STT: subtropical transitional
SPT: subpolar transitional (Talley et al., 1994).

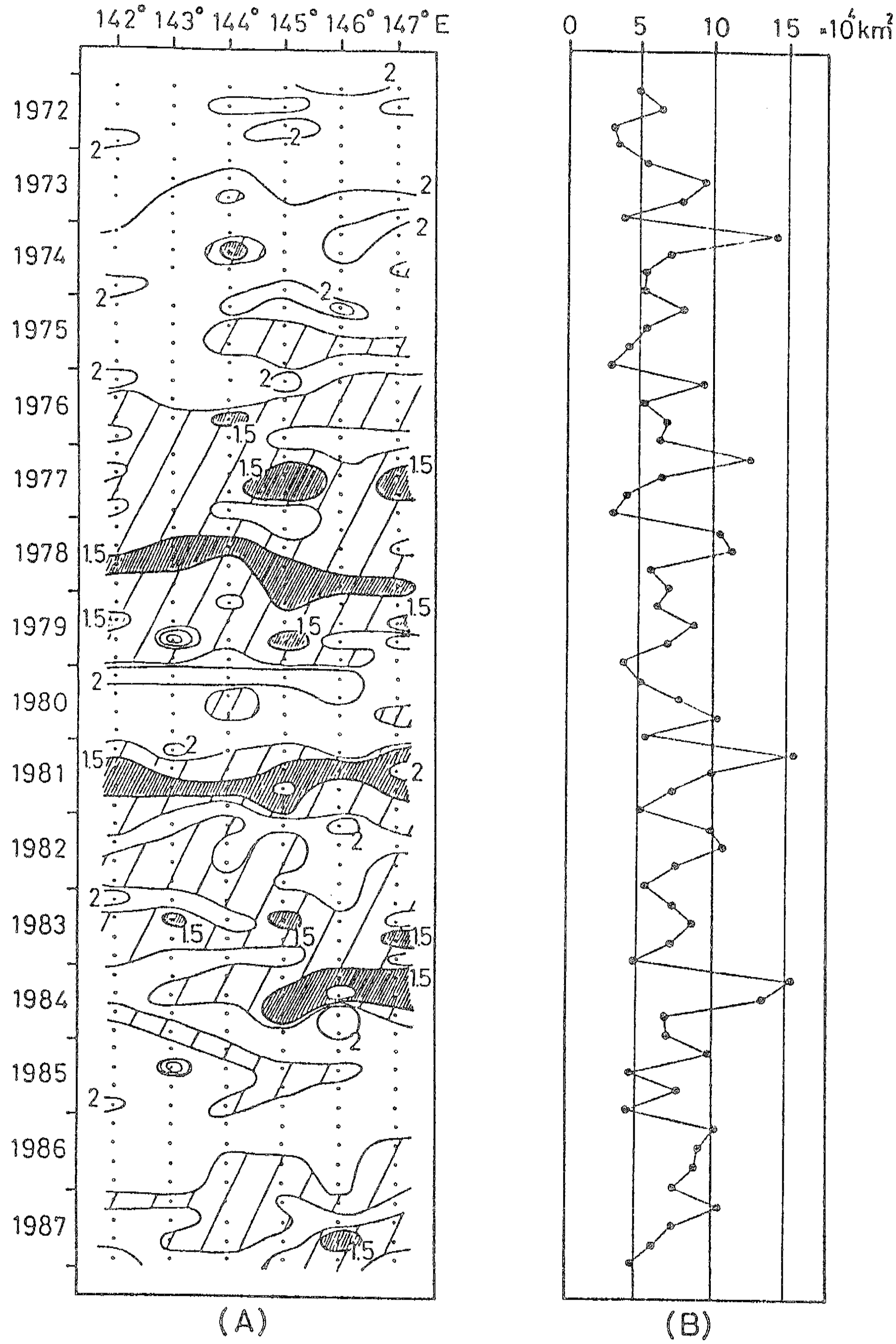


Fig. 2.5.25. (a) Dissolved oxygen along the 41°30'N line and (b) the area of Oyashio water at 100m depth in the Tohoku area. Anomalous intrusions of Oyashio water are seen in 1974, 1981, and 1984, corresponding to lower oxygen, which indicates a greater proportion of East Kamchatka Current water relative to Okhotsk Sea water. (Ishikawa, 1988).

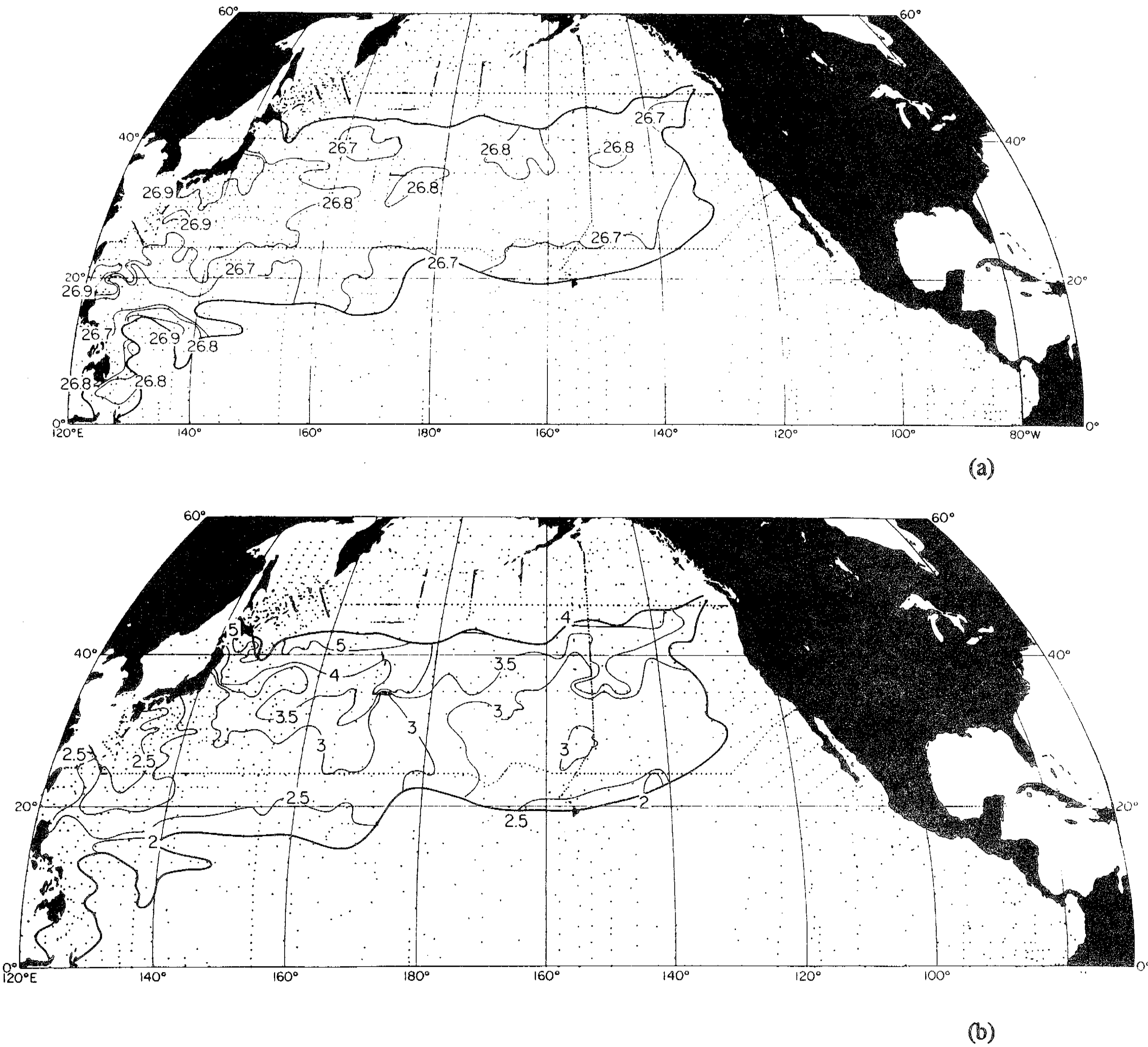


Fig. 2.5.26. (a) Potential density and (b) oxygen at the main salinity minimum of the subtropical gyre (Talley, 1993).

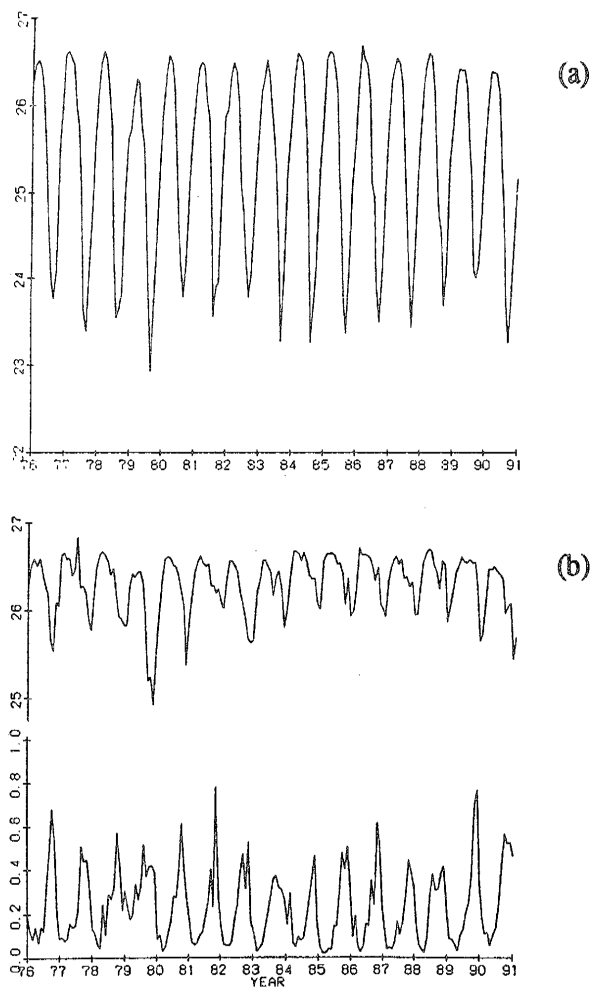


Fig. 2.5.27.

(a) Monthly-averaged density σ_t at 10 meters depth at 39° 30'N, 142°30'E just east of the northern coast of Honshu

(b) The same but at 100 meters depth, with its standard deviation (Nagata et al., 1993).

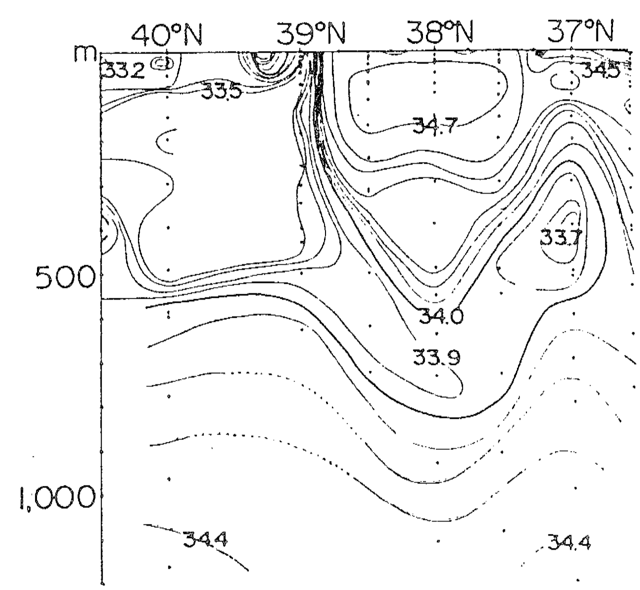


Fig. 2.5.28.

Salinity section in the mixed water region along 143°30'E in summer, 1979 (one of many examples in Mutoh et al., 1975), illustrating the salinity minimum found beneath the main warm core ring located between the Kuroshio and Oyashio.

