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Analysis of Seawater Circulation in the Whole Region of the Arctic Ocean

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Abstract : Research has been underway to clarify a situation resulting from the dumping of nuclear submarines into the local area (the Barents Sea and the Kara Sea) of the Arctic Ocean by the former Soviet Union. As the first step of research, the flow analysis in the local area (the Barents Sea and the Kara Sea) in the Arctic Ocean was studied. Using the observed data of water temperature and salinity, the flow was analyzed using a hybrid box model. The results obtained agreed with the observed features in many aspects (WADA and OCHIAI, 2004). As the second step of research, the entire Arctic Ocean was studied (Regional model). A numerical hybrid box model was developed. The results obtained agreed with the observed features in many respects. Especially, stream flows in the Norwegian Sea, Barents Sea and Kara Sea showed fairly realistic features. The flow field in the surface layer in the central Arctic Ocean agreed with that in previously known data. In the intermediate and deep layers, there was a stream flow that agreed with the known cyclonic circulation. East of Greenland, a stream flow equivalent to the East Greenland Current was recognized.

Keywords : *Arctic Ocean, Flow analysis, Hybrid box model, Regional model*

1. Introduction

The Arctic Ocean receives warm and saline water from the Atlantic, while cold and fresh water exits the Arctic Ocean with East Greenland Current. The warm inflow of Atlantic water gives the major oceanic heat input for the Arctic Ocean. It influences the sea ice distribution and thickness. The saline water inflow influences the stratification and mixing processes in the interior of the Arctic Ocean. North Atlantic water enters the Arctic Ocean through two main pathways. Part of the Atlantic inflow takes a route through the Barents Sea. The remainder of the Atlantic water enters through Fram Straight as the West Spitzbergen Current (GERDES & SCHAUER, 1997).

The most important connection of the Arctic Ocean with the rest of the World Ocean is through the 2600m deep Fram Strait between Greenland and Svalbard. Shallower openings in the land belting the Arctic Ocean connect it to the Pacific and to the Atlantic through the Bering Strait and the Canada Archipelago, respectively (Figs. 1 and 2).

The Arctic Ocean has an area of 9.2×10^6km^2 with a volume of 1.7×10^7km^3 and it is semi-enclosed by land. Part of it is as deep as 4,000m. There are three major water masses, as described below. (IAEA report IASAP–7, 1998, COACHMAN and AAGAARD, 1981)

i. Arctic surface-layer water: This water mass exists up to a depth of 200m from the surface, and both temperature and salinity undergo remarkable changes depending on the ice cover.
ii. Atlantic water: The warm and salty Atlantic layer extends below the pycnocline down to depths of 800–900m and is characterized by a mid-depth temperature maximum ranging between 0.5℃ and 4℃, and salinity is around 35 psu. This water mass is generated from the North Atlantic waters inflowing through the Fram Strait

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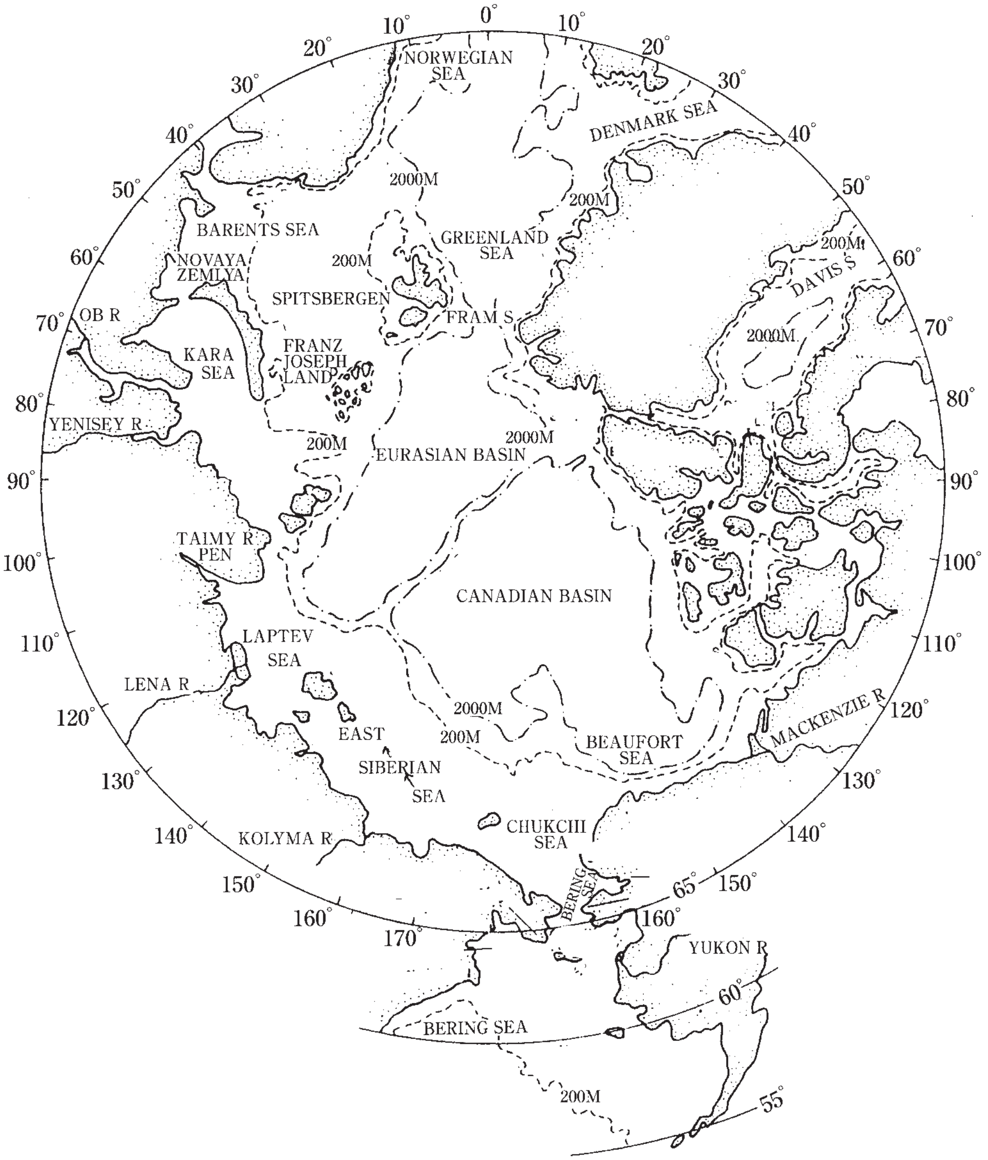

Fig. 1. Basins of the Arctic Ocean (Smith and Grebmeier, 1990).

and over the Barents and Kara Sea shelves.

iii. Arctic deep-layer water: This water mass, extending below the Atlantic layer to the bottom of the ocean, has relatively high and uniform salinity (34.93 to 34.99 psu) and temperature (−0.8℃−0.4℃).

The water of the Arctic Ocean is balanced by flows which pass through the Bering Strait and the Norwegian Sea, by precipitation and river run off and by outflow to the Barents and Greenland Seas and through the Canadian Arctic archipelago. The relative contributions of the thermohaline and wind-driven circulation to the Arctic flow are not yet clear.

The idea of “thermohaline” circulation assumed that water exchange between the Arctic Ocean and the Greenland and Norwegian Seas was caused by differences in water temperature and salinity between these basins. This idea is believed that the Arctic Ocean circulation was mainly thermohaline driven.

