Sea-ice flow from the Okhotsk Sea to the Pacific Ocean through the Nemuro Strait in 2008

Tatsuo Motoi[1], Wing-Le Chan[2], Takuya Miyakawa[3] and Norihisa Usui[1]

1: Meteorological Research Institute, JMA
2: Frontier Research Center for Global Change, JAMSTEC
3: Meteorological Satellite Center, JMA

Abstract

Observations from the satellite, Multi-functional Transport Satellite (MTSAT)-1R, show that Okhotsk sea ice flowed southward in the Nemuro Strait and reached the northern coast of the Nemuro peninsula on 25 February 2008. Wind data observed at Nossapu Cape and Rausu town indicate that north-northwesterly to northwesterly winter monsoon wind with speeds of 5 to 10 m/s blew across the sea surface all day long and drove sea surface ice and water southward.

Sea-ice drift from the Nemuro Strait through the Goyoumai Pass to the Pacific Ocean was clearly observed on 28 and 29 February by MTSAT-1R. The observed direction of the sea-ice drift in the Pacific was distinctly southwestward during this period against west-northwesterly to southwesterly wind of speeds 2 to 8 m/s. Oyashio Current is a possible factor for southwestward drift of sea ice.

Sea-ice flow from the Nemuro Strait through the Goyoumai Pass and its drift in the Pacific Ocean were also observed on 2, 3, 7, 8 and 9 March by MTSAT-1R. In these cases, the path of sea-ice drift was near the coast along Coastal Oyashio Current. Sea ice finally floated off Tokachi District and parts of them reached the shores of the Pacific coast of the southeastern Hokkaido around Kushiro city on 8 March due to westerly to south-southwesterly wind of 3 to 18 m/s which started on 7 March and continued until 9 March.

1. Introduction

Okhotsk sea ice reached the shores of the Pacific coast of southeastern Hokkaido, around Kushiro city on 8 March 2008. During late February to early March, sea ice usually drifts into the Nemuro Strait from the Sea of Okhotsk and flows to the Pacific Ocean through the Goyoumai Pass. However, sea ice does not reach the shores of the Pacific coast of Hokkaido frequently.

Uda and Watanabe (1936) reported sea-ice drift off the Pacific coast of southeast of Hokkaido. Uda (1943) and Akagawa (1959) study melting process of drifting sea ice in this region by theoretical approach. Akagawa (1964) pointed out a hazard of sea ice to

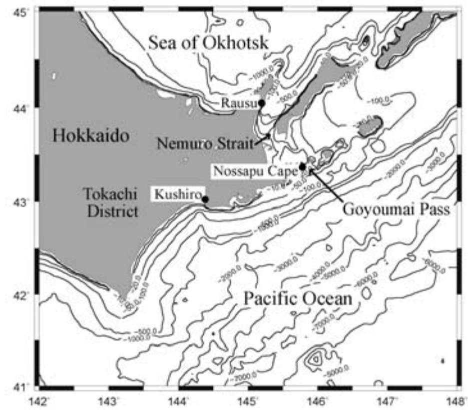

Fig. 1 Land-sea distribution and bottom topography (10, 20, 50, 100, 500, 1000, 2000, 3000, 4000, 5000, 6000, 7000m) in the study area. Nemuro Strait and Goyoumai Pass are pointed by arrows. Rausu town, Nossapu Cape, and Kushiro city are marked by solid circles.

shipping and fishery, focusing on the drifting of sea ice in the Pacific Ocean.

Sea ice carries freshwater, salt, organic matter, stones and nutrients, which provide a productive environment for creatures, for example, phytoplankton, zooplankton, seaweed, shellfish, fishes and mammals. These include ice algae, krill, tangle, sea urchins, scallops, abalone, crabs, Walleye Pollock, seals, dolphins and whales. However, sea ice sometimes poses a threat to seaweed, especially tangle, by scraping along on the shores which causes continual damage to the ecosystem.