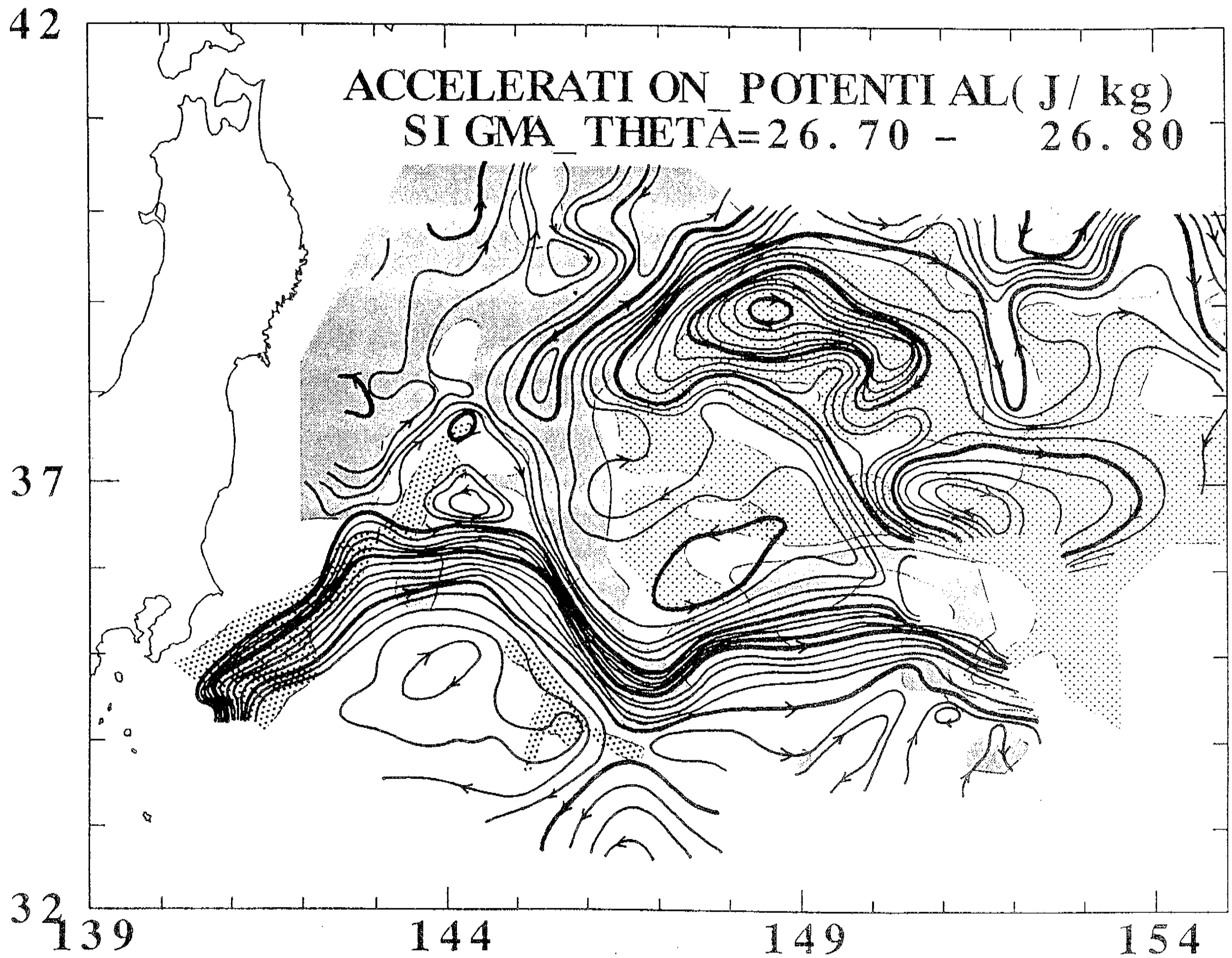


Fig. 2.5.29.

Salinity and acceleration potential relative to 1000 dbar at 26.7-26.8 σ_θ, in the mixed water region in May-June, 1992. The freshest water is seen to be pulled southward and into the Kuroshio axis (Yasuda et al., 1994).

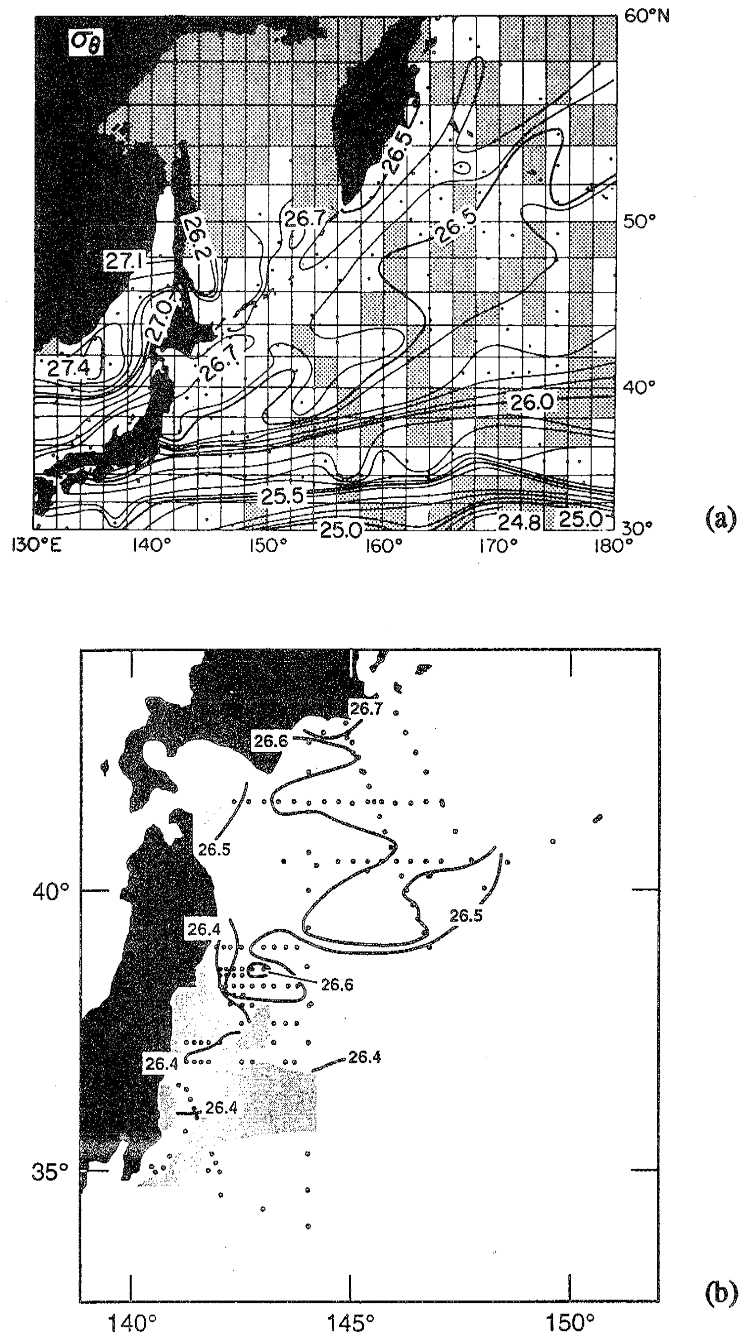


Fig. 2.5.30. (a) Maximum surface density in March based on all bottle data archived at WDCA (Talley, 1991).
(b) Nominal winter surface density based on density of the near-surface Brunt-Vaisala frequency minimum, from CTD data collected between April and June, 1989 (Talley et al., 1994).

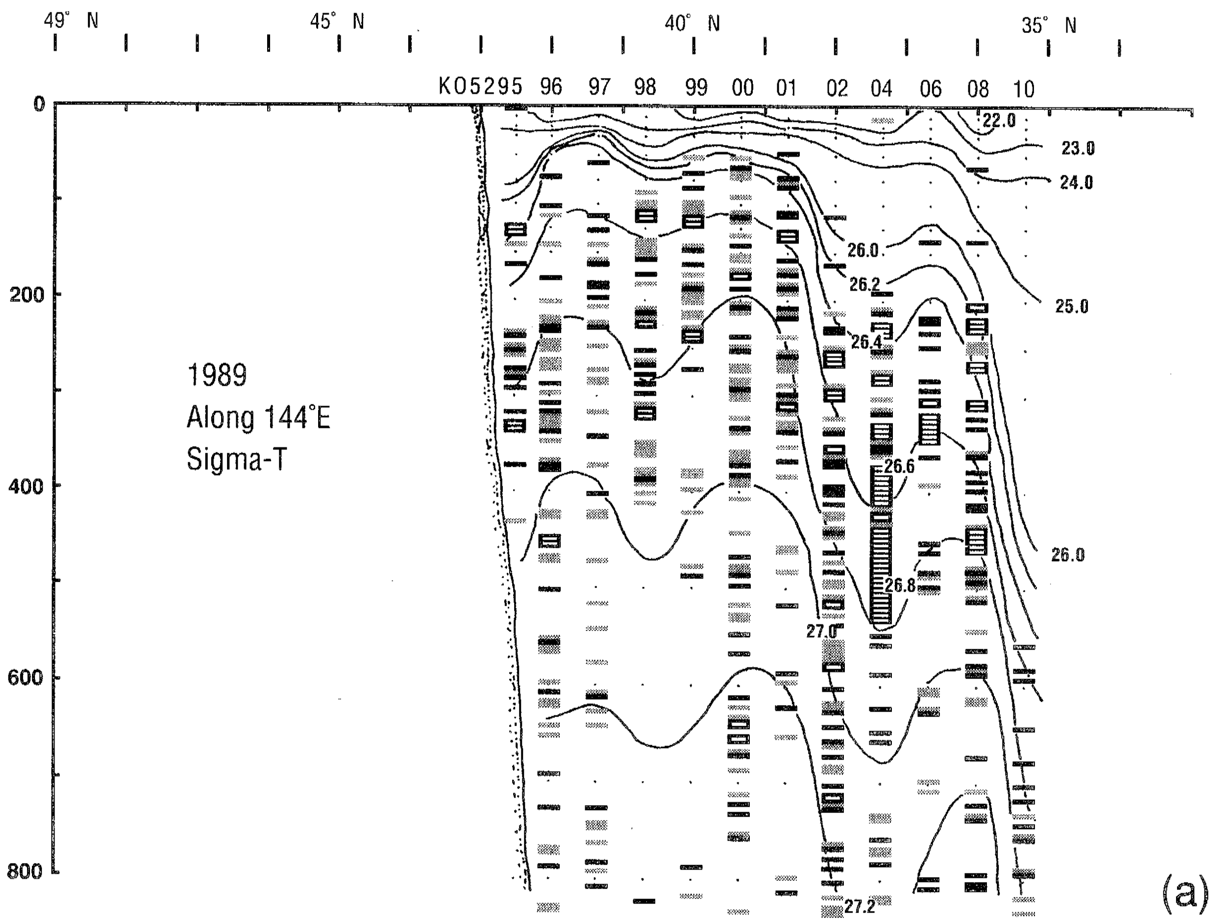


Fig. 2.5.31. (a) Strong diffusive layers (shaded) and strong salt finger layers (closed) on the 144°E section