In contrast to the "thermohaline" idea, some scientists insisted that the inflow of Atlantic water into the Arctic Basin was caused by wind-forced outflow of surface water to the Greenland Sea. A series of 2-D numerical model results showed that wind were the major factor driving the Arctic Ocean circulation. Recently, 3-D coupled ice-ocean models were presented by some researchers. All of these models were directed to developing new models and describing better observed features of water and ice dynamics. WALSH and CHAPMAN (1996), SERREZE *et al.* (1992) and other scientists showed that the sea ice drift was done by the action of the atmosphere.

On the other hand, HOLLAND *et al.* (1996) demonstrated that buoyancy forcing is critical to maintain the mixed-layer circulation. It is considered that both thermohaline and wind-driven forcing are important to the Arctic Ocean's circulation (PROSHUTINSKY and JOHNSON, 1997). At the present stage, there is insufficient information for clearly separating the roles of atmospheric and thermohaline forcing in the Arctic Ocean.

The purpose of this study consists in analyzing flow characteristics of the whole area of Arctic Sea, in order to evaluate environmental effects of dumping radioactive wastes in this sea. For analyzing diffusion of radionuclides in the sea and for evaluating radiation exposure dosage of the inhabitants, it is necessary to know water circulation of the sea area. As the first step of the study, we conducted flow analysis employing the hybrid box model, by dividing specified areas of Barents Sea and Kara Sea into boxes of 4° by 1° horizontally and 6 layers vertically. Obtained results of the analyses proved to be in good agreement with established flow patterns so far reported (WADA and OCHIAI, 2004). In the second stage of the study, we took the whole region of Arctic Sea as an object area, dividing into horizontal boxes as shown in Fig. 2 and 5 layers in the vertical direction. We adopted the hybrid box model as used in the first step. The model used in this paper is an approach for applying conservation of mass with high accuracy not only in each calculation box but also over the whole system. This model is named a hybrid box model, intermediate between the box model and the hydrodynamic model. The method developed in this report has been developed to cover the regional field (Arctic Ocean).

2. Method of analysis

In this research, the method of analysis based on the box (compartment) model was used. The objective of this model is to determine a exchange flow rate that can reproduce the water temperature and salinity observed in each box by creating the equations of preservation for seawater, salinity and heat balance for every box. As the second step following the first step of research, the entire Arctic Ocean was studied, using horizontal boxes of 222×222 km which varied with locations on the spherical coordinate system, which were divided vertically into 5 layers (0–50m, 50–100m, 100–200m, 200–500m and 500–4250m). (Regional model, Fig. 2)

The upper 4 layers in both models (the first and the second steps) have the same layer thickness. The annual mean horizontal and vertical exchange flow rates in a total of 892 compartments were calculated to examine the movement of seawater.

Data used are:

(1) Water temperature and salinity

The data shown in the Climatological Atlas of the World Ocean (Levitus, 1982) relate to annual mean and seasonal mean fields. Of these data, flow analyses were conducted using the annual mean field. It is because flow calculations used in assessing exposure dose rates are based on the results of flow calculations using annual mean data from the viewpoint of the character of assessment.

(2) Topography

Topography is based on the ETOPO5 Data (NOAA, 1988) which are given in 5'grids.

(3) River flow rate (See Fig. 2)

From the mean flow curves shown in the monthly continental flow data (PAVLOV *et al.*, 1993), months corresponding to the seasonal classification of water temperature and salinity are taken out and integrated.

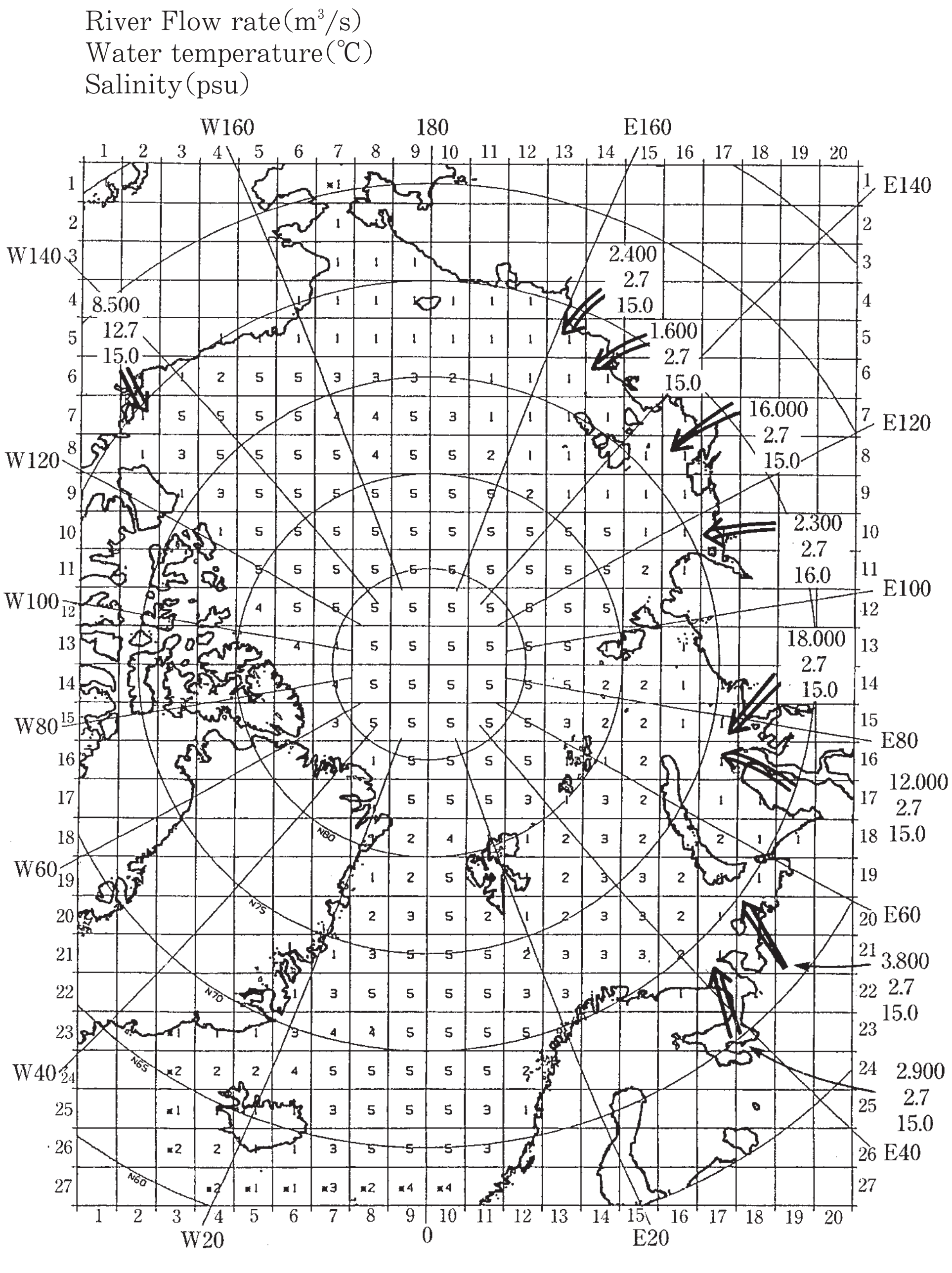

Fig. 2. Division of grids, the number of layers and river inflow positions in the Arctic Ocean.