Floating sea ice can block access to bays, ports and navigation routes, disrupting both the transport of goods and the economic infrastructure. One dangerous aspect of sea ice is its ability to damage ships and cause disasters at sea. On 17 March 1970, sea ice destroyed 8 fishing boats and 30 fishermen went missing as they attempted to make their way to Hitokappu Bay on Etorofu Island while fleeing a severe storm in the Pacific Ocean.

Okhotsk Sea gateways such as the Soya and Nemuro Straits play an important role in the environment of the Japan Sea and the Pacific Ocean by transporting sea ice through them from the Sea of Okhotsk. Sea-ice rafted materials are carried to remote area through the gateways. Figure 1 shows the land-sea distribution and bottom topography in a study area. Goyoumai Pass, to the south of the Nemuro Strait, is the most important gateway for the Pacific coast of eastern Hokkaido since it faces Nossapu Cape and is closest to the coast of eastern Hokkaido.

The purpose of the present study is to investigate the path of sea-ice drift and to detect the dominant forcing factors of the drift, focusing on the drift and reaching the shores of the Pacific coast of southeastern Hokkaido around Kushiro on 8 March 2008. In section 2, the dataset used in this study is described. Four observed events of sea-ice drift, which are southward sea-ice drift in the Nemuro Strait, sea-ice drift along Oyashio Current, sea-ice drift along Coastal Oyashio Current and sea-ice drift reaching the shores of southeastern Hokkaido around Kushiro in late February and early March, are presented in chapter 3,4,5 and 6, respectively. In section 7, we discuss the problems of Okhotsk sea-ice drifting to adjacent oceans through the gateways. A summary of the results and our proposal for future work are presented in the final section.

2. Dataset

The data used in this study are satellite data, atmospheric reanalysis data, meteorological data at observational stations and oceanic reanalysis data. Satellite data are obtained by Multi-functional Transport Satellite (MTSAT)-1R visible sensor for each hour. Atmospheric reanalysis data are daily wind stress from the Japanese 25-year Reanalysis Project (JRA25)(Onogi et al., 2007). Meteorological data are wind data observed at Rausu town, Nossapu Cape and Kushiro city. Oceanic reanalysis data is daily surface current from MOVE/MRI.COM-WNP, which is western North Pacific version of Meteorological Research Institute multivariate ocean variational estimation (MOVE) system (Usui et al., 2006) using Meteorological Research Institute community ocean model (MRI.COM)(Ishikawa et al., 2005; Tsujino and Fujii, 2007; Nakano et al., 2008). The model does not represent tidal currents explicitly but tidal mixing is expressed by the estimation of St. Laurent et al. (2002).

In order to study sea-ice drift, clear MTSAT-1R images of hourly sea-ice conditions on 25, 28 to 29 February, 2 to 3, and 7 to 9 March are selected. The spatial resolution of the satellite observation is 1 km, which can resolve narrow sea ice bands and streams of about 10 km. The time resolution of the satellite observation is one hour, which is suitable for studying sea-ice drift with timescales of about one to three days.

3. Southward sea-ice drift in the Nemuro Strait

Okhotsk sea ice piled up off Rausu town and flowed southward in the Nemuro Strait in late February 2008. Figure 2 shows sea-ice conditions in the Nemuro Strait at 10 and 16 in JST on 25 February, observed by MTSAT-1R. Sea ice moved southward by 8 km within 6 hours, with an average speed of about 35 cm/s. It reached the northern coast of the Nemuro peninsula at 16 JST.

As shown in Fig.3, a low-pressure field developed in the northern North Pacific. Strong northwesterly

