Sub-Arctic Gyre Experiment in the North Pacific Ocean (SAGE)

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Dr. Nobuo Suginohara is Professor at the Center of Climate System Research (CCSR), University of Tokyo. He is a modeler leading the CCSR Ocean Modeling Group and develops an ocean model as part of a climate model useful for predicting climate changes of decadal through centennial time scales. At the same time, he has been organizing inter-agency programs related to the World Ocean Circulation Experiment (WOCE) in Japan, and is now Chairman of the Subarctic Gyre Experiment (SAGE) program, a research program for the Research Promotion Fund by the Science and Technology Agency. Dr. Suginohara is a member of PICES' Physical Oceanography and Climate Committee.

1. Introduction

1.1 Why does the subarctic gyre in the North Pacific need to be studied?

Almost two decades have passed since the role played by the ocean in determining climate changes was recognized: TOGA (Tropical Ocean and Global Atmosphere) led to deeper understanding of El Niño-Southern Oscillation of several years' time scales; WOCE (World Ocean Circulation Experiment) has increased our knowledge on the deep ocean which controls climate changes of decadal to centennial time scales.

There is evidence of the importance of the subarctic gyre in the North Pacific in understanding climate changes. According to results of a recent climate model (Tokioka et al., 1995), the subarctic North Pacific as well as the tropical Pacific is very sensitive to climate change. In fact, the observed sea surface temperature exhibits a significant decadal signal in the subarctic North Pacific (e.g., Zhang et al., 1997). Also, the subarctic North Pacific is considered to be an area for anthropogenic CO_2 absorption (Tsunogai et al., 1993). At intermediate depths in the subtropical region, there is a water mass called North Pacific Intermediate Water (NPIW), which is characterized by its low salinity. NPIW is formed in the subarctic North Pacific, and flows into the subtropical region, thus playing an important role in transporting the anthropogenic CO_2 to the whole North Pacific intermediate depths. Therefore, the subarctic North Pacific is a key area to be understood for accurately predicting climate change. We need to understand the subarctic region from the sea surface to the bottom for developing and validating climate models, for understanding oceanic response to changes in atmosphere, and for estimating the absorption rate of anthropogenic CO_2.

However, the subarctic North Pacific is an area where the weather, particularly winter weather, is very severe. This severe weather has hindered observations. Now, we have a big research vessel "*Mirai*", which enables us to obtain data even in wintertime. Data for all seasons will contribute to the development of climate models, which is one of the major objectives of WOCE and CLIVAR (Climate Variability and Predictability), and will also provide important information necessary for setting up the monitoring system of GOOS (Global Ocean Observing System). In addition, circulation fields in the subarctic North Pacific obtained from data will provide an environment for GLOBEC (Global Ocean Ecosystem Dynamics) and JGOFS (Joint Global Ocean Flux Study).

1.2 What do we know about the subarctic North Pacific?

Figure 1 shows salinity sections along 165 ˚E and 30˚N obtained by Japanese ships under one-time WOCE Hydrographic Program (WHP). We can clearly see that the water of salinity minimum occupies the intermediate depths of almost all of the subtropical North Pacific, although characteristics of the water along the eastern and the southern perimeter of the subtropical gyre look different. This water called NPIW is formed in the subarctic gyre and transported into the subtropical gyre near the western boundary (Talley, 1993; Yasuda, 1997) and also near the eastern boundary (You et al., 1999).

Figure 2 shows results of a numerical model for the North Pacific by Tsujino and Suginohara (1998). On the surface, σ_q= 26.6, where the core of NPIW exists in their model, we can see a cross-gyre flow both near the western boundary and the eastern boundary. The water introduced into the subtropical gyre near the western boundary flows eastward to the eastern boundary. There it mixes with the water from the north, and turns first southward and then westward, crossing the Pacific again. Along the western boundary, part of it flows into the tropical gyre forming a southward western boundary undercurrent. Note that state-of-the-art models are