3. Results of flow analysis in the whole Arctic Ocean

Let us now compare the results of flow analyses in the Arctic Ocean with available data (mainly surface flows).

Fig. 3 shows well-known observed flow patterns in the Arctic Ocean (PICKARD and EMERY, 1990). The circulation of the surface waters of the Arctic Ocean is increasingly well understood based on studies of sea-ice drift. The

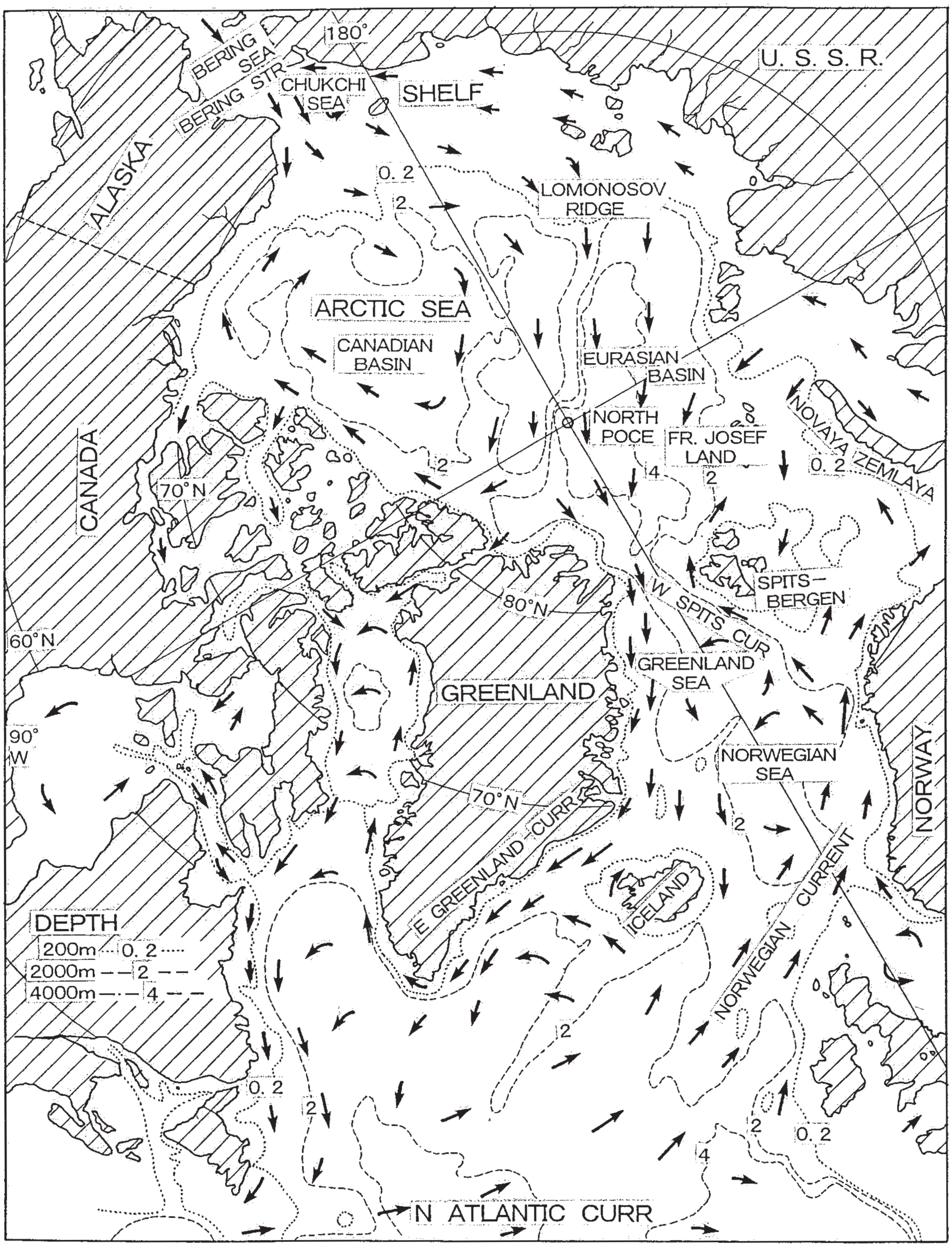

Fig. 3. Observed flow patterns in the Arctic Ocean (PICKARD and EMERY, 1990).

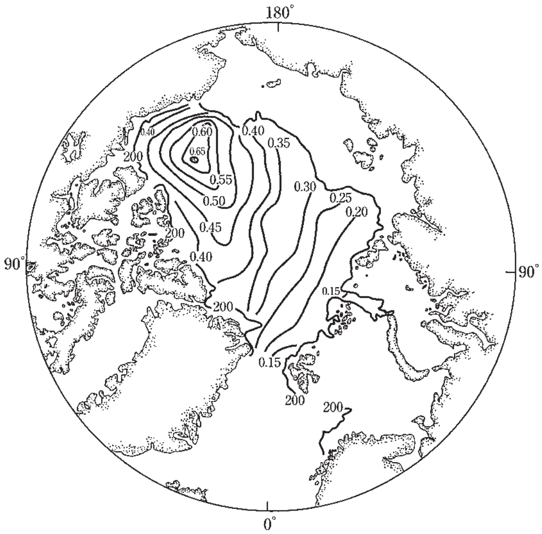

Fig. 4. Surface currents in the Arctic Ocean (0/1200 dbar) based on Coachman and Aagaard (1974).

prominent long-term features of the Arctic ice drift are the anticyclonic Beaufort Gyre occupying most of the Canadian Basin and the Transpolar Drift Stream flowing from the pole toward Fram Strait (Figs. 3 and 4). Here, the authors examine the velocity field at different depths in the model.

Results are shown in Figs. 5 through Figs. 6 (1), (2) and (3). Fig. 5 shows five lines illustrating the vertical behavior of water particles. Figs. 6 (1), (2) and (3) show horizontal velocity vectors in each layer. Fig. 7 shows schematic diagram of flows in the vertical direction along five lines shown in Fig. 5.

(1) Norwegian Sea and Greenland Sea

Fig.8 shows schematic of mean ocean circulation in the Fram Strait portion of the Greenland Sea (Muench *et al.*, 1992, Walker *et al.*, 1995). Two main currents exchange water between the Arctic and the outer ocean through Fram Strait. The west Spitzbergen Current (WSC) is a northward-flowing extension of the Norwegian-Atlantic current. It flows through Fram Strait off the west coast of Spitzbergen, carrying warm, relatively salty water into the Arctic Ocean. The East Greenland Current (EGC), which lies west of the East Greenland Polar Front, is the main current out of the Arctic Ocean.

The Fram Strait region appears to be a region of pronounced recirculation of Atlantic water, much of it joining the southward-moving East Greenland Current to flow-back into Greenland (Muench *et al.*, 1992, Walker *et al.*, 1995, Gascard *et al.*, 1995)

According to the results of tracking (Wada and Ochiai, 2004), shown in Figs. 6 (1), (2), (3) and 9, it is illustrated that a seawater particle in the Norwegian Sea (in the first layer) enters the Barents Sea, where it circulates anticlockwise, and that it submerges to the second layer in the south of Spitzbergen. Then the particle goes northward in the West Spitzbergen Current (WSC), and turns to the south by the East Greenland Current (EGC) flowing southward. The particle flows further toward the North Atlantic Ocean, moving to the third layer. These behaviors of seawater particle agree with the observed data (Wada and Ochiai, 2004, Hunkins, 1990).