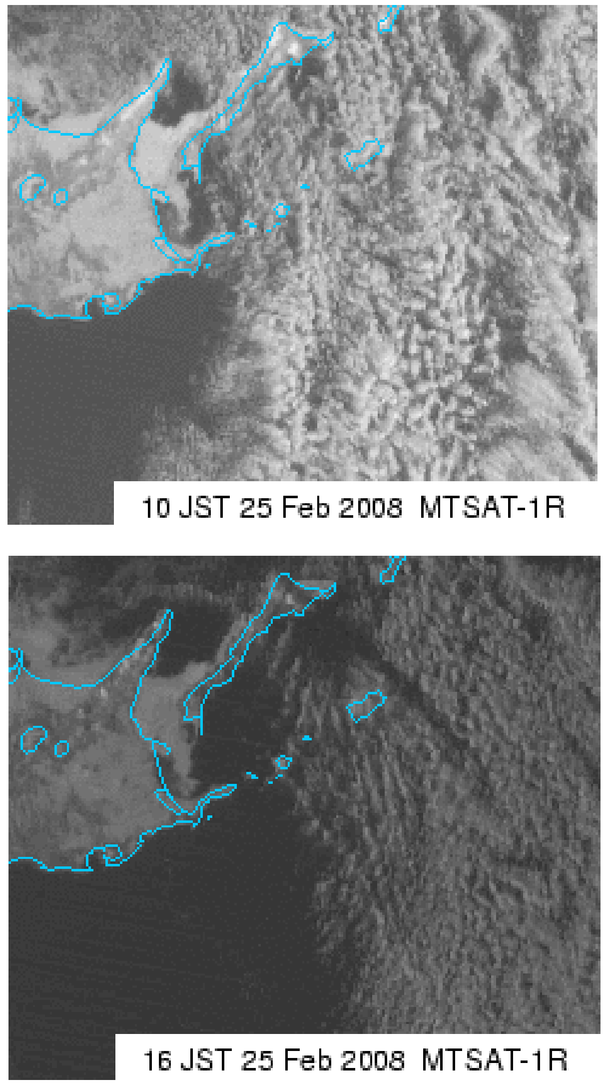

Fig. 2 Sea-ice conditions in the Nemuro Strait at 10 (upper panel) and 16 (lower panel) in Japan Standard Time on 25 February 2008, observed by Multi-functional Transport Satellite (MTSAT)-1R.

wind with a cold surge was induced in the southwestern part of the low-pressure field, and passed over Rausu town and Nossapu Cape on 25 February. Clouds of Karman Vortex in the upper right corner of fig.2 clearly reveal the north-northwestern wind over the ocean off eastern Hokkaido at 10 JST (Japan Standard Time), 25 February.

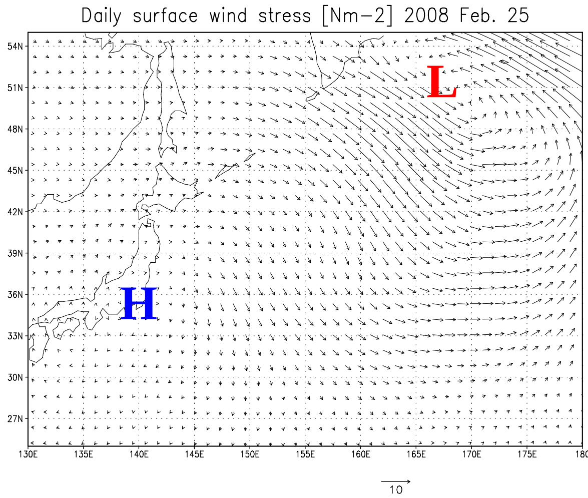

Fig. 3 Daily surface wind stress on 25 February 2008 from JRA-25. Unit is N/m^2.