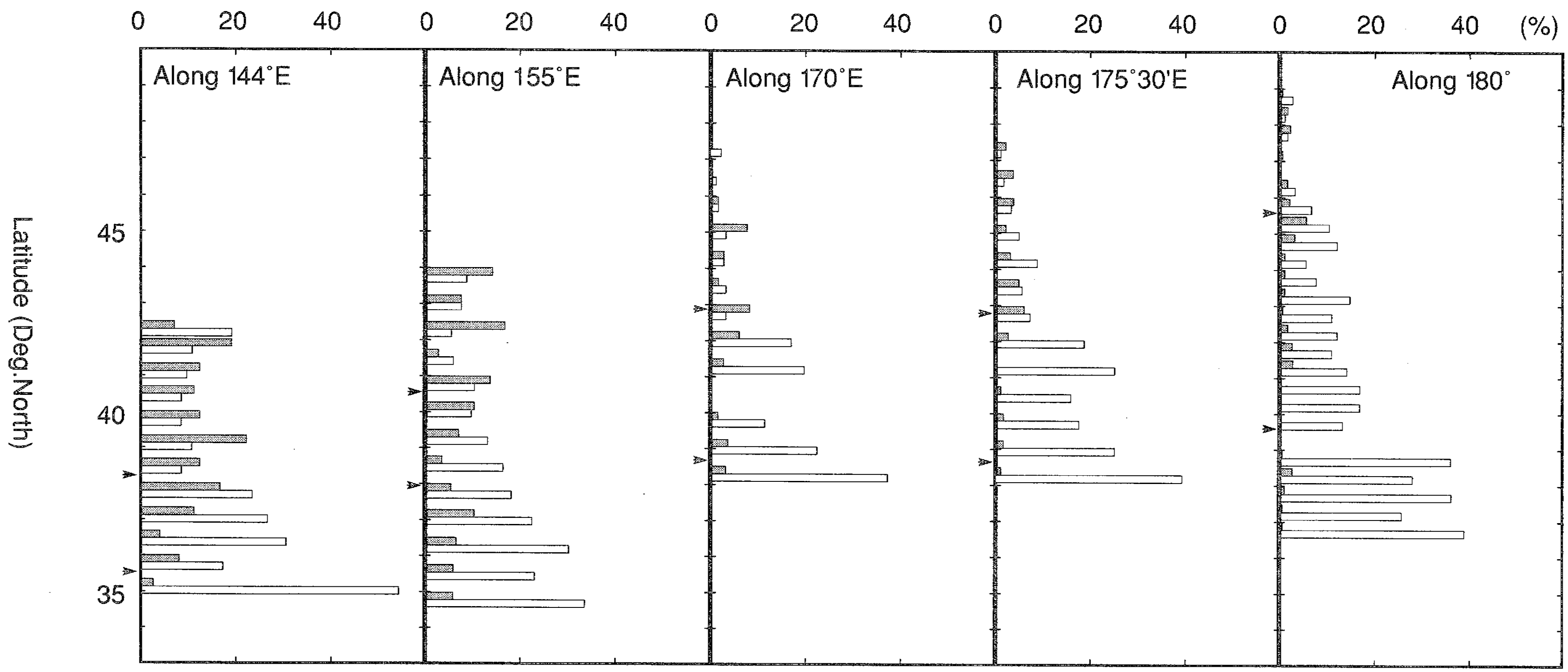


Fig. 2.5.31 (b) Incidence of density ratios indicative of strong double diffusive fingering as a function of latitude and longitude, based on high resolution CTD data (Shonai and Miyake, 1993).

6.0 REFERENCES

The bibliography is organized into four sections. The first three sections were prepared by Y. Nagata and L. Talley and comprise a special effort in collection of Japanese activities, but also include those papers published in other countries which are referenced in the report. If an English language version of a Japanese article was published, the Japanese language reference was omitted even if pubished earlier. The fourth section is a special collection of Russian activities, prepared by G. Yurasov, V. Lobanov and S. Gladyshev. Articles are in English unless noted.

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APPENDICES (A)

Acronyms

Institutions

FERHRI	Far Eastern Regional Hydrometeorological Research Institute (Vladivostok)
FERRC	Far Eastern Regional Receiving Center (Khabarovsk)
HRC	Head Receiving Center (Moscow)
IAPC	Institute for Automation and Process Control (Vladivostok)
JFA	Japan Fisheries Agency (Hokkaido branch in Kushiro, Hokkaido)
JMA	Japan Meteorological Agency (Hakodate Marine Observatory, Japan)
JODC	Japan Oceanographic Data Center (MSA) (Tokyo)
MSA	Maritime Safety Agency: Ocean Surveys Division, Hydrographic Department (Tokyo)
NOAA	National Oceanographic and Atmospheric Administration (Washington D.C.)
ODC	Oceanographic Data Center (Obninsk)
PMEL	Pacific Marine Environmental Laboratory (NOAA, in Seattle, WA, USA)
POI	Pacific Oceanological Institute, Russian Academy of Sciences (Vladivostok)
RHA	Regional Hydrometeorological Administration
ROC	Research Oceanographic Data Center of the Naval Hydrographic Service (St. Petersburg)
TINRO	Pacific Research Institute of Fisheries and Oceanography (Vladivostok)
WDCA	World Data Center A (Washington, D.C.)
WDCB	World Data Center B (Moscow)

Other

APT	Automatic Picture Transmission (AVHRR low resolution product)
AVHRR	Advanced Very High Resolution Radiometer (satellite instrument)
ESMR	U.S. Nimbus 5 electrically scanning microwave radiometer (satellite instrument)
GMS	Japanese geostationary meteorological (Himawari) satellite
HRPT	High Resolution Picture Transmission (AVHRR product)
IR	Infrared (satellite instrument)
MSS-M	Multichannel Scanning System of medium resolution
NPIW	North Pacific Intermediate Water
SLR	USSR "Ocean" side-looking radar (satellite instrument)
SMMR	U.S. Nimbus 7 scanning multichannel microwave radiometer
SST	Sea surface temperature

Institutions where Okhotsk Sea and Oyashio region data are held

Far Eastern Regional Hydrometeorological Research Institute (Vladivostok, Russia)
Institute for Automation and Process Control (Vladivostok, Russia)
Japan Fisheries Agency (Hokkaido branch in Kushiro, Hokkaido, Japan)
Japan Meteorological Agency (Hakodate Marine Observatory, Japan)
Japan Oceanographic Data Center (JMA, Tokyo, Japan)
Maritime Safety Agency (1st Regional Maritime Safety Headquarters, Otaru, Hokkaido, Japan)
National Oceanographic and Atmospheric Administration (Washington D.C., USA)
NOAA/Pacific Marine Environmental Laboratory (NOAA, in Seattle, WA, USA)
Oceanographic Data Center (Obninsk, Russia)

Pacific Oceanological Institute, Russian Academy of Sciences (Vladivostok, Russia)
P.P. Shirshov Institute of Oceanology RAS (Moscow, Russia)
Pacific Research Institute of Fisheries and Oceanography (TINRO) (Vladivostok, Russia)
Research Oceanographic Data Center of the Naval Hydrographic Service (St. Petersburg, Russia)
Sakhalin Regional Hydrometeorological Administration (Yuzhno-Sakhalinsk, Russia)
World Data Center A (Washington, D.C., USA)
World Data Center B (Moscow, Russia)

WG 1 Terms of Reference

With regard to the importance of the Okhotsk Sea and Oyashio Region to the ventilation of the North Pacific Ocean, such as the formation of the North Pacific Intermediate Water:

- Review the present level of knowledge of the oceanic circulation and water mass modification in the this area, and identify gaps in this knowledge;

- Review studies relating chemical, biological and geographical regimes, and encourage interactive understanding and planning of multidisciplinary experiments;

- Identify the scientific and logistical difficulties of ocean studies in the area;

- Encourage the planning of experiments and discussion of related physical processes in the area.

Members of WG 1 and additional observers who participated in the Nemuro WG 1 meeting, 19-23 September 1993

WG 1 members (* - attended Nemuro meeting):

Canada	Dr. R.J. Beamish Dr. Ed Carmack	China	Prof. Ming-Yu Zhou*
Japan	Dr. Makoto Kashiwai* Dr. Hiroyuki Yoritaka* Prof. Yutaka Nagata*	U.S.A.	Dr. Stephen C. Riser* Dr. Lynne D. Talley (Chairman)* Dr. John L. Bullister

Observers at Nemuro meeting who contributed to report:
Dr. Masaaki Aota (Japan)
Dr. Howard J. Freeland (Canada)
Dr. Toshihiko Kono (Japan)
Dr. Vyacheslav Lobanov (Russia)
Dr. Victor Sapozhnikov (Russia)

Also contributing to report:
Dr. Seelye Martin (U.S.A.)

Appendices (B)

The following reports are taken from the monograph Hydrometeorology and Hydrochemistry of the Seas, Vol.9, Okhotsk Sea. Part 1 - Hydrometeorological conditions. Gidrometeoizdat: Sankt-Petersburg, 1993, in press (in Russian)

RUSSIAN HYDROGRAPHIC STUDIES IN THE OKHOTSK SEA - HISTORICAL BACKGROUND

Vladimir A.Luchin

1. Temperature and salinity distribution

The first review on the Okhotsk Sea hydrography was written by L.I. Shrenk (1869, 1874). Later it was defined and developed by S.O.Makarov (1894). He prepared maps of temperature and density distribution at the surface of Okhotsk Sea. Makarov also noted an existence of cold intermediate layer as a result of surface water deepening due to winter convection, he found an upwelling areas off Koni-Piagina Peninsula and off Kuril Islands and mentioned large diurnal variations of water temperature.

First Soviet expedition was carried out in 1932 headed by K.M. Deryugin (joint expedition of TINRO and State Hydrological Institute). They obtained the main features of spatial temperature distribution in the sea.

The next stage started in the 50's with a few expeditions of r/v "Vityaz" of P.P. Shirshov Institute of Oceanology (Moscow). One of the main problems investigated in these expeditions and developed by following studies was the importance of Kuril Straits for the Okhotsk Sea hydrography and complex physical structure of water masses distributions and currents at the straits (Bogdanov, 1958; Ushakov, 1947; Bruevich et al., 1960; Batalin and Vasyukova, 1960; Yakunin, 1974; Peregudin, 1976; and Rumyantsev, 1974).

The thermal regime of the sea was studied by Vinokurova, 1964, 1965; Glagolieva and Kovalev, 1965; Tsapko, 1974 and Chernyavsky, 1973 while relations of hydrographic structure with hydrochemistry and biology was presented by Ushakov, 1947; Bruevich et al., 1960; and Kharitonova, 1965; a role of heat balance components in the sea hydrography - Batalin and Vasyukova, 1960; Yakunin, 1974; convective mixing and an active layer structure variability - Tyuryakov, 1970; Dobrovolsky and Vladimirtsev, 1973.

Besides that the Okhotsk Sea hydrography was summarized in the monographs by Leonov, 1960; Moroshkin, 1966; and Supranovich, 1969. Studying the water masses distribution Leonov (1959, 1960) found an influence of Pacific water inflow, continental discharge and atmospheric precipitations on water mass characteristics and classified T,S-indexes of the sea water masses. Having a larger data set (about 11,000 stations) Moroshkin (1966) defined water mass parameters and described more exactly boundaries between the water masses. He was the first who showed an existence of a second layer of temperature minimum at the depth of 250-600 m.

From the second half of the 60's and till the end of 70's an observational activity in the Okhotsk Sea was stopped, however the data summarizing and analyzing were still going on. L.I. Veselova studied vertical temperature stratification and made an attempt to calculate the coefficient of vertical temperature diffusion (Veselova, 1972a), added information on spatial distribution of surface temperature and explained some local peculiarities of it (Veselova, 1972b). She also studied temporal variations of water temperature of different scales including annual cycle of SST in southern part of Okhotsk Sea (Veselova, 1975) and forecast of thermal regime (Veselova, 1974).

An influence of Amur river discharge on temperature and salinity distribution of adjacent areas of Okhotsk Sea (including Sakhalin Bay) was investigated by G.A. Tsapko (1974). It was shown that two maxima and minima are present in an annual cycle of surface salinity which are connected with ice melting and with inflow of river floods. The first salinity minimum in Sakhalin Bay occurs in June and the second in September, while the maxima are in late July-early August and in February-March.

On the basis of 150 cruises (4,617 hydrographic stations) T.I. Supranovich (1973) studied seasonal variability of water mass structure in the Kuril Straits and surrounded areas of Okhotsk Sea and Pacific. T,S-indexes of three water mass types present in the area were defined and their transformation from season to season was traced. It was found that the lower boundary of an intermediate cold layer is deepened down to 400 m in the straits and no minus temperature observed there.