In Fig. 10, a seawater particle deposited at the surface near the North Pole moves to the second layer as it passes between Franz-Josef Land and Novaya Zemlya Island, and abruptly turns toward the west. As in the case of Fig. 7, it then moves to the third layer and flows southward.

Vertical movements of water particles occur mainly between the first and third layers. Line (1–1') in Fig. 7 clarifies the behavior of seawater particles in the vertical direction.

- In the second and third layers (50–200m deep), the water mass which has come up north from the southern Norwegian Sea and part of the water mass which has come out of the Barents Sea pass through the circulating current zone and enter the Arctic Ocean from west of Spitzbergen (Figs. 6 (2) and (3)).
- The North Atlantic water settles in the circulating current zone southwest of Spitzbergen and enters the Arctic Ocean through the middle and deep layers as shown in Figs. 6 (1), (2), Fig.7 and Fig. 9, thus agreeing closely with the observed data as shown in Fig. 8.
- Circulation in the Fram Strait is represented schematically in Fig. 8 which are described by Gascard *et al* (1995), Hunkins (1990), Paquette *et al.* (1985),

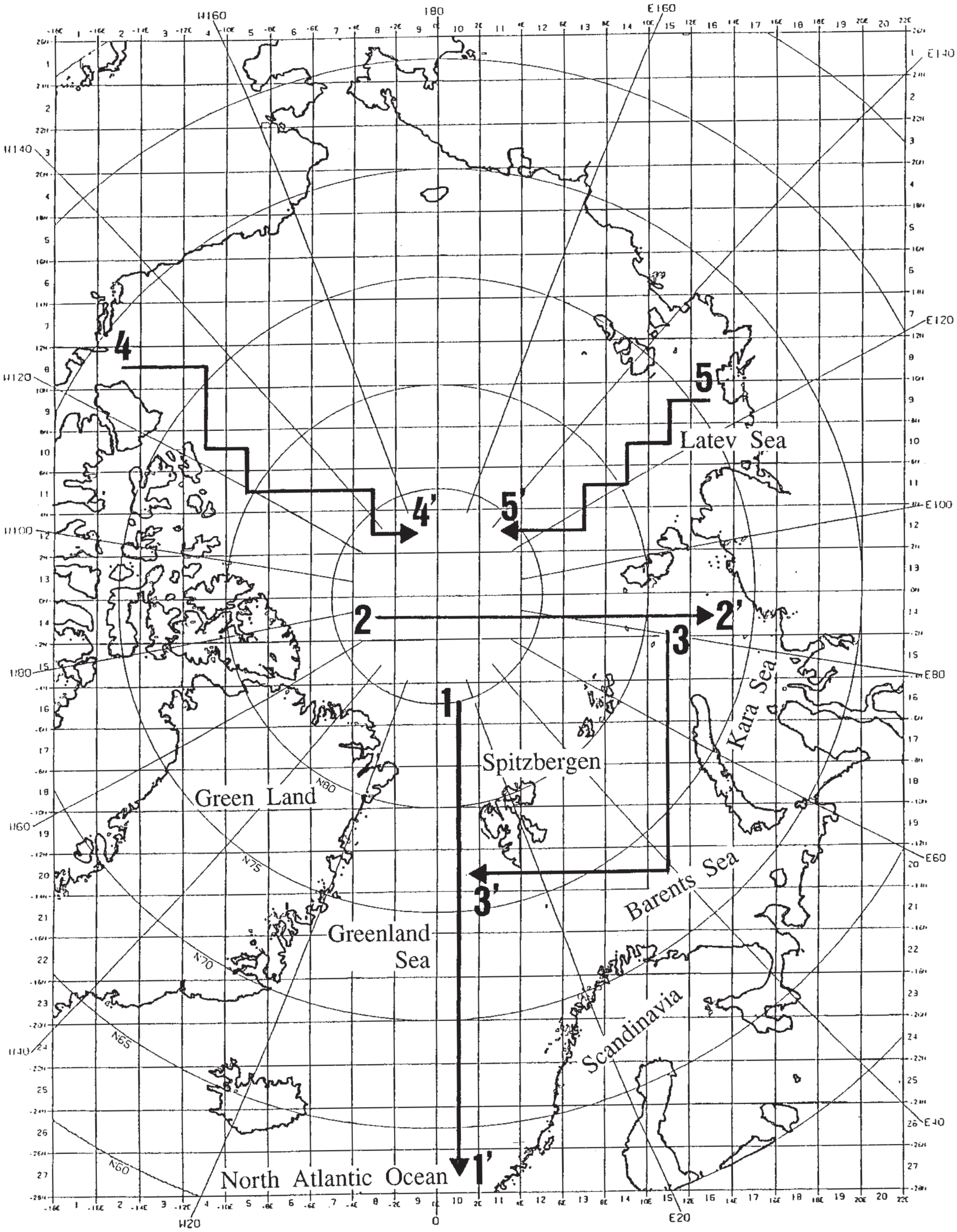

Fig. 5. Five measuring lines for studying the flow patterns.