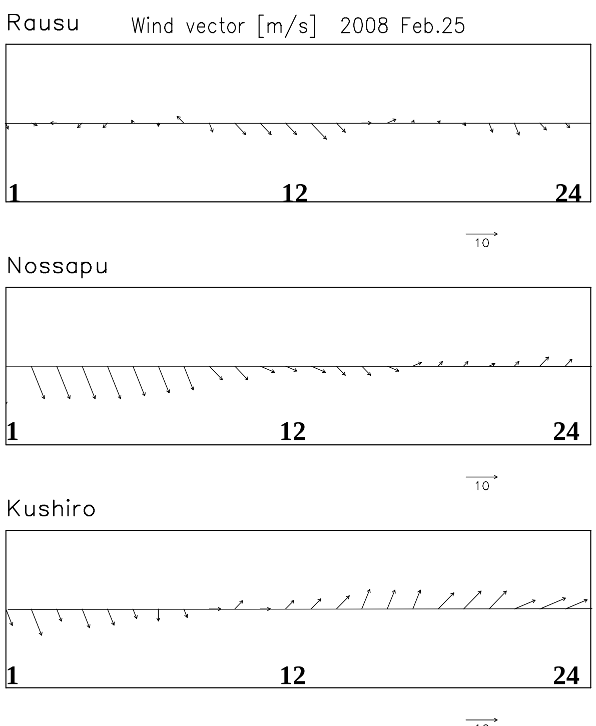

Fig. 4 Wind vectors for each hour on 25 February 2008 at observational station in Rausu town, Nossapu Cape and Kushiro city. North and east are up and right. Unit is m/s.

Wind vectors for each hour on 25 February at observational stations in Rausu town, Nossapu Cape and Kushiro city are shown in Fig.4. The data at Rausu town and Nossapu Cape indicate that north-northwesterly to northwesterly winter monsoon winds with speeds of 5 to 10 m/s blew across the sea ice continuously for more than a half day.

Figure 5 shows the surface current around eastern Hokkaido on 25 February from MOVE/MRI.COM-WNP. Oyashio Current flows southwestward over the continental slope along the contours of 2000 to 5000 m depth (see fig. 1) with about 80 km width, influenced by an anti-cyclonic eddy of about 160 km in diameter. The speed of the Oyashio Current is estimated to be 60 cm/s in the center of its jet. In the Sea of Okhotsk, meandering currents with speeds of of 35 cm/s are represented by a 30 km width along the contours of depths 100 to 1000 m north of Shiretoko Peninsula and Kunashiri Island. Over the continental shelf, at depths shallower than 100 m, a Coastal Oyashio Current of width 20 km develops with a west-southwestward velocity of 30 cm/s along the Pacific coast around the Goyoumai Pass.

A weak southward current of 10 cm/s is produced in the Nemuro Strait, connecting the Okhotsk meandering current with the Coastal Oyashio Current. A southward flow of sea ice and surface water was driven by north-northwesterly to northwesterly wind which blew across the Nemuro Strait all day long.

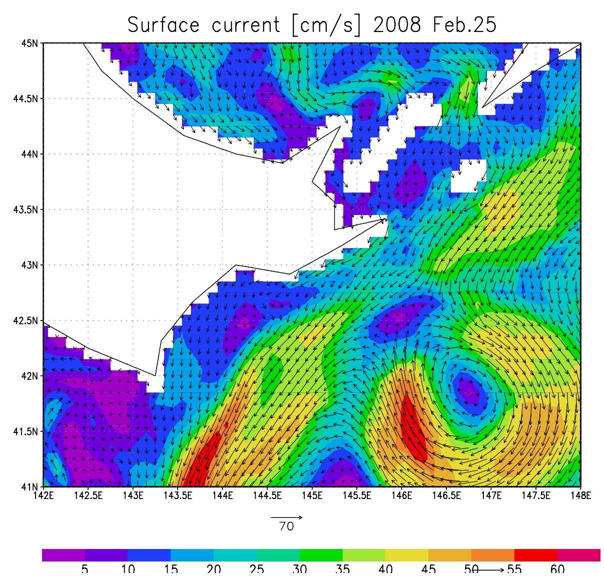

Fig. 5 Daily surface current around the eastern Hokkaido on 25 February 2008 from MOVE/MRI.COM-WNP. Unit is cm/s.

4. Sea-ice drift along Oyashio Current

Figure 6 shows sea-ice conditions off the southeastern coast of Hokkaido at 10 JST on 28 and 29 February by MTSAT-1R. It is revealed that sea ice flowed out east-southeastward from the Nemuro Strait to the Pacific through the Goyoumai Pass. After sea ice flowed out to the Pacific, it turned southwestward as it crossed the Coastal Oyashio Current. The southwestward drift of sea ice continued for 50 km off the southeastern coast of Hokkaido along the Oyashio Current, forming a sea-ice band of about 10 km. The southern most edge of the sea-ice band moved about 25km during one day, from 28 to 29 February, with an average speed of about 30 cm/s.