Since the second half of the 70's, large scale observational studies in the Okhotsk Sea were started again with governmental programs, "Shelf" and "The Seas of the USSR". Research vessels of State Hydrometeorological Committee conducted hydrographic cruises (the majority of stations were with full hydro-chemistry) both in summer and winter seasons. The quality and amount of TINRO observations were also increased. Academy of Sciences and Naval Hydrographic Service carried out special observational experiments. A database of more than 50,000 stations have been collected by FERHRI and analyzed and published in the monograph, Hydrometeorology and Hydrochemistry of the Seas, Vol.9, The Okhotsk Sea. Gidrometeoizdat: Sankt-Petersburg, 1993 (in press).

General circulation

The first scheme of Okhotsk Sea surface currents presented by Shrenk (1869, 1874) was based on a different sort of observations over the 100 years period including ship, ice and timber drift, some climatic phenomena and a few (not many) water temperature measurements (Fig.1). It was criticized by S.O. Makarov (1894) especially the existence of a southward current along Kamchatka coast and the southwestward flow from Shelikhov Bay to the northern part of Sakhalin Island. Using data on water temperature and summarizing the experience of navigators and fishermen Makarov pointed out that wind stress and the Koriolis force on sea water circulation should form of a gyre. M.E. Zhdanko (1910) found the same thing. Studying the tracks of drifting bottles he showed a northward current along Kuril Islands and western Kamchatka.

B.V. Davydov (1923) essentially defined the circulation pattern by demonstrating that northward current along Kamchatka (Makarov, 1894) does not come close to the coast but flows at a some distance of it. So a compensation southward current with water of lower temperature exists in a narrow zone (20-30 miles) just off the coast of Kamchatka to the south of Utkolonsky Cape.

The results of the expeditions in 1932-1933 and some previous data on current measurements in the Kuril Straits were the basis for Leonov (1959, 1960) circulation scheme (Fig.2). He constructed the complete cyclonic gyre over the whole Okhotsk Sea. This stationary gyre is maintained by the annual northwestern winds (southward currents) and compensation inflow from Pacific Ocean.

Moroshkin (1964) presented more detailed circulation pattern calculated on about 11,000 hydrographic stations (Fig.3). On the large scale cyclonic gyre background he constructed three stable local anticyclonic gyres: to the west of southern Kamchatka, over the Kuril Deep Basin and over the TINRO Deep Basin. He noted the barotropic character of the currents.

The main features of Moroshkin's pattern were confirmed and some new features were found by Pomazanova (1970), Kozlov (1972), Zyryanov (1977) and Luchin (1982). In particular, the existence of stationary and migrated mesoscale eddies was demonstrated and the existance of small-scale anticyclonic eddies in Kamchatka coastal areas of river mouths was confirmed by direct current measurements (Pomazanova, 1970).

The results of Magadan Branch of TINRO expeditions of more then 8,000 hydrographic stations were used by Chernyavsky (1981) to calculate geostrophic currents of Okhotsk Sea circulation. He presented a more detailed analysis and found some new structures, for example, the Middle Current which departs from Kamchatka Current at 52°N and turns westward to Sakhalin Island. He also noted the stability of coastal currents that produce convergent downward motion and downwelling of warm surface water in summer.

Currents in the Kuril Straits

Investigation of non-periodical currents in the area of Kuril Straits was started by L.I. Shrenk (1869, 1874). According to his scheme a current flowing along Kamchatka coast from Shelikhov Bay enters the ocean through the First and Second Kuril Straits. Pacific water flows into the Okhotsk Sea through the straits between Simushir and Onekotan Islands while water flows out of the sea through the southern straits. In the upper layer of Bussol' Strait there is a seaward current in its northern part and a backward flow in southern part. Along the whole Pacific coast of the islands the currents have a south westward direction. In general this scheme is very close to contemporary views.

Shrenk explained the low temperature zone around the islands as a result of cold water advection by the south westward currents flowing along the islands from Kamchatka coasts. (Another explanation for this phenomenon is the result of tidal mixing was presented by Makarov (1894)). Analyzing the possible tracks of drifting bottles deployed in Okhotsk Sea over 1907-1910 Zhdanko (1910) affirmed the existence of a northward current along the sea side of the islands.

Studying the north eastward area Davydov (1923) also noted an outflow of Okhotsk Sea water through the First and Second Kuril Straits pointed out by Shrenk.

Summarizing previous results and analyzing direct current measurements and water mass distribution of 1932-1952 Leonov (1941, 1959, 1960) and Zhukov (1954) found the Kuril straits consisted of the three parts: through the northern straits the main flow is directed into the sea while through the southern straits it is oceanward and it is in both directions in the straits of the central part of Kuril Islands. Zhukov (1954) also found the water flowing out of the Okhotsk Sea through the southern Kuril Straits is the main source of the Oyashio Current.

Direct current measurements in the Kuril area were summarized and analyzed by Supranovich (1969). It was found that there are no straits with only one direction flow. Water flows into the sea through the northern part of each strait and flows out to the ocean through the southern part. Outflowing water is carried southwestward by the Oyashio Current and an anticyclonic circulation is formed around each island. Direct current measurements were taken down to 500 m and showed no significant current variability with depth.

Current measurements down to 1,200m taken from moored stations in winter in the 70's (Supranovich, 1975, 1979; Luchin, 1982b) showed that the flow in Bussol' and Kruzenshterna Straits changes direction to opposite down from the depth 400-500 m. An intensification of the Okhotsk Sea water outflow was found through central and southern straits in winter. No seasonal variations of the current field in the 4th Kuril Strait were found.

SYSTEM OF CURRENTS AND PECULIARITIES OF TEMPERATURE DISTRIBUTION IN THE OKHOTSK SEA

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1. Introduction

The large-scale spatial distribution of hydrological characteristics for different seasons in the Okhotsk Sea have been studied rather well, and factors responsible for them have been analyzed /1,4-8,12,14,15,17,21,25/. We have a true understanding on the vertical parameters structure at the sea /8,12,15,20/. An attempt to compile the prognostic dependences characterizing the changes in water density conditions have been made /2,3,20,22/. However, the problems of characteristic variability at different scales have been poorly studied. By these observations daily variability in the active layer of the Okhotsk Sea can be compared with the annual one. The problem of revealing the hydrological seasons and the lower boundary of the active layer has not been studied in full measure.

Data of the instrumental current measurements (approximately, 1,000, mainly daily recordings) are not sufficient to represent the whole picture of the Okhotsk Sea water movement (Fig.1). Such data are irregular and have been obtained, as a rule, in the summer period. Our observations cover only the periphery regions of the sea, but it is impossible to get characteristics of the annual current variabilities for them.

The complicated bottom topography and the dynamical processes in the island shelf zone of the Kuril range hamper the current system analysis (within one model) of the Okhotsk Sea. The sea currents and currents along the Kuril Island arc are traditionally considered different.

The current characteristics in the region of the Kuril Straits and along the sea water areas, directly adjacent to them, have been studied by many authors on the basis of a constantly (continuously) supplemented instrumental observation /9,12,15,16,24, Supranovich, 1969/. For the Okhotsk Sea, besides a generalization of the instrumental measurement /15,16/, the traditional current calculations, based on the density field, (known from observation) have been conducted /13,15,23/. Within the frame of different theoretical models attempts have been made to determine the causal and resulting dynamical processes occurring in the sea and atmosphere /1,10,11,15/. All authors of the current schemes, with the exception of S.O. Makarov /14/, emphasize that the atmospheric circulation is essential in the circulation current formation, directed counter-clockwise, in the Okhotsk Sea.

The present study was carried out within a frame of the project "Seas of the USSR". After implementation of this project the scheme of the Okhotsk Sea water circulation was obtained, the results of diagnostic calculations and data of instrumental current measurements were put in the basis of this scheme. The vertical structure peculiarities and spatial changes of hydrological and hydrochemical parameters distribution at the standard levels have been studied as well. Individual aspects of daily, annual and inter-annual characteristics variabilities have been considered. The charts have been created, the peculiarities characterizing the boundary position and temperature, and salinity distribution in the sea water cores have been analyzed.

2. Data and method

The information on the deep-sea hydrographic observations along the Okhotsk Sea from 1930 up to 1988 served as the initial data to carry out the present work. The total number of implemented stations is estimated to be 51,607. The monthly data spatial distribution is demonstrated in Fig. 1.1.3 while the data distribution is shown in Table 1. The data set has been sorted out in the spherical trapezia of one degree size. The assumed trapezium dimensions were substantiated by the density distribution of the initial information along the studied sea water area. For temperature, salinity, and sea water density in the active layer, monthly and seasonal data averaging has been undertaken. At the lower levels annual mean averaging has been considered within the seasonal scale of the initial data averaging.

One thousand, mainly daily, current observation data have been used. More than a half of them have been conducted in the region of the Kuril range. The observations were conducted either at the autonomic buoy stations or on board anchored ship. The total currents were divided into the tidal and non-periodic compositions. A major part of the instrumental observation results was processed and summarized (generalized) earlier in N.P. Pomazanova /16/ and T.I. Supranovich, 1969. Within the frame of the present work the data from 67 observational stations, located in the Kuril region, were processed. The period of current records is estimated to be 3-8 days.

Applying A.S. Sarkisyan's model D1 /18/ and the created charts of sea water density from the surface down to the bottom levels of the Okhotsk Sea Current scheme has been calculated. Monthly density has been used in the layer of 0-100 m, seasonal means in the layer of 150-250 m, and nonvariable estimation of water density during a year starting from 300 m down to the near bottom levels have been calculated. The atmospheric pressure fields have been taken from I.P. Timofeeva's work.

3. Currents

The results are evidence that the basic elements of a level surface topography exist during a year. The main peculiarity of the Okhotsk Sea water circulation in the Northern hemisphere is its cyclonic character. The main links of the general cyclonic gyre are: (Fig.2) the Kamchatka Current transporting the Pacific waters to the north along the meridian of 152°E, the North-Okhotsk Current moving along the northern sea coast and the East-Sakhalinsk Current is a flow of the cold southern waters along the Sakhalin Island coast.

Against a background of the general cyclonic movement in the open sea regions, the system of eddy formation is of different scale and sign. The eddy scale is estimated to be approximately 150-200 miles. In the eastern and southern sea parts, adjacent to the coast of Kamchatka Peninsula and the Kuril Islands, the eddy formation is anticyclonic, and in the north-west they are the cyclonic (Fig.2).

The Pacific waters enter through the straits of the Kuril range (from the Fourth Kuril up to the Strait of Ekaterina). However, their direct influence on the sea water dynamic is limited to the great extent by the southeast periphery of anticyclonic circulation over the southern deepsea hollow. Only the Pacific water penetration through the Bussol' straits and the Fourth Kuril give an essential contribution to the south and south eastern current formation (Fig. 2).

A comparison of calculations and current measurements (400 examples) in the warm period of a year was conducted. The current vectors, obtained with the current measurements, do not contradict the Okhotsk Sea movement (Fig. 2). However, in consequence of different temporal scale averaging of the current measurements and the initial fields for the diagnostic calculations, the results are considered to be preliminary.

To build the chart of non-periodic currents in the region of the Kuril range (Fig. 3), data measure-ments for the period of 1949-1977 have been used. As the measurements were conducted in different months and years, the assumption was that the basic elements of water circulation preserve their feature during a year and are not characterized by the interannual variabilities. T.I. Supranovich's results from 1969 show that the basic regularities of water movement do not change during a year and from year to year in the strait narrows of the Kuril range. On the Pacific side of the Kuril range, starting from the First Kuril Strait to the Ekaterina Strait the Kuril Current transports the cold water to Hokkaido Island (Fig. 3).