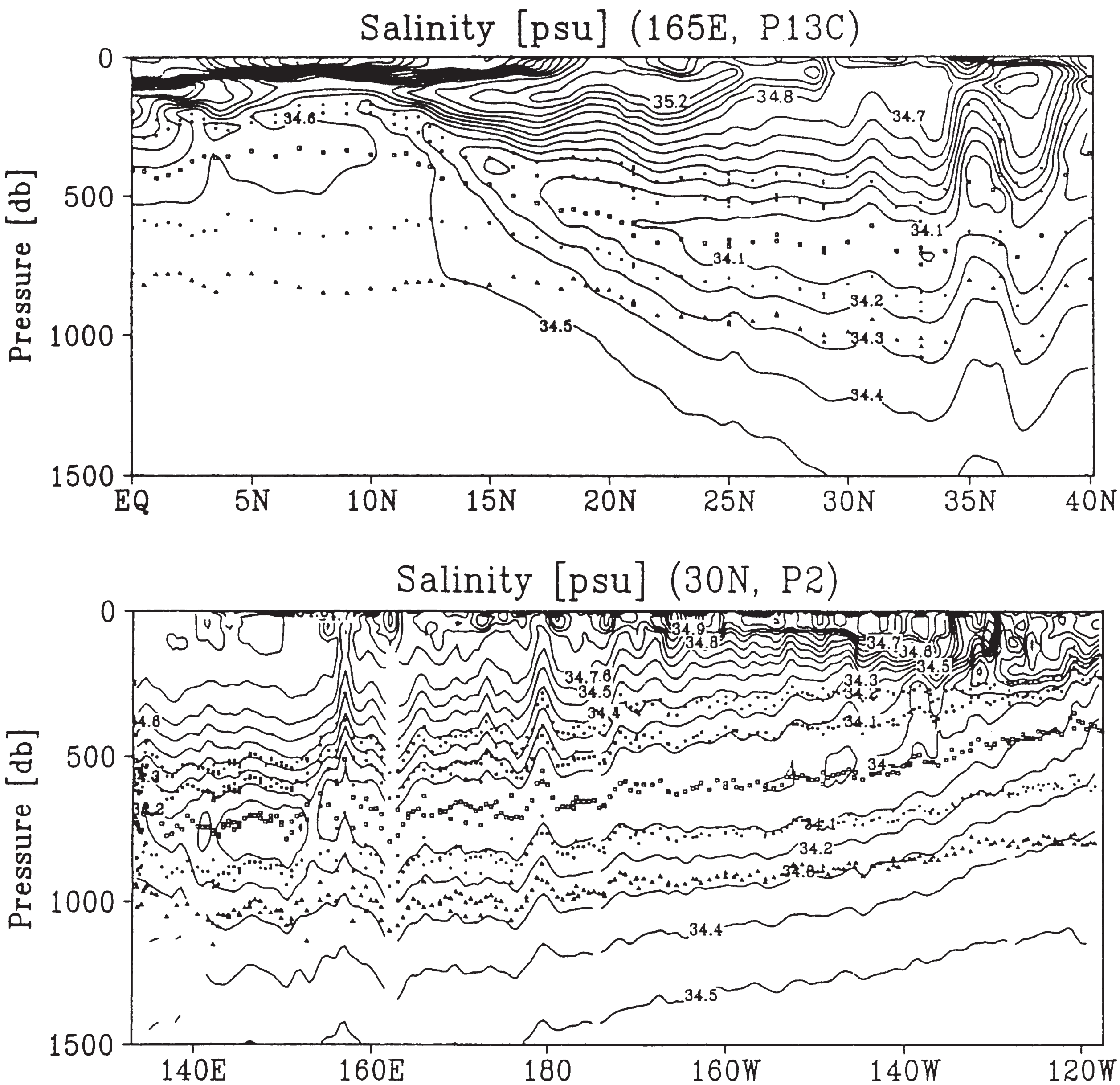

Fig. 1 Meridional salinity section along P13 (165˚E) (upper panel) and zonal salinity section along P2 (30˚N) (lower panel) with the depths of five neutral density surfaces σ_N = 26.2 (o), 26.5 (■), 26.9 (□), 27.2 (•) and 27.4 (Δ) (after You et al., 1999).

not good enough to reproduce the separation of the Kuroshio from the coast of Japan.

According to the model, in the density range of σ_q=26.6 - 26.8 the net cross-gyre transport is about 1.5 Sv (see *Figure 3*). There are a few of observational estimates for this transport. For example, Talley (1994) obtained about 3 Sv for the density range of σ_q=26.64-27.4 in the mixed water region, but this value includes a lot of uncertainties. Therefore, we still do not know how much NPIW is formed in the subarctic North Pacific and transported into the subtropical gyre. Furthermore, we do not know their temporal variability at all.