The sea-ice band had a wavy structure with a wavelength of about 10km. The band usually consists of many sizes, thickness and types of floes such as rotten ice, brash ice, small floe and hummock ice. Sea

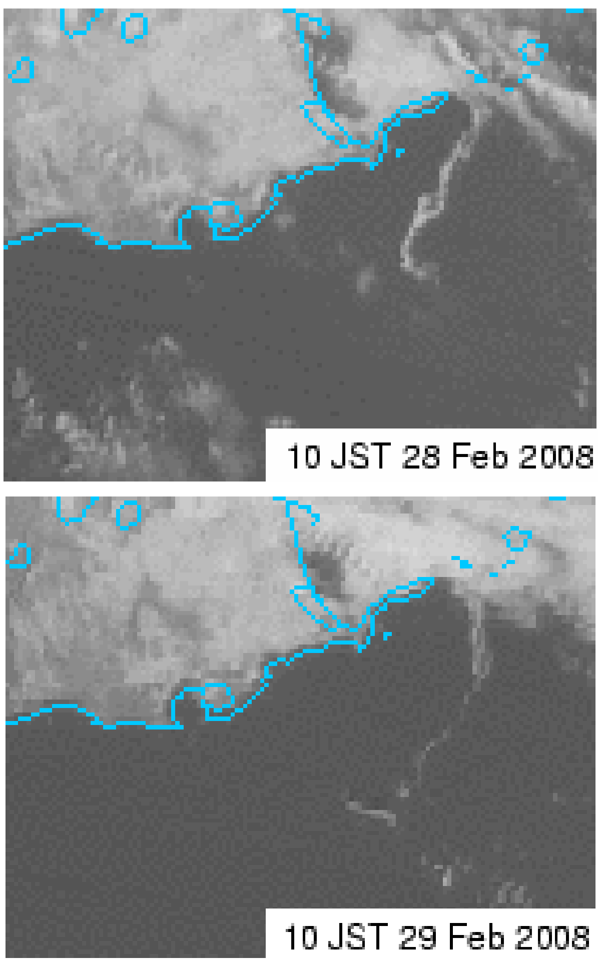

Fig. 6 Sea-ice conditions off the southeastern coast of Hokkaido at 10 in Japan Standard Time on 28 (upper panel) and 29 (lower panel) February 2008, observed by Multi-functional Transport Satellite (MTSAT)-1R.