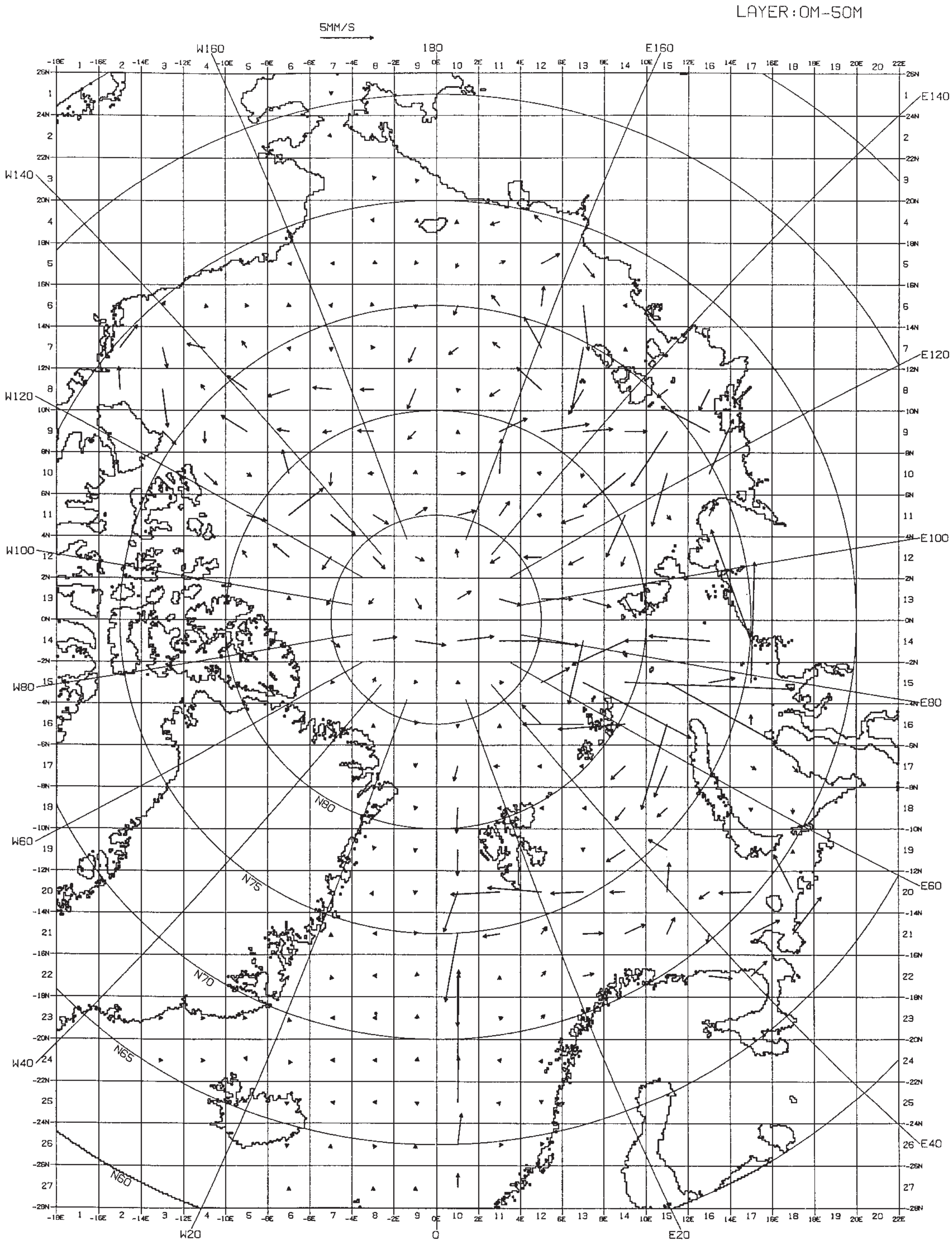

Fig. 6. (1) Velocity vectors in the surface layer (0–50m).

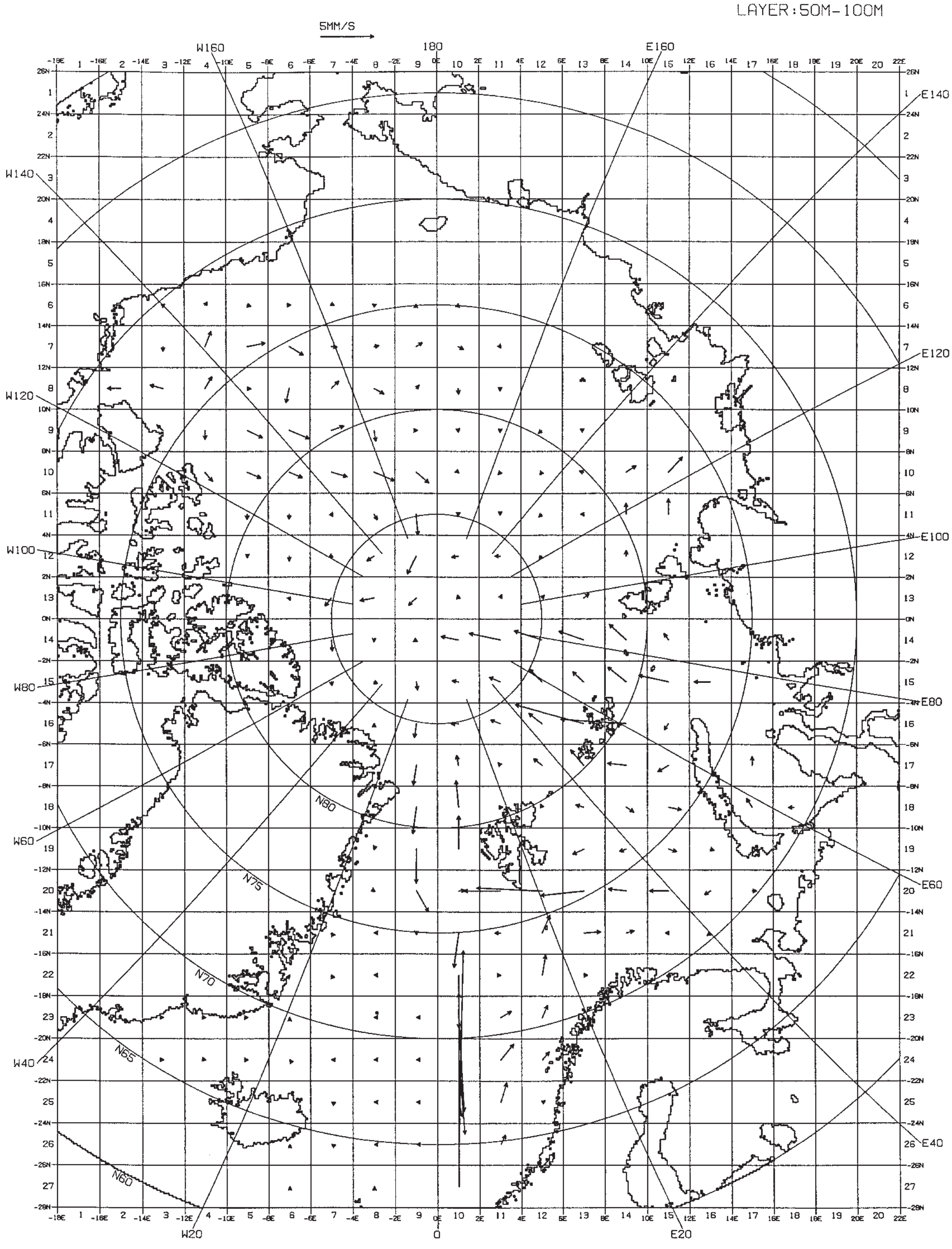

Fig. 6. (2) Velocity vectors in the second layer (50–100m).