2. *Outline of the program*

Major objectives of the SAGE program are to estimate the formation rate of North Pacific intermediate waters such as NPIW, and to clarify their distribution processes and decadal/ interdecadal variability. To accomplish the objectives, the following four core projects (CP) are set up.

CP1: *Observational study on the structure and variability of the subarctic gyre*

- Surface layer circulation (Thermal structure and current field)

Sea surface topography measured with satellite altimetry will be analyzed. We will keep a network of XBT and XCTD observation including TRANSPAC-XBT, and conduct Lagrangian measurements of the current field using surface and subsurface drifters.

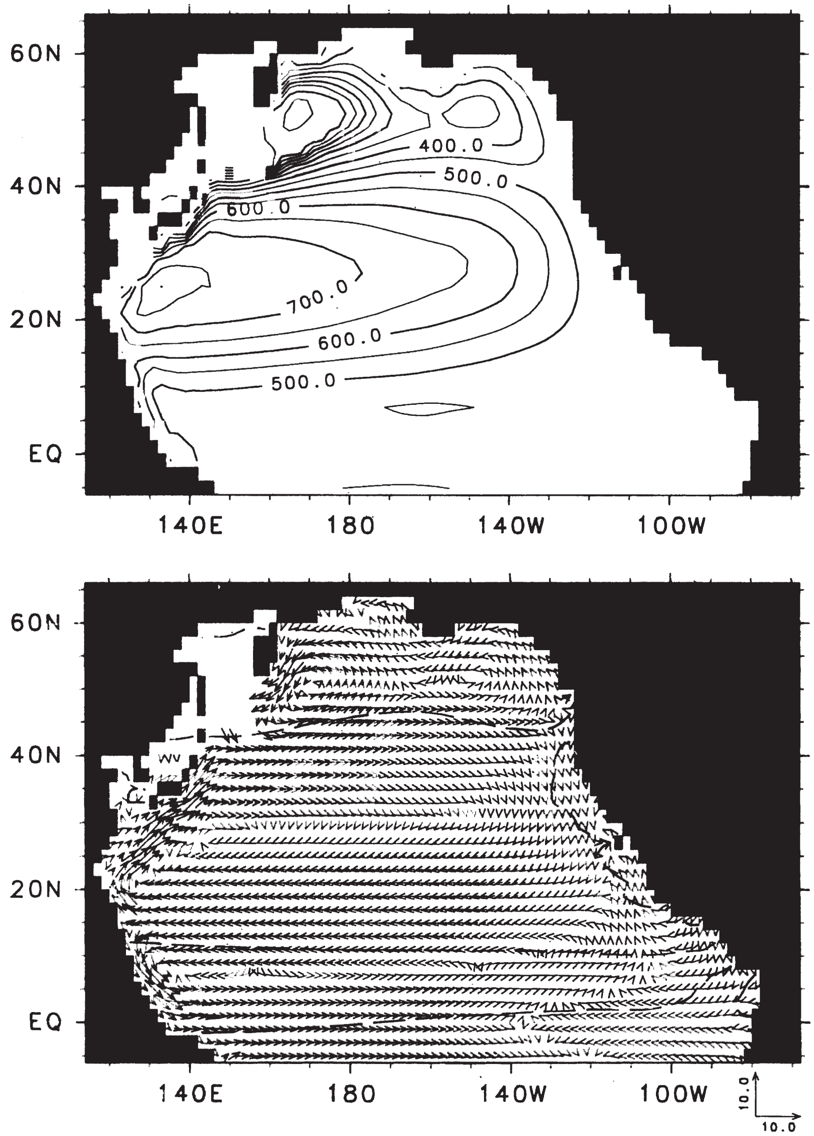

Fig. 2 *Depth in meters and horizontal velocity on the* σ_q *=26.6 surface modeled by Tsujino and Suginohara (1998).*

- Hydrographic structure of the subarctic gyre (temperature, salinity, and tracers)

We will revisit one-time WHP lines such as P1 (47˚N), P16N (152˚W), and P13 (165˚E) to detect decadal changes of the subarctic North Pacific.