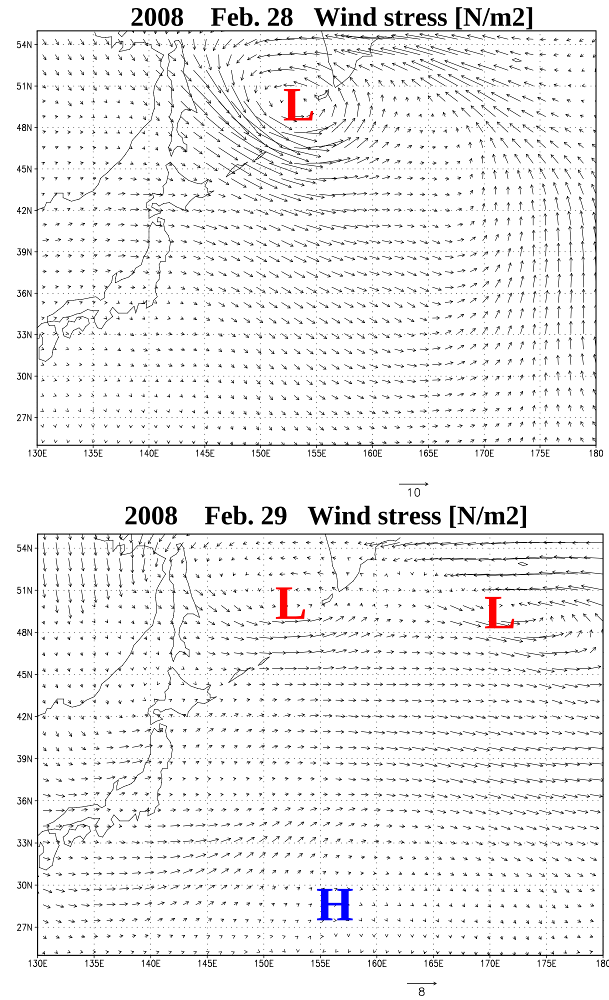

Fig. 7 Daily surface wind stress over the northwestern North Pacific and the adjacent seas on 28 (upper panel) and 29 (lower panel) February 2008 from JRA-25. Unit is N/m^2.

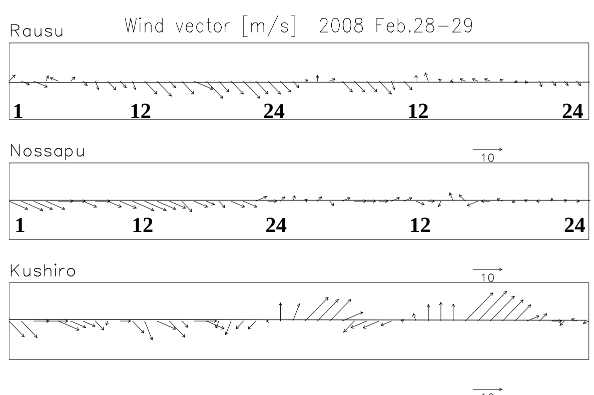

Fig. 8 Wind vectors for each hour at observational stations in Rausu town, Nossapu Cape and Kushiro city on 28 and 29 February 2008. Northerly wind is shown as downward. Unit is m/s.

ice in the southern part of the band melted on 29 February, probably due to heating from warmer seawater above freezing point in the warm and saline open ocean region.

Reanalyzed daily surface wind stress fields over the northwestern North Pacific and the adjacent seas on 28 and 29 February are shown in Fig.7. A low-pressure field developed southwest of Kamchatka in the Sea of Okhotsk. Cyclonic winds in a low-pressure field cause west-northwesterly to southwesterly winds in the southern region off the southeastern coast of Hokkaido. Figure 8 shows wind vectors for each hour at observational stations in Rausu town, Nossapu Cape and Kushiro city on 28 and 29 February. West-northwesterly and southwesterly winds were clearly observed as the dominant winds with a maximum wind speed of 8m/s. The direction of the wind off the