The data show that the anticyclonic water circulations are formed around the large islands of the Kuril range (or around the groups of not large ones). Thus, the water movement in the strait narrows of the Kuril range is characterized by the Okhotsk Sea water outflowing in the ocean through their southern parts, and the Pacific water inflowing takes place through the northern ones. The First Kuril, the Second Kuril and the Middle Straits, where the water transport in one direction is observed, are the exception (Fig. 3).

It should be noted that very strong tidal currents were recorded in the region of the Kuril range, their velocity at the individual strait parts can reach (particular, in shallows) 5-7 knots. The tidal current at a major part of the Kuril range have a combined character with a diurnal component prevailing (Fig.4). Fig.5 shows the parameters of maximal tidal currents: the main axis of a tidal ellipse direction and the maximal current speed. Analysis of current measurements in the Kuril Straits from 40 moorings with 7-8 days duration of individual records revealed that a current vector rotates with depth by the angle of no more then 10-30 degree and only in Bussol' strait it may turn by 40- 90 deg. No conformity to any law for the direction of current vector rotation with depth in different straits was found. As the non-periodic currents are not an essential part in the total currents in the Kuril region, the represented non-periodic current scheme (Fig. 3) will essentially differ from the actually existing resulting water movement at a specific moment of time.

4. Temperature distribution

From previous studies /1,6-8,12,14,15,17,21,22/, the state of Okhotsk Sea water, to a great extent, depends on the dynamical processes occurring at its boundaries and in the deep water layers of open area. The advective factors prevail along the studied area, as well the vertical and lateral tidal water mass mixing in the dynamical active regions.

The annual variabilities of sea surface temperature fields are evidence that two periods are distinguished at the sea; they differed by the large-scale peculiarities of the sea water temperature distribution. As a criterion for such periods and transition situations, it is assumed the thermal state of the Kuril range region is related to the temperature field of the rest part of the Okhotsk Sea (Fig. 6). From December to April the formation of high temperature values in the mentioned region is observed because of the Pacific water entering. Also, the increased temperature is observed in the Kamchatka Current (Fig. 2, 6a). Such distribution is mainly related to the more high temperature of the Pacific surface water. Furthermore, the intensive vertical water exchange in the range straits (against background of the thermal cooling of the sea surface water during this period) leads to heat transport from the lower level up to surface. With the Pacific water extension and mixing with the Okhotsk cold waters, gradual decreasing of the sea surface temperature has occurred (for example, Fig. 6a).

From June up to September the large-scale distribution of the Okhotsk Sea surface temperature is opposite to the winter one. In this period light winds and calms have the highest frequency over the considered water area. Therefore, in the shelf regions where the seasonal thermocline is the most pronounced and is located near the sea surface, the sea surface temperature is the highest. The lowest temperature values are observed in the dynamical active regions (the Kuril range, enter to Shelikhov Bay and adjacent sea water areas). Characteristics exchange between the surface and lower layers leads to heat transmission down to lower levels and to more weak heating of the surface water (for example, Fig. 6c).

The transition of the surface temperature distribution is noted in May, October and November. During these months the thermal contrasts between separate sea parts disappear. In spring (Fig. 6b) the coastal water freshening, gentle breeze over the sea, and the surface formation of a pronounced thermocline lead to quick surface water heating. In the dynamical active regions, intensive mixing of the surface and subsurface water mass resolution the surface waters being warmed slowly.

Insignificant heat content of the upper quasi-homogeneous layer in the shelf regions increase probability of storms and the low air temperature over the sea contribute to an intensive heat exchange in the atmosphere during the autumn season. In the intensive water mixing zones (the Kuril range and the southern sea part, enter to Shelikhov Bay, the area of the Shantar Islands), where the heat exchange from the lower level up to the surface has taken place, the sea surface temperature in autumn is comparatively high. The whole mentioned processes lead to thermal contrasts smoothing between the separate sea parts (Fig. 6d).

The estimation distribution of annual sea temperature oscillations at the surface and at the level of 50m is presented in figure 7a, b. The variations, to great extent, are defined by the intensive dynamical processes in the separate sea parts. The maximum values (14-18°C) are referred to the area of the warm Soya Current extension and to the areas of an insignificant vertical and lateral water mass exchange (North and central sea parts, as well the East-Sakhalin Current zone). The dynamical active sea regions, annual variability of the sea surface temperature decreases to 6-9°C. At the level of 50m the large-scale peculiarities of annual temperature changes do not differ from the surface ones, however, their values decreases in 2-3 times (Fig. 7a, b).

Different intensity of the thermal-dynamical processes in the remote sea parts leads to the spatial inhomogeneous distribution of the sea surface maximum heating and cooling (Fig. 7c, d).

The reason for the sea surface maximum temperature lag in the region to the east of Terpenie Cape (it comes in September), more probable, is river run-off. This factor, though to less extent (in relation to the tidal mixing) occurs in the region of the Shantar Islands (Fig. 7 c).

One of the basic features of the Okhotsk Sea structure is the cold intermediate layer which is formed as a result of the winter-autumn cooling. In the autumn-winter period of maximum convection development, its core wedges in the surface, and in spring it becomes the subsurface layer. The summer warming-up is not sufficient to destroy the cold intermediate layer completely. Only annual variability of its vertical extension and core characteristics is observed.

In August (it is a period of the most vivid occurrence of the cold subsurface layer) the lowest temperature and the closest locations of its core to the surface are observed in the points of the cyclonic gyre location (north-eastern of the Shantar Islands, center of the north sea part to the east of the Sakhalin Island). In the direction of Kamchatka Peninsula and the Kuril Islands the temperature values and the depth of its core location increase (Fig. 8a,b).

The peculiarity of the Okhotsk Deep Sea Water is the presence of Pacific origin temperature maximum in it. With the extension and the Pacific and the Okhotsk waters mixing, the temperature values decrease, and the depth of the warm intermediate core location increases. The temperature minimum in the most southern sea part, probably, is a result of downwelling of the colder upper level waters in the system of anticyclonic circulation (Fig.8c, d). Below the deep sea maximum temperature layer, slight decrease occurs, and at the near bottom levels of the Okhotsk deep-sea hollow the water temperature does not exceed 1.6-1.8°C. To the present it is very difficult to determine the regularity of the spatial temperature variability near bottom levels. It is due to insufficient high accuracy observation data.

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* - All the main references above are presented in a translated and corrected form in the Bibliography of the Okhotsk Sea except such ones as Supranovich,1969 and Luchin, 1982b, which are not available for foreign readers.

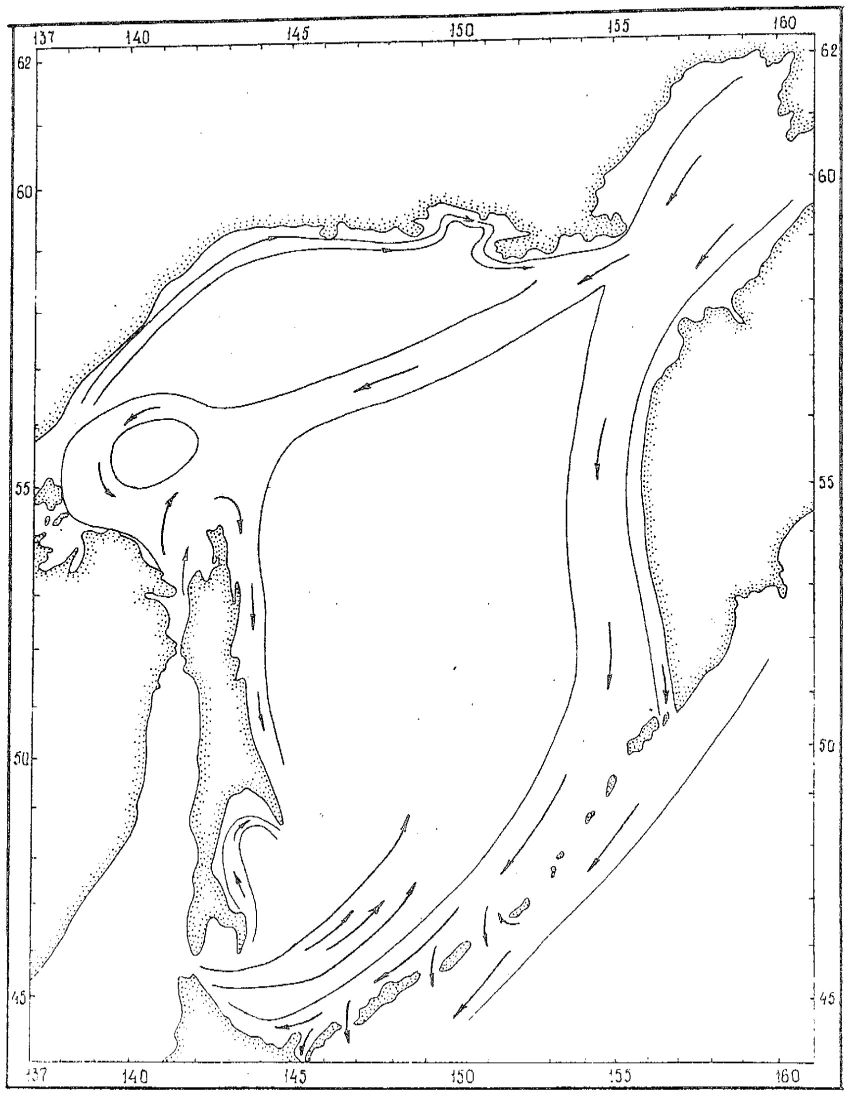

Fig. 1. Scheme of the Okhotsk Sea circulation by L. I. Shrenk (1874)

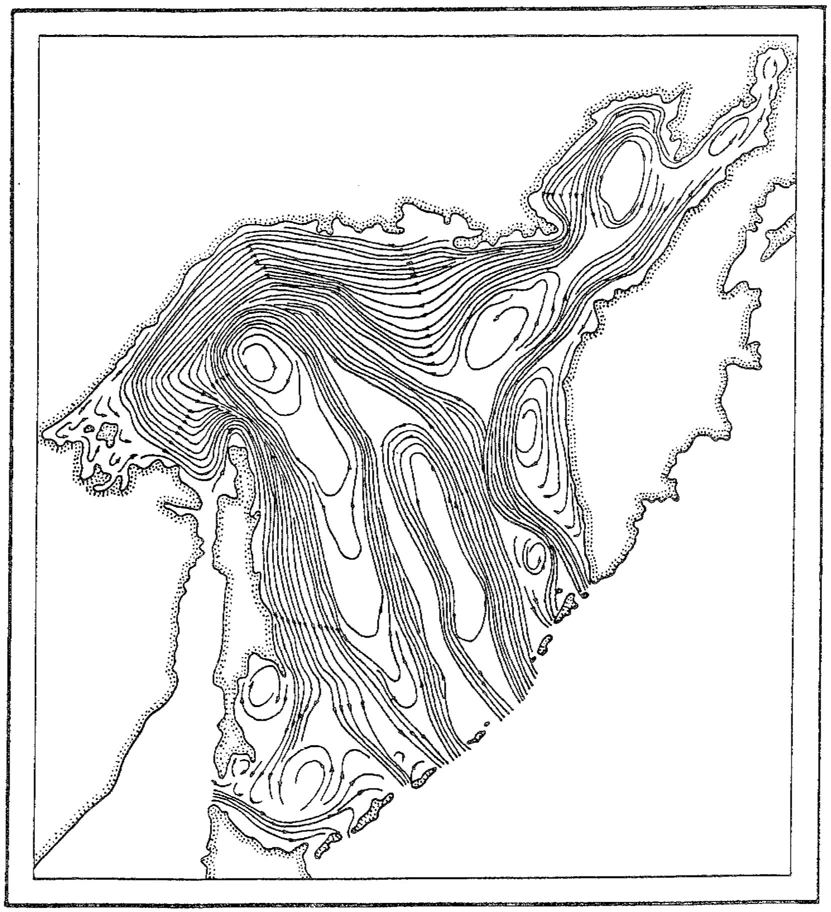

Fig. 2. Circulation scheme by A. K. Leonov (1960)