CP2: *Research on the interaction between the subarctic and the subtropical circulation*

- Formation and distribution of NPIW in the western North Pacific -

We will try to identify the formation processes of the origin water of NPIW in the Okhotsk Sea, interaction between the Okhotsk Sea and the subarctic gyre, and advection process of NPIW including cross-gyre flow.

CP3: *Behavior of* CO_2 *in the subarctic circulation system*

We will map air-sea exchange of CO_2 in the subarctic North Pacific and estimate seasonal variations of TCO_2, pH, pCO_2, etc. in the mixed water region.

CP4: *Modeling of the subarctic gyre*

We will develop inverse models for the intermediate and deep layer circulation, assimilation models, and an eddy resolving model for the North Pacific. For an eddy resolving model, we try to reproduce the Kuroshio separation at a realistic latitude.

Participating institutes and organizations are listed in *Table 1*. They own many ships, which we will make full use of to accomplish the objectives of the SAGE program.

3. Preliminary results

The program is in progress according to plan. Here are some of the results obtained so far.

Figure 4 plots observation lines occupied in April to July 1998. This multiple-ship survey is for identifying the formation and transformation processes of NPIW in the mixed water region. *Figure 5* shows one of the preliminary results. The cold and fresh water around 34˚N, 145˚E is thought to be transported from the Oyashio region. It is expected that the exact amount of the cross-gyre transport be obtained and the formation and transformation processes of NPIW be clarified.

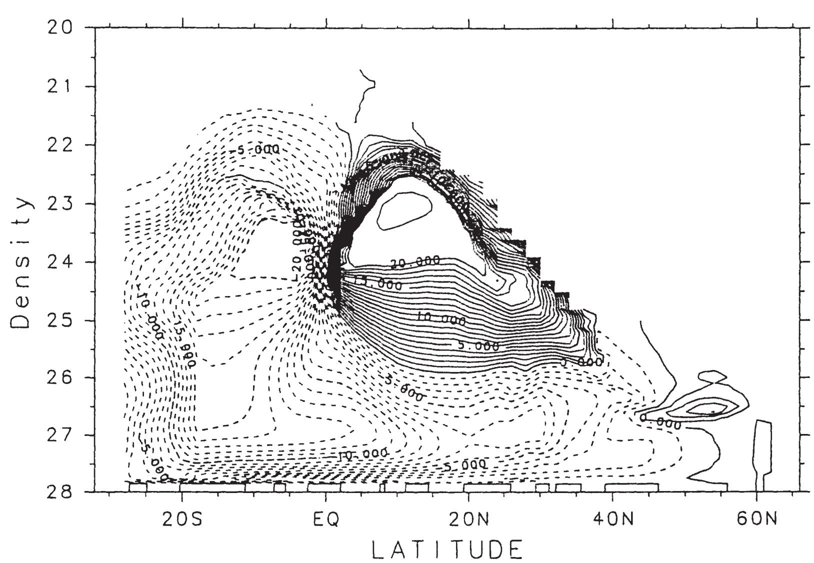

Fig. 3 *Meridional stream function in Sv against potential density modeled by Tsujino and Suginohara (1998).*

Table 1. List of participating institutes and organizations.

Fisheries Agency
- Hokkaido
- Tohoku
- Central
- Far Seas

Agency of Industrial Science and Technology
- National Research Institute of Resources and Environment

Maritime Safety Agency
- Hydrographic Department

Meteorological Agency
- Climate and Marine Department
- Meteorological Research Institute

Japan Marine Science and Technology Center

Universities
- Tohoku University
- University of Tokyo
- Kyoto University
- Tokai University

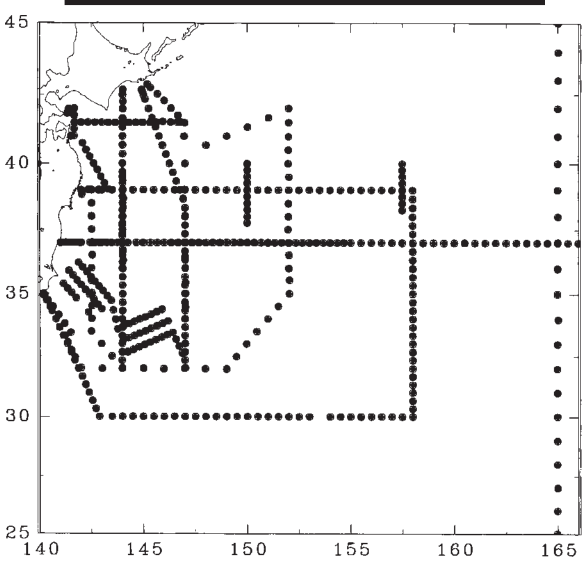

Fig. 4 Observation lines occupied by the R/V's Soyo-Maru, Kofu-Maru, Ryofu-Maru, and Wakataka-Maru in April to July 1998.