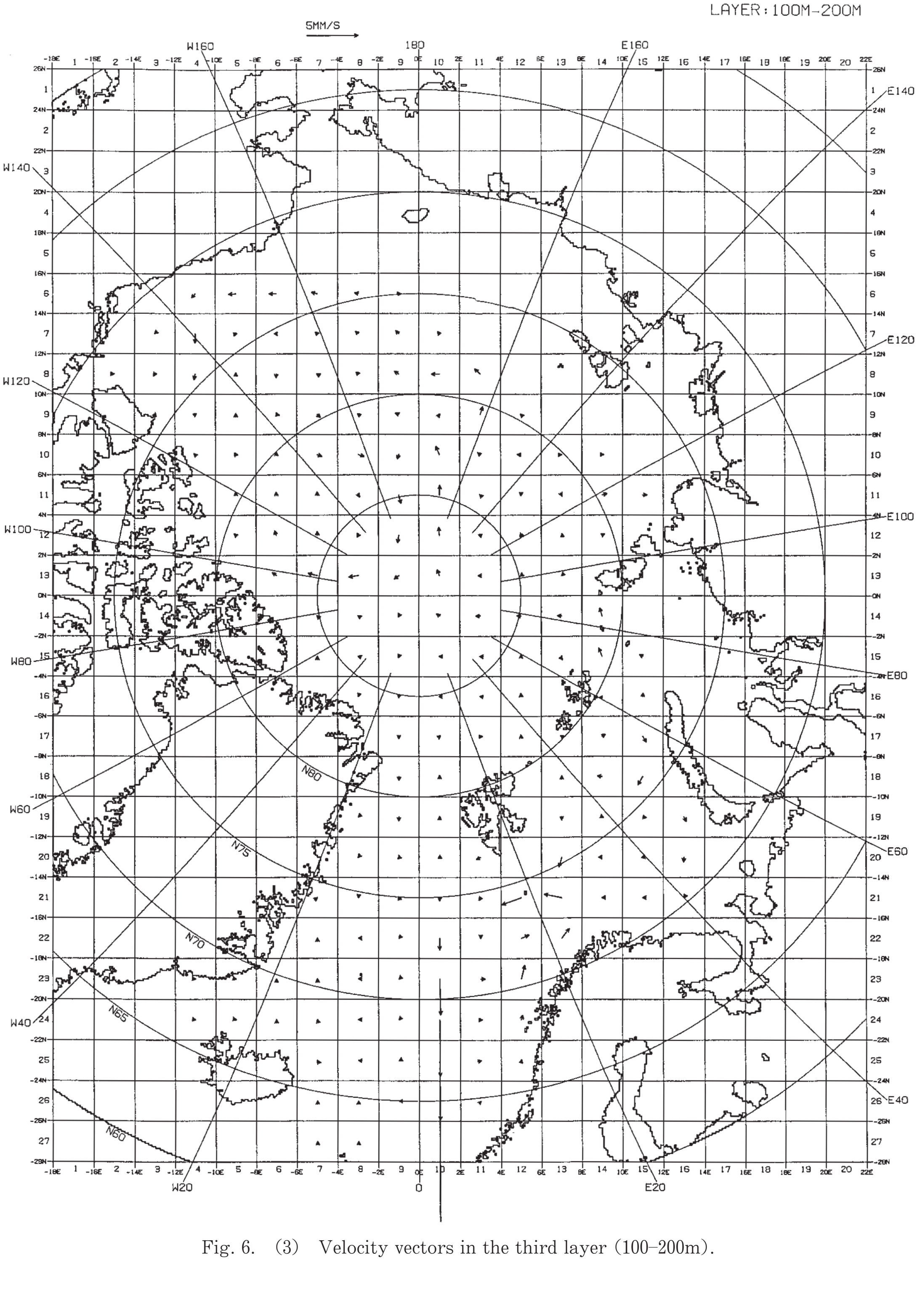

Fig. 6. (3) Velocity vectors in the third layer (100–200m).

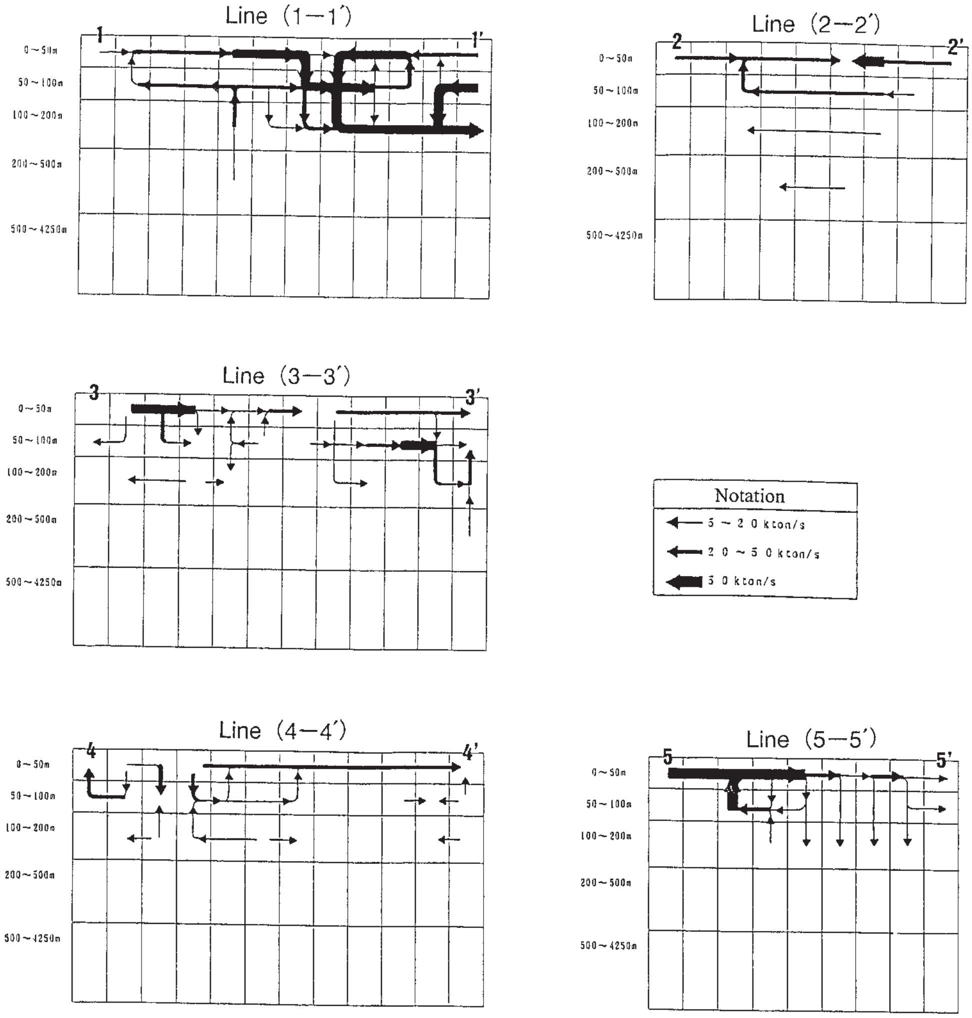

Fig. 7. Schematic diagram of vertical flows in the Arctic Ocean.

based on measurement. The model results shown in Figs. 6 (1), (2) and Fig. 9 resembles the situation of Fig. 8.

—The results of analysis given above confirm our assumption that density differences between the fresher Arctic Ocean and the more saline Atlantic Ocean waters are considered to be the primary driving force.

(2) Bering Strait exchange (Figs. 3 and 6 (1))
The northward flow through the shallow and narrow Bering Strait connects the Pacific (Bering Sea) and Arctic (Chukchi Sea) oceans. COACHMAN and AAGAARD (1981) note that the flow through Bering Strait is driven by a mean sea level slope of order 10^{-6} down toward the north, due to an effect related to the lower density of the Pacific relative to the Atlantic.

(3) Barents Sea and Kara Sea (Figs. 6 (1), (2) and 9)

—In the Barents Sea, the water mass which has come out of the Norwegian Sea joins the water mass coming out of the Kara Sea and the water coming out of the Pechora River while circulating counterclockwise in the central part of the Barents Sea, and flows westward to the south of Spitzbergen.

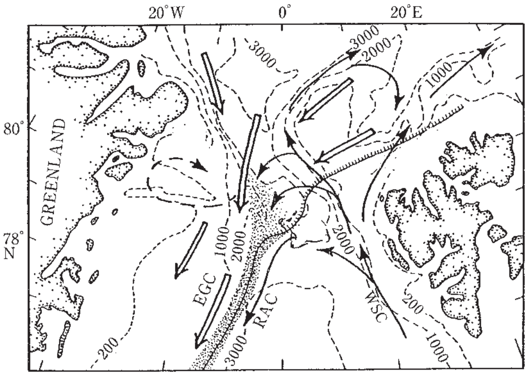

Fig. 8. Schematic of mean ocean circulation in the Fram Strait portion of the Greenland Sea. Hollow arrows depict flow of cold Polar Water, and solid arrows depict flow of warmer Atlantic Water. In areas where both water types occur, the Atlantic Water lies beneath the Polar Water. The hachured line indicates a typical summer ice edge location. The East Greenland Polar Front is indicated by the stippled region.

Major currents are labeled as follows: WSC, West Spitsbergen Current; EGC, East Greenland Current; and RAC, Return Atlantic Current. Dushed lines are isobaths, with depths in meters.

— This current agrees closely with the observed data (Fig. 3, Figs. 8 and 10, WADA and OCHIAI, 2004), though there is some difference in position.