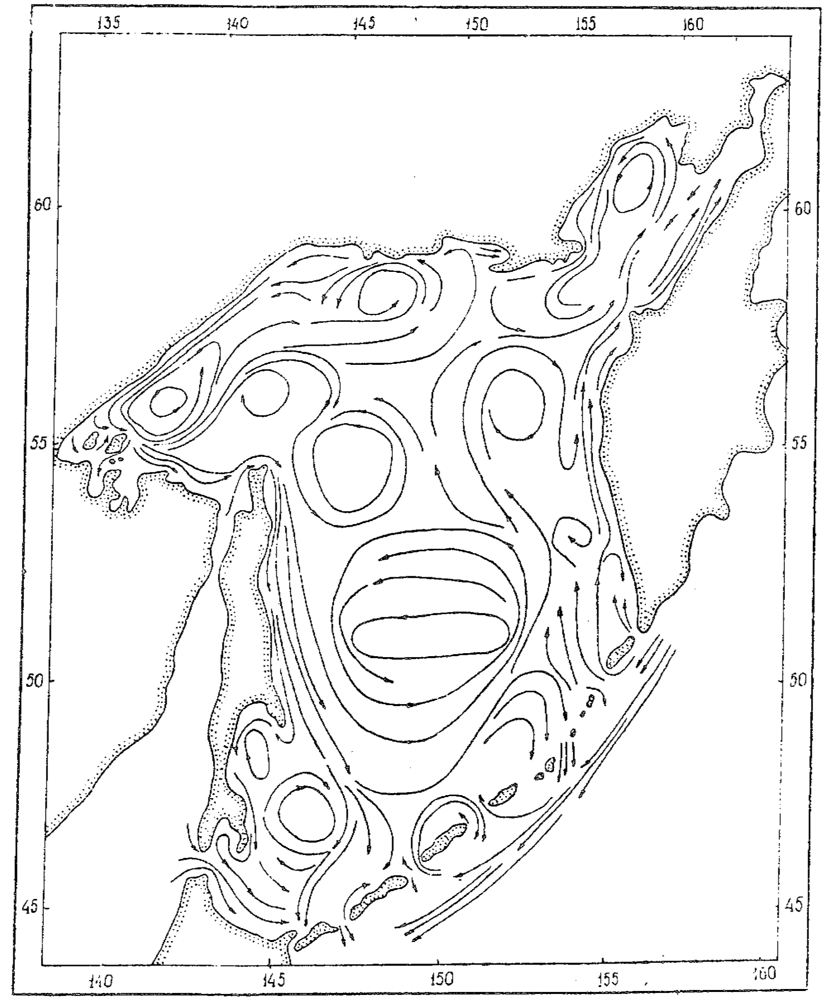

Fig. 3. Current scheme by K. V. Moroshikin (1966)

Table 1
Annual distribution of hydrographic observations (T/S) in the Okhotsk Sea

	MONTH												
Depth	1	2	3	4	5	6	7	8	9	10	11	12	Total
0	801	1021	1184	2375	3720	7923	9545	10409	6390	4503	2269	1467	51607
	259	429	408	961	2218	5318	6724	7693	4172	2896	1644	1082	33798
100	443	646	684	1017	1741	4009	4157	4103	2723	2147	1293	973	23936
	185	337	303	462	1395	3228	3289	3083	1845	1471	1048	879	17525
200	240	447	492	528	1023	2638	2361	2215	1536	1190	766	644	14080
	129	283	260	313	863	2343	1905	1700	1119	866	663	585	11029
500	74	106	119	115	449	1015	980	920	478	571	279	242	5348
	73	96	113	108	415	953	852	740	353	455	268	243	4668
1000	39	7	48	36	155	439	320	286	132	187	167	121	1931
	42	7	47	68	155	317	303	262	116	160	159	115	1751
1500	23	3	27	11	73	207	96	158	51	68	56	75	848
	23	3	25	23	72	200	95	122	51	63	48	59	784
2000	10	-	7	1	46	134	27	39	14	33	30	37	378
	10	-	5	2	44	122	24	37	15	33	27	29	348
3000	-	-	-	-	17	32	8	10	2	16	4	8	97
	-	-	-	1	17	31	8	10	1	16	5	8	97

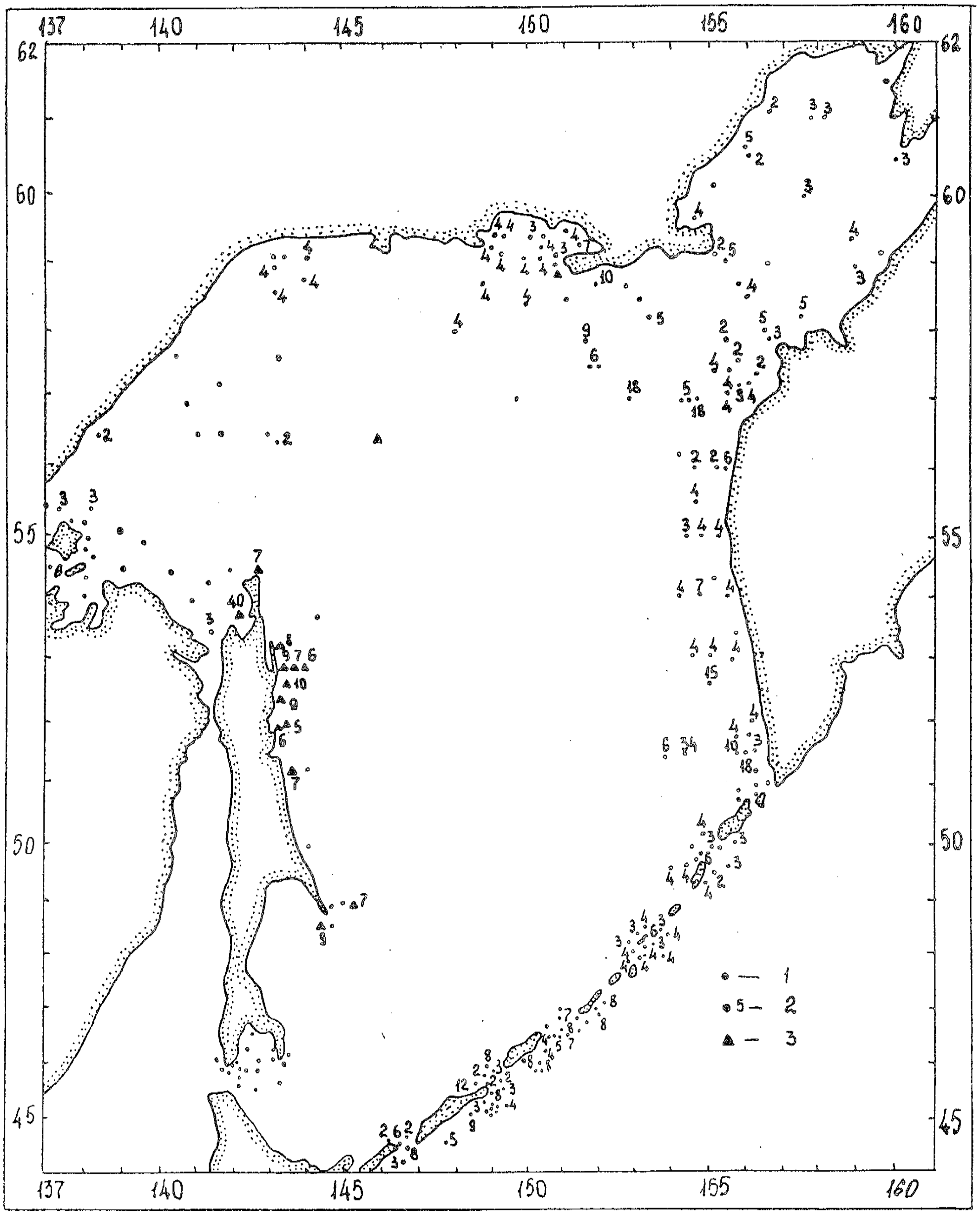

Fig. 1. Position of direct current measurements
1) duirnal station; 2) number of duirnal stations at one point; 3) multiduirnal station

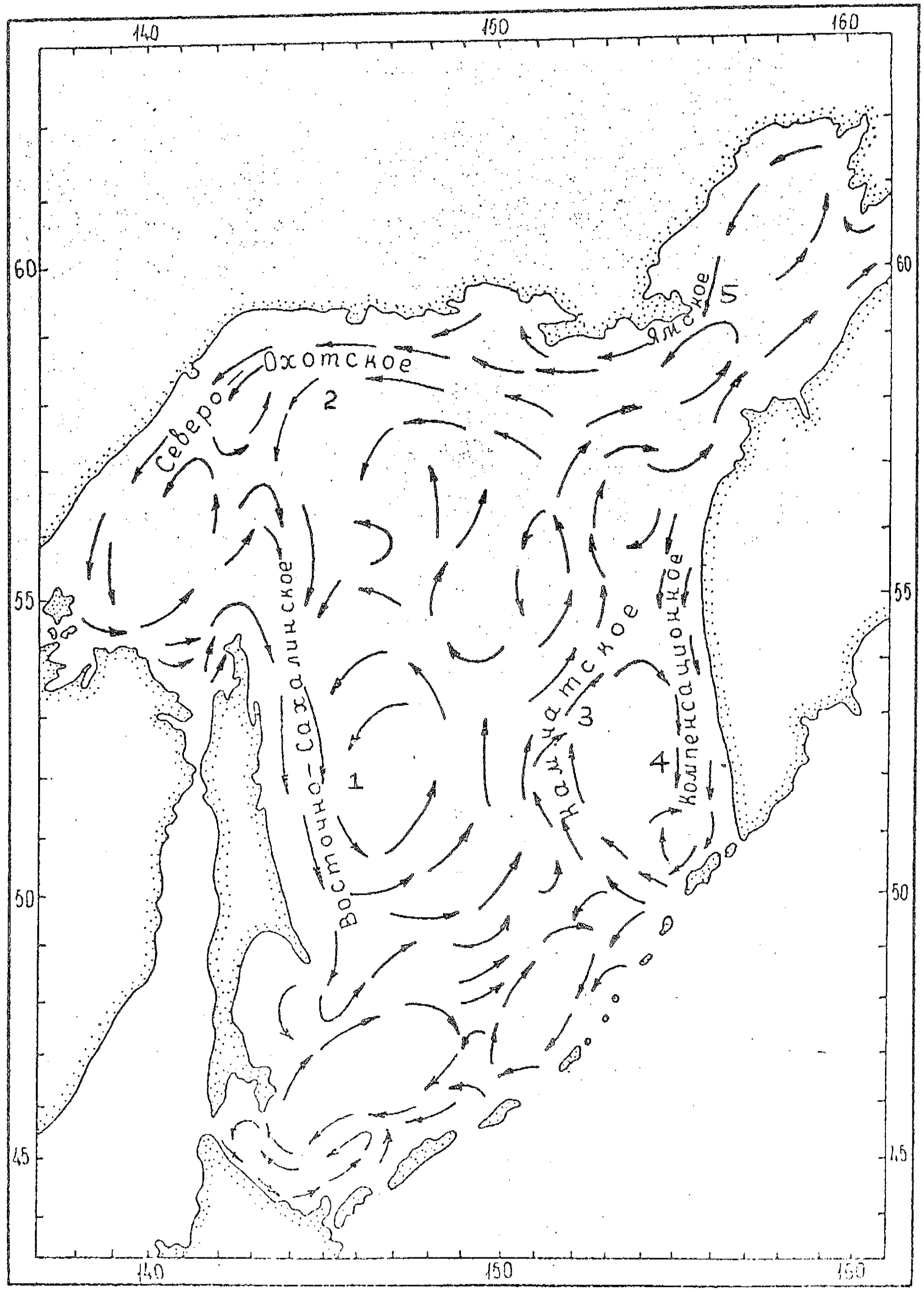

Fig. 2. Generalized scheme of the Okhotsk Sea circulation
Russian words are names of currents:

1 - East-Sakhalin
2 - North - Okhotsk
3 - Kamchatka
4 - Compensational
5 - Yamskoe

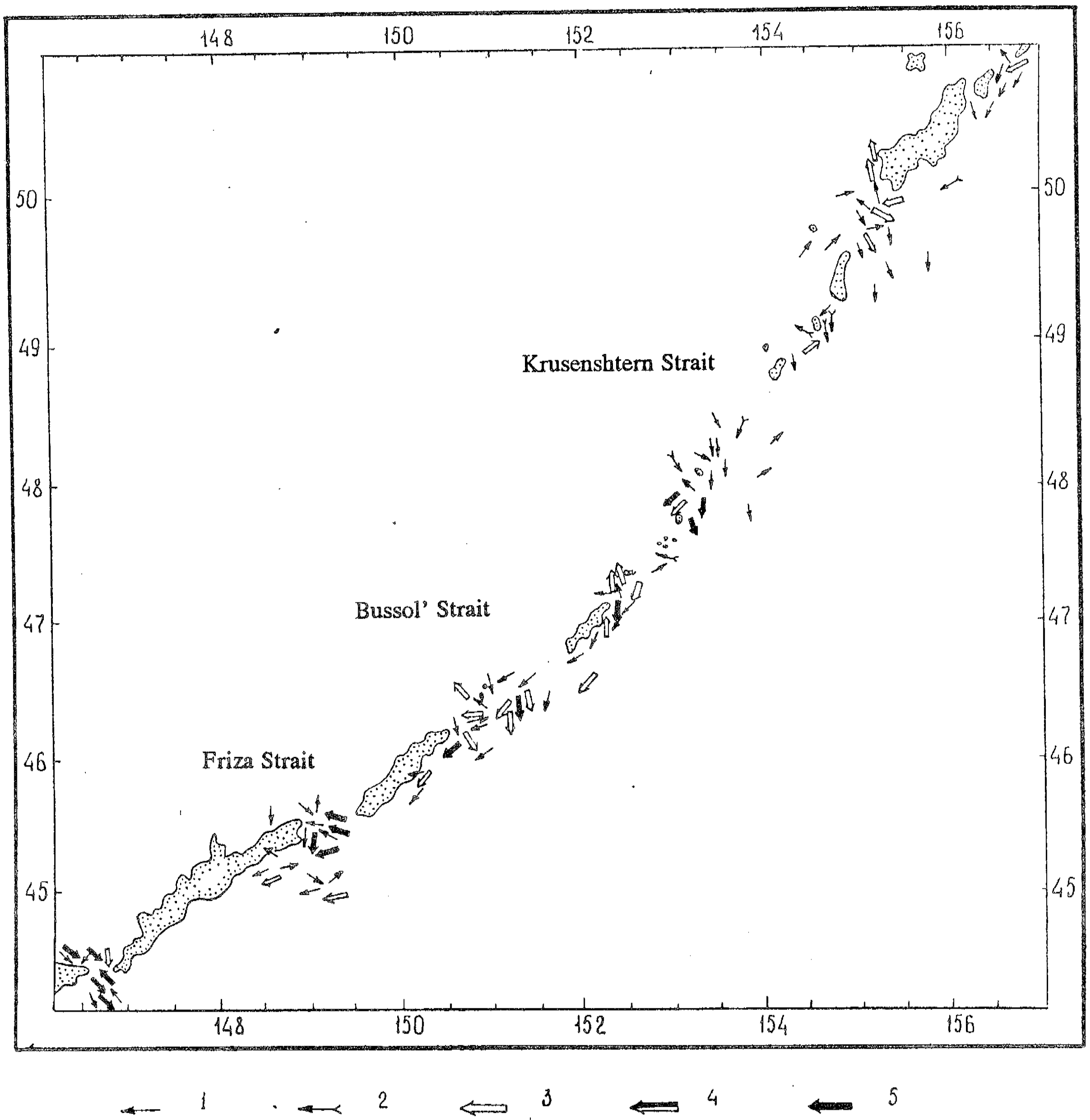

Fig. 3. Non-periodical currents in the shelf area of Kuril Islands
1) less than 10 cm/s; 2) 11-20; 3) 21-30; 4) 31-40; 5) 41-50

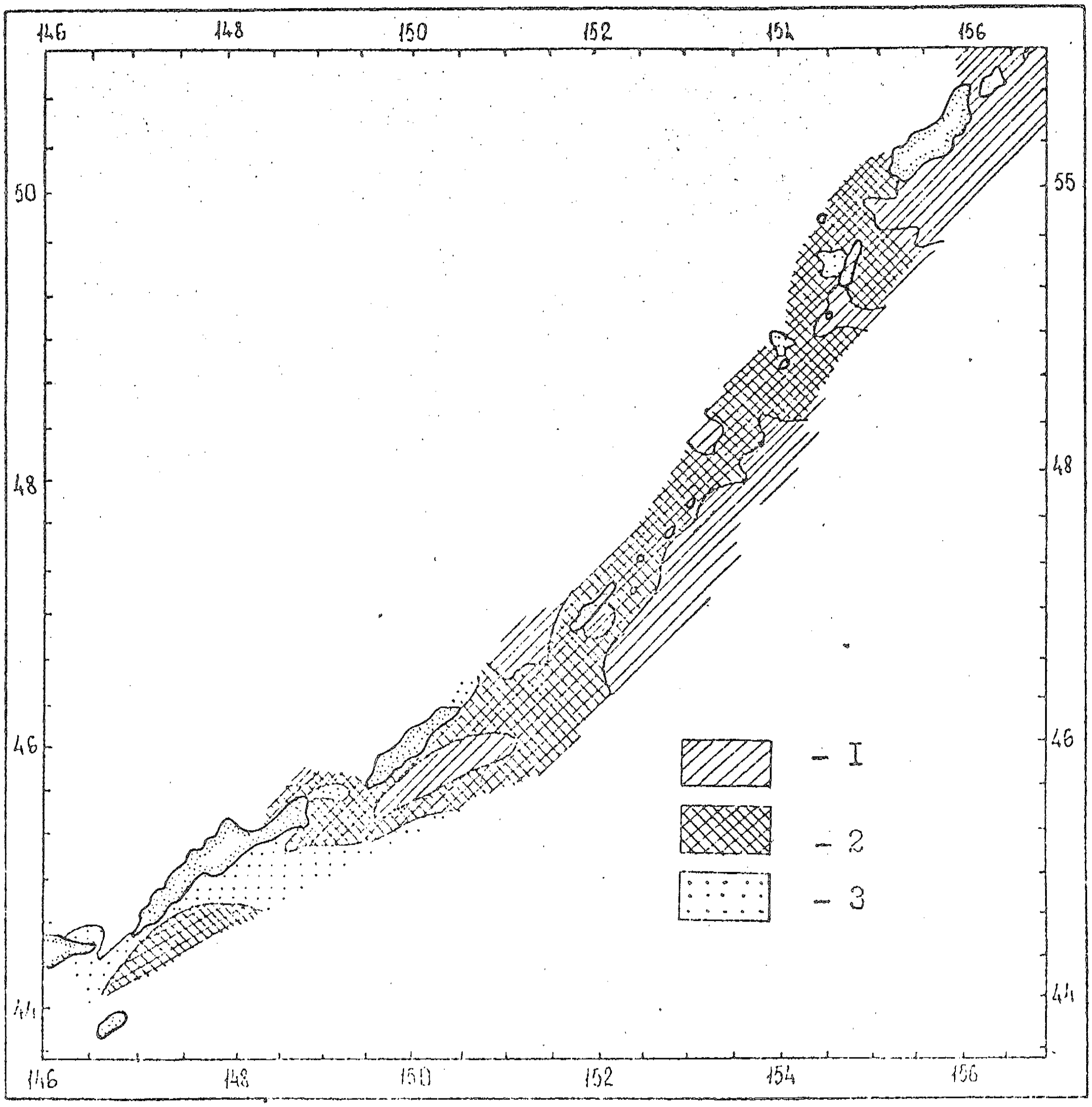

Fig. 4. Type of the tidal currents (in 0-25 m layer)
1) complex with prevailing semidiurnal tides; 2) complex with prevailing diurnal; 3) diurnal

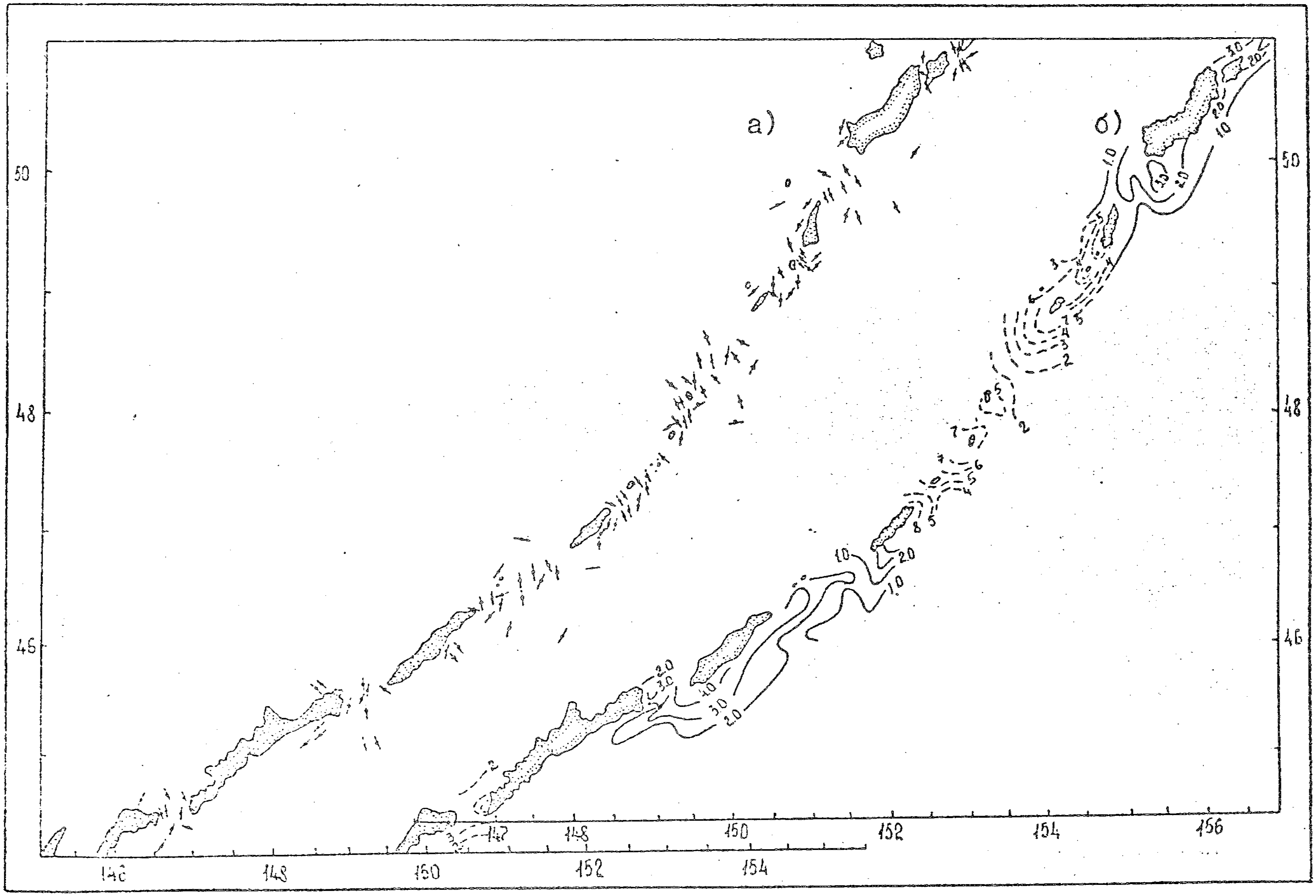

Fig. 5. Distribution of tidal parameters (0-25 m layer):
a - tidal ellipse main axis direction; b - maximal velocities (knots)