Figure 6 shows the temperature and salinity in the western part of P1 along 47˚N for two periods, 1985 and 1997. The observation in 1997 was preliminary for the revisit of P1 in 1999. There were no tracer observations in 1997. The comparison clearly shows that the deep layer in 1997 became colder by 0.01-0.05˚C and saltier by 0.005-0.01 psu in the west of 165˚E, while it was warmer by 0.01-0.05˚C in the east

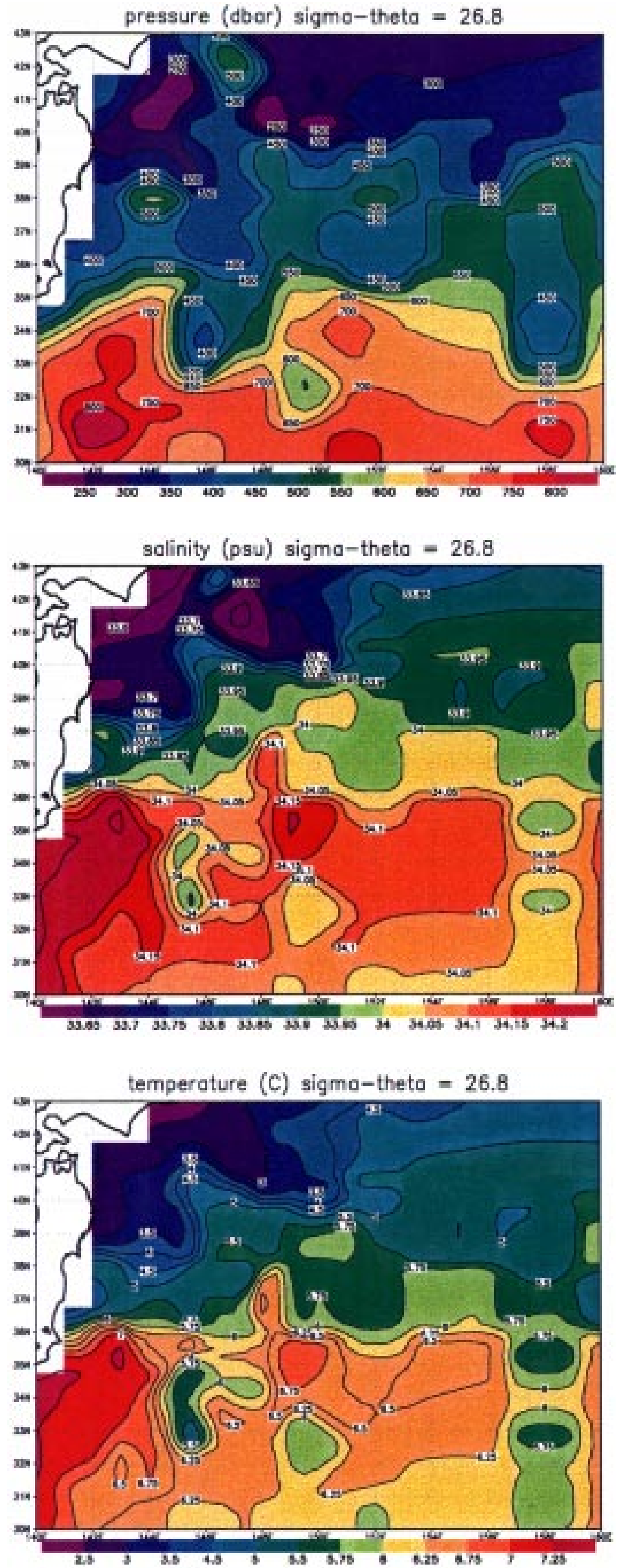

Fig. 5 Depth, temperature, and salinity on the σ_θ=26.8 surface from the multiple-ship survey in Fig. 4.