— In the western Kara Sea, the water mass which has come eastward from the polar point joins the water mass from the Kara Sea (fresh water mass from the Yenisey River and Ob River) and flows southward to the Barents Sea.

(4) Arctic Ocean

— In the surface layer of the Arctic Ocean, we tracked the particle injected on the 1st layer near the Laptev Sea.

Result of the particle track is shown in Fig. 10. The particle drifted in a clockwise circulation, gradually moving to the 2nd and 3rd layers. In the Canadian Basin, it entered a small-scale clockwise circulation, and returning to the 1st layer, moved towards the central part of the Arctic Sea.

— In the second and third layers, part of the water mass which has entered from the Norwegian Sea circulates cyclonically in the Arctic Ocean, the opposite direction to that of the Arctic water above it. It closely agrees with the circulation route (estimated) of the North Atlantic Ocean water in the intermediate and deep layers of the Arctic Ocean (SCHLOSSER *et al.* 1995, GERDES and SCHAUER 1997).

Due to the paucity of high-quality deep data, the sense of circulation in the deep layers is not well established. AAGAARD and CARMACK (1989) and SMETHIE *et al.* (1988) deduced from mooring and tracer data a cyclonic flow around the Eurasian basin.

— After circulating in the Arctic Ocean, water enters the Norwegian Sea again from the northeast coast of Greenland, which agrees with the observed data (PICKARD and EMERY 1990).

4. Consistency with the local model (Kara Sea, Barents Sea)

The authors compared the results of flow analyses with the local model (WADA and OCHIAI, 2004) and the results obtained with the regional model. Both models agree that Atlantic Ocean water enters the Barents Sea along the Norwegian Peninsula, circulates counterclockwise in the Barents Sea and enters the Arctic Ocean and Norwegian seas again. Both models reproduce the current which enters from the Arctic Ocean and the current which flows into the Barents Sea between Franz-Josef and Novaya Zemlya. The consistency between the two models is high.

5. Estimation of Errors

As we research for flows which reproduce the distribution of salinity and temperature in each box, errors in salinity and heat amount could be neglected. As for flow, we calculated errors of the conservation equation of seawater for each box. Errors of flow were evaluated both by the absolute error which is the difference of in- and outflows and the relative error which is the difference divided by the inflow. Table 1 shows coordinates in which the maximum error occurs (See Fig. 2), residual errors by the least square method, and the maximum value of relative error (residue/inflow) and coordinates.

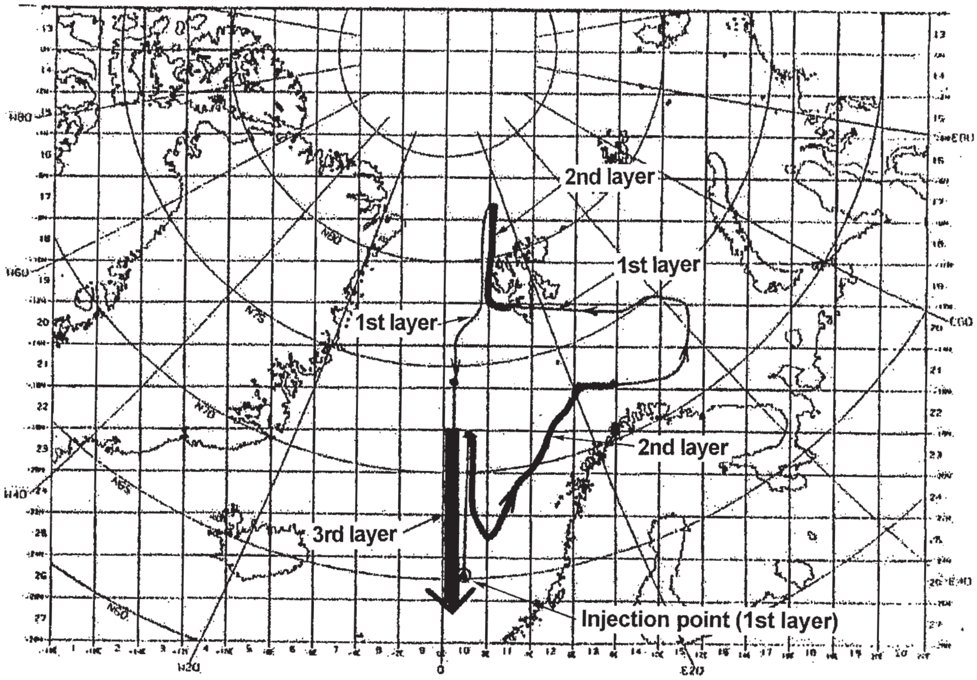

Fig. 9. Tracking of seawater particle in the Greenland Sea.

1st layer

2nd layer

3rd layer

Table 1. Errors of conservation of seawater volume.

	Coordinates	Absolute error	Relative error
1st layer (0−50m)	(17, 16)	-9×10^{-5}(kton/s)	2×10^{-7}
2nd layer (50−100m)	(10, 20)	6×10^{-5}(kton/s)	2×10^{-7}
3rd layer (100−200m)	(10, 20)	-8×10^{-6}(kton/s)	4×10^{-7}
4th layer (200−500m)	(10, 20)	8×10^{-6}(kton/s)	3×10^{-7}
5th layer (500−900m)	(11, 14)	-8×10^{-6}(kton/s)	1×10^{-7}

The values above indicate the errors of the boxes which showed the largest error in each layer.