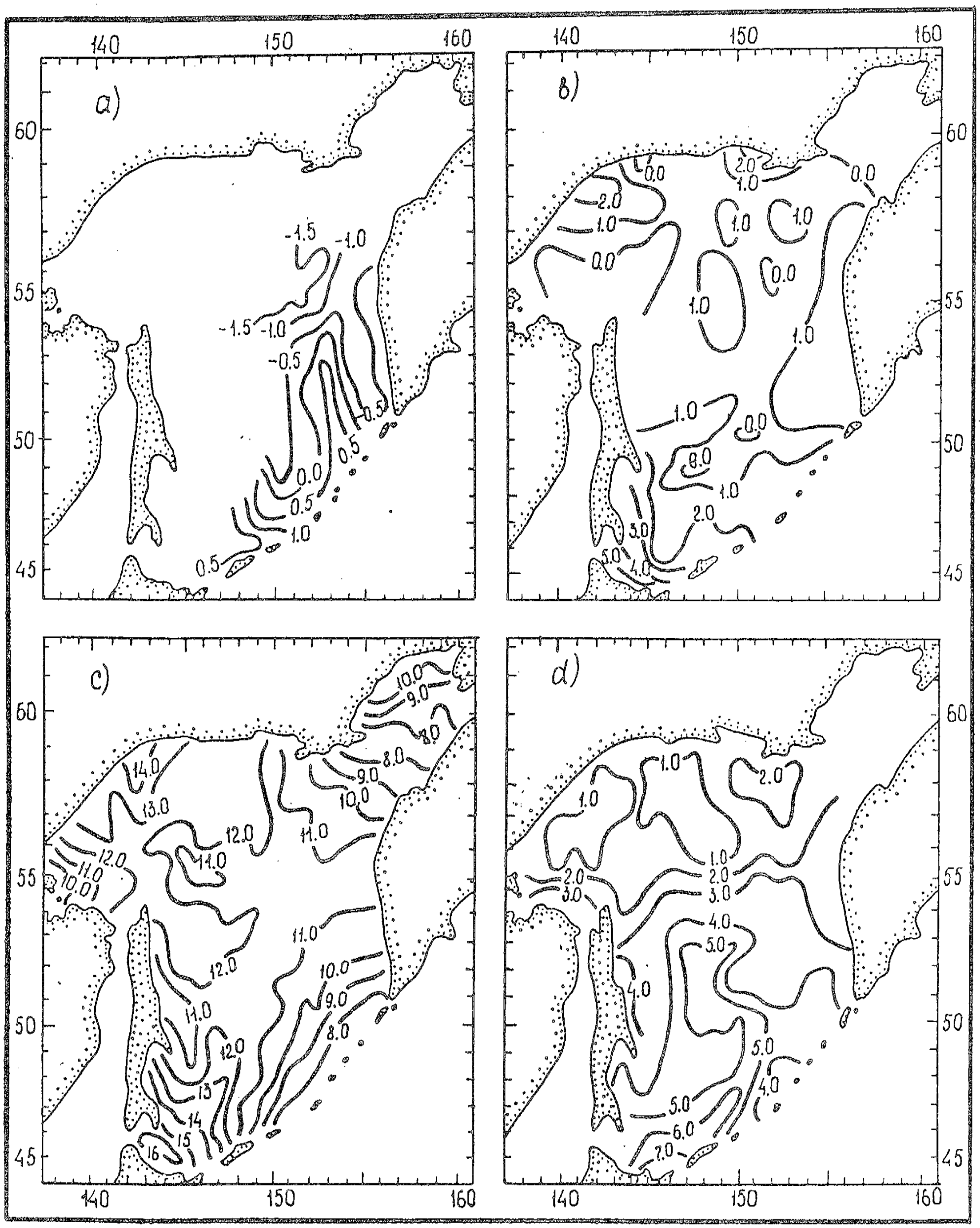

Fig. 6. Temperature distribution at the Okhotsk Sea surface
a - February; b - May; c - August; d - November

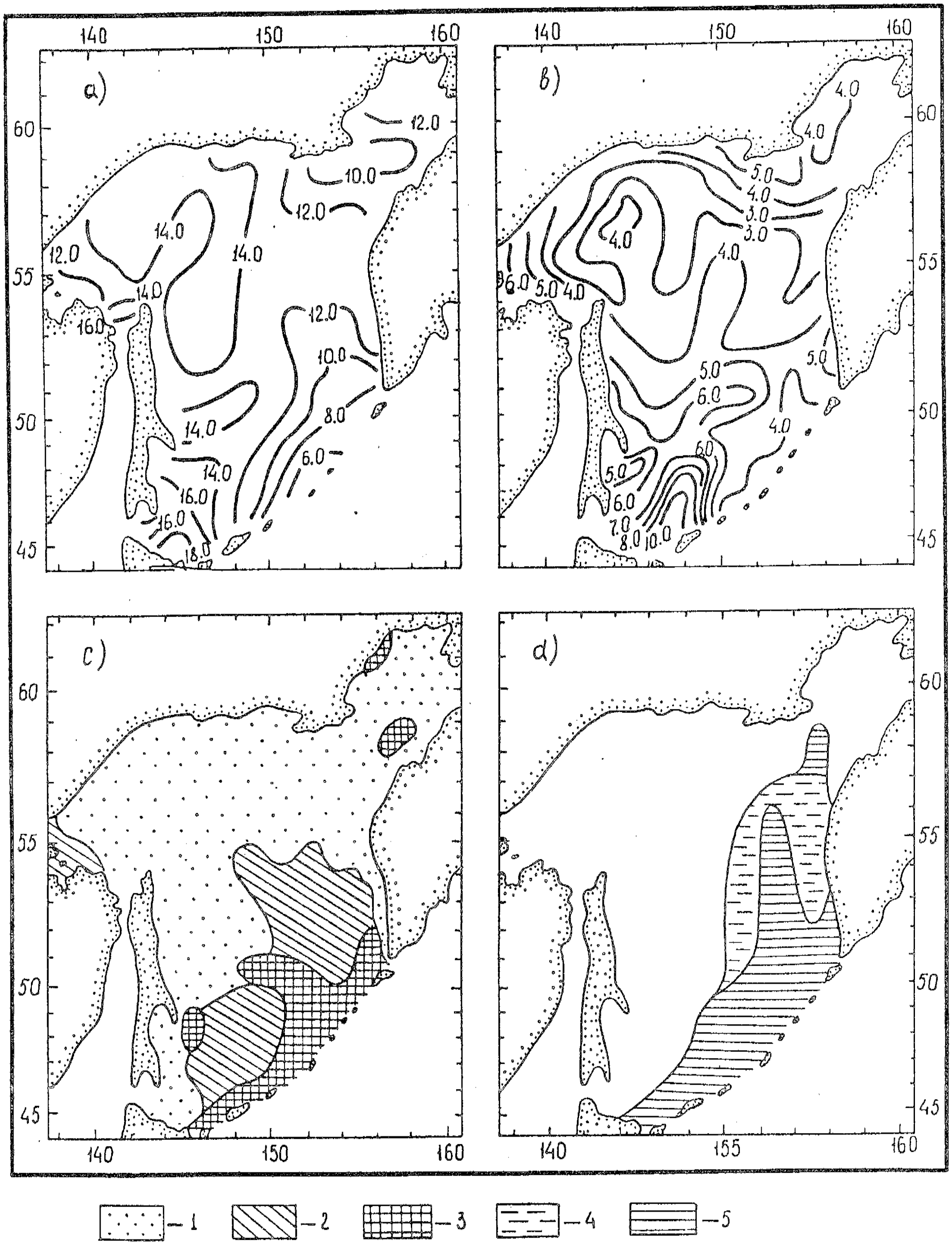

Fig. 7. Annual water temperature variations (a - surface; b - 50 m) and time of maximum (c) and minimum (d) temperature values appearance at the surface (1 - August; 2 - August-September; 3 - September; 4 - January - March; 5 - February-April)

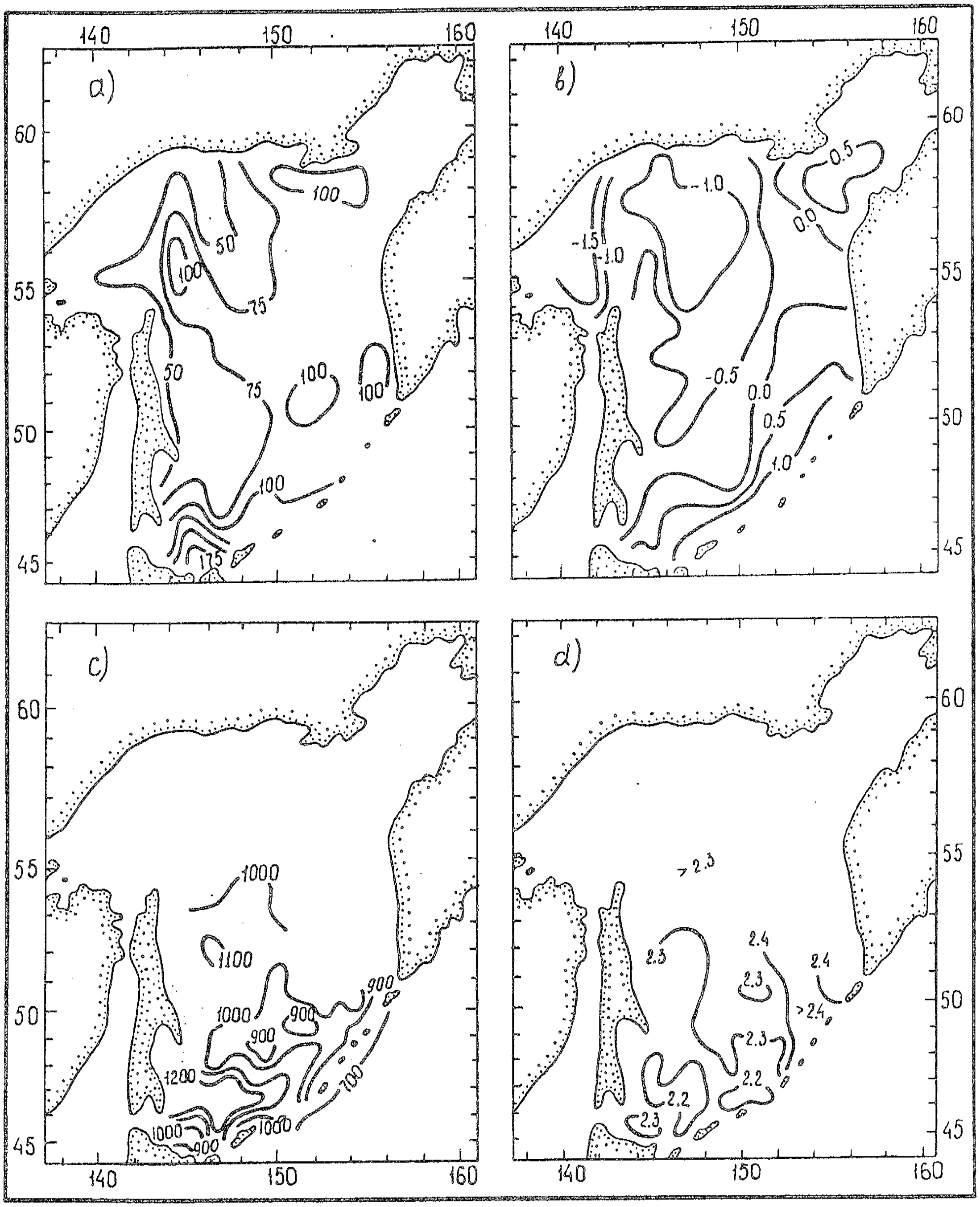

Fig. 8. Characteristics of the cold intermediate layer in August
(a - depth of the core in m; b - its temperature in C) and the warm intermediate layer (c - depth of the core in m; d - its temperature in C)