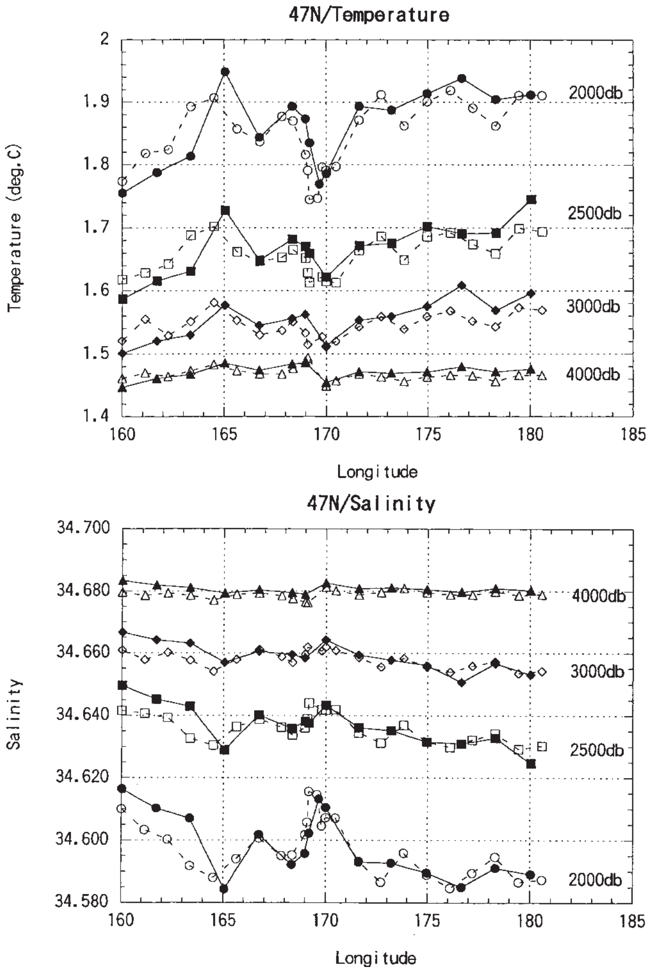

Fig. 6 Temperature (upper panel) and salinity (lower panel) along 47˚N at different depths. Solid lines with solid symbols are for R/V Shoyo's *observations in August 1997, and dashed lines with open symbols are for R/V* Thompson's *observations in August 1985.*

of 165˚E. Detailed analyses of the 1997 data are still being made. The whole P1 line will be revisited in June to September 1999, by the R/V *Kaiyo-Maru* of Japan Fisheries Agency and the R/V *Mirai* of JAMSTEC. Details of the changes will be learned soon by using observations of temperature, salinity, nutrients, and various tracers such as freons and ^{14}C.

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coccolithophores dominated. During mid-September the coccolithophore bloom was still prevalent.

Although these unusual conditions did not seem to have an immediate effect on the groundfish of the area, they may impact future abundance. NOAA fishery surveys in 1997 and 1998 located fewer young-of-the-year pollock than in previous years. Participants on the July 1998 *Oshoro Maru* cruise reported that the abundance of age-0 pollock seemed low relative to the previous four years. However, observations from the Inner Front Project in August 1998 suggest that young pollock, in fact, were quite abundant but located further onto the shelf than usual. This displacement could derive from wind-driven transport of pollock larvae northeastward from their spawning area during the stormy spring. Ramifications of these recent changes will not be known for several years until the young pollock mature into adult fish and are harvested.

SEBSCC has extended the knowledge base of the southeastern Bering Sea at a critical moment. More and more attention is focused on the Bering Sea. Just a few years ago, as other fisheries of the United States were suffering serious declines, the eastern Bering Sea fishery was considered stable. In the past two years there have been indications that this may not be the case.

Commercial salmon failures, curtailment of fishing areas and times because of declining marine mammal populations, massive deaths of seabirds, and indications that a major shift in Bering Sea climate may be occurring, all suggest that the Bering Sea ecosystem is changing in a significant way. It is clear that we must understand this change in order to manage responsibly the bountiful resources that this region provides. SEBSCC contributes measurements and results that are vital to a more complete understanding of the Bering Sea ecosystem.