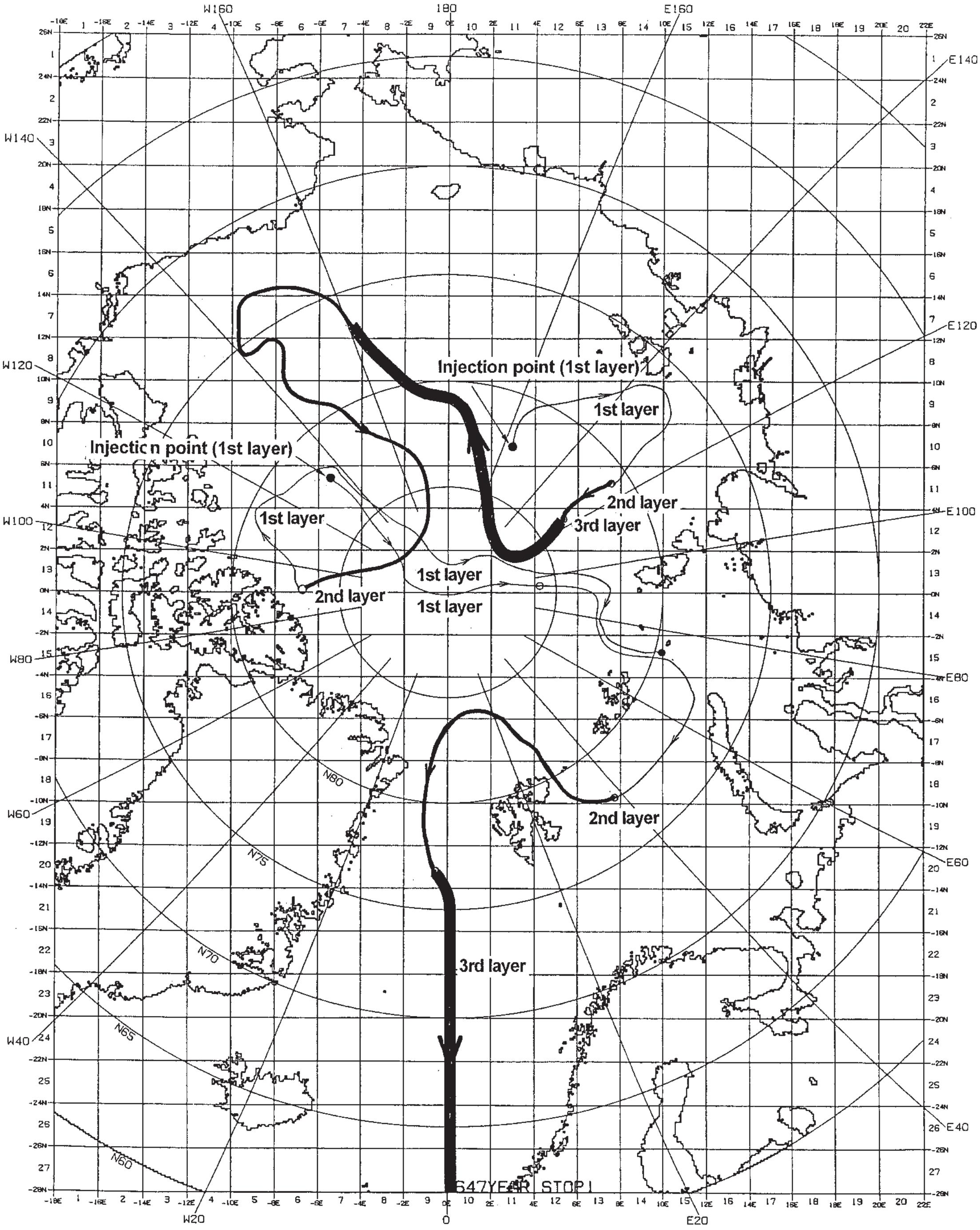

Fig. 10. Tracking of water particle in the whole Arctic Ocean.

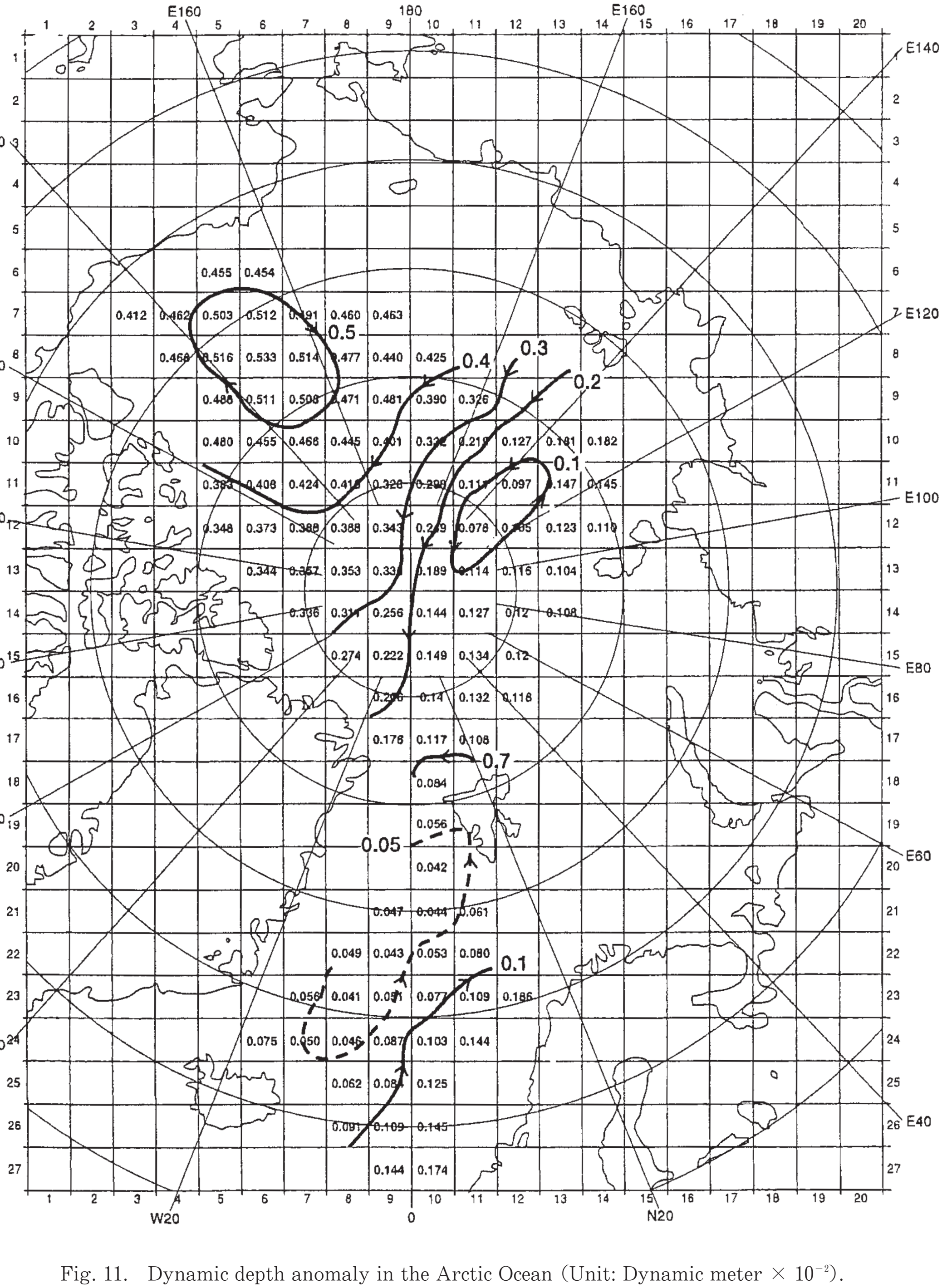

Fig. 11. Dynamic depth anomaly in the Arctic Ocean (Unit: Dynamic meter $\times 10^{-2}$).

6. Comparison with geostrophic flow field

In this section, we calculated the surface dynamic height from the density flow in the whole Arctic Sea, and compare the result with that obtained by the hybrid box model which is illustrated in Fig. 6 (1), (2) and (3). In the present calculation, the level of no motion is assumed to be at 350m depth based on the results of the hybrid box model. Fig. 11 shows the obtained dynamic topography. Main features of the calculated result are:

• A clockwise circulating current exists with a center at 150° W, 76° N.

• A small-scale anti-clockwise circulation exists with a center at 140° E, 84° N.

• There exists a current that starts from the coast of Russia and passing through the North Pole, reaches near the coasts of Greenland and Canada.

From comparison of Fig. 10 and Fig. 11, it is noticed that although size of the clockwise circulation in the Canadian Basin is similar in the both cases, direction of the circulation off the Laptiv Sea is opposite. The current from the North Pole to Norwegian Basin is similar in the both cases.

7. Conclusions

A numerical hybrid box model was developed. The results reproduced many of the observed features such as the currents described below.

Particularly, stream flows in the Norwegian Sea, Barents Sea and Kara Sea agree closely with the observed data. The flow field in the surface layer of the Arctic Ocean agrees with the observed data. We could reproduce stream flows such as the West Spitzbergen Current (WSC) and the East Greenland Current (EGC) in the Fram Strait which showed a very complex flow structures.

The method of analysis used in this research was aimed at determining the flow field on the basis of observational data such as water temperature and salinity. Therefore, the importance of this data is unfathomable. Most notably regarding the Arctic Ocean, the availability of oceanographical data is very limited in comparison with other seas, so that further accumulation of data is required.

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