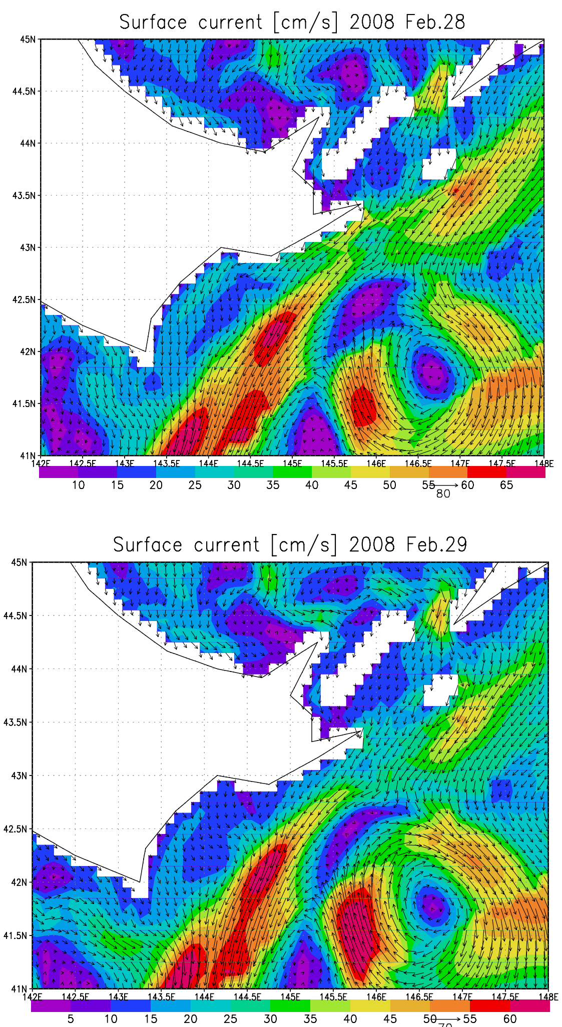

Fig. 9 Daily surface current around the eastern Hokkaido on 28 (upper panel) and 29 (lower panel) February 2008 from MOVE/MRI.COM-WNP. Unit is cm/s.

southeastern coast of Hokkaido is west-northwesterly to southwesterly as shown in Fig.7, which is different from that of sea-ice drift toward the southwest as shown in Fig.6.

Figure 9 shows daily surface currents around eastern Hokkaido on 28 and 29 February from MOVE/MRI.COM-WNP. The Oyashio Current flows mainly southwestward off the southeastern coast of Hokkaido as seen in fig.5 and 9. The direction and magnitude of the sea-ice drift shown in Fig.6 are the same as those of the Oyashio Current.

From atmospheric and oceanic reanalyzed data, it is seen that sea-ice drifts southwestward along the Oyashio Current against a west-northwesterly to southwesterly wind on 28 and 29 February. The southwestward drift of sea ice is probably driven by water stress due to the Oyashio Current.

5. Sea-ice drift along Coastal Oyashio Current

MTSAT-1R clearly observed sea-ice drift along the Coastal Oyashio Current from 2 to 3 March 2008. Figure 10 shows sea-ice conditions off the southeastern coast of Hokkaido at 11 JST on 2 and 3 March 2008. Sea ice flowed from Goyoumai Pass and spread west-southwestward, forming an extended sea-ice band about 20 km off the coast. The southern most edge of sea-ice band moved about 35km during one day, from 2 to 3 March, with an average speed of about 40 cm/s.

The sea-ice band had a wavy structure with wavelength of about 10km, similar to that observed on 28 and 29 February. However, it drifted closer to the coast and remained intact for a longer time, probably due to the colder sea water (near freezing point) around it.

Reanalyzed daily surface wind stress fields over the northwestern North Pacific and the adjacent seas on 2 and 3 March are shown in Fig.11. A low-pressure field developed south of Kamchatka and cyclonic winds blew around it. The cyclonic wind system induces a northwesterly wind over eastern Hokkaido. The strength of the northwesterly wind stress was less than 1 N/m2.

Figure 12 shows wind vectors for each hour at observational stations in Rausu town, Nossapu Cape and Kushiro city on 2 and 3 March 2008. Northwesterly winds were observed to be the dominant winds at stations in Rausu town and Nossapu Cape with a maximum wind speed of 5m/s.

As revelaed in fig.11, the direction of the wind off the southeastern coast of Hokkaido is northwesterly, different from the southwestward direction of sea-ice drift, as shown in Fig.10.

Figure 13 shows the daily surface current around eastern Hokkaido on 2 and 3 March 2008 from MOVE/MRI.COM-WNP.West-southwestward Coastal Oyashio Current flowed south of the Goyoumai Pass and developed significantly, with speeds of 30 to 40 cm/s, on 3 March. The directions and magnitudes were exactly the same as those for sea-ice drift observed off the southeastern coast of Hokkaido (see fig.10).

These atmospheric and oceanic reanalyzed data suggest that observed west-southwestward sea-ice drift on 2 and 3 March is probably driven mainly by water stress due to the development of the Coastal Oyashio Current. Both the Oyashio Current over the continental slope and anti-cyclonic eddy in the open ocean are clearly revealed in Figs. 5, 9 and 13. However, the Coastal Oyashio Current varied over a shorter time scale (days). Coastal ocean response to the atmospheric cyclone might be a key factor in the variability of the Coastal Oyashio Current and sea-ice drift along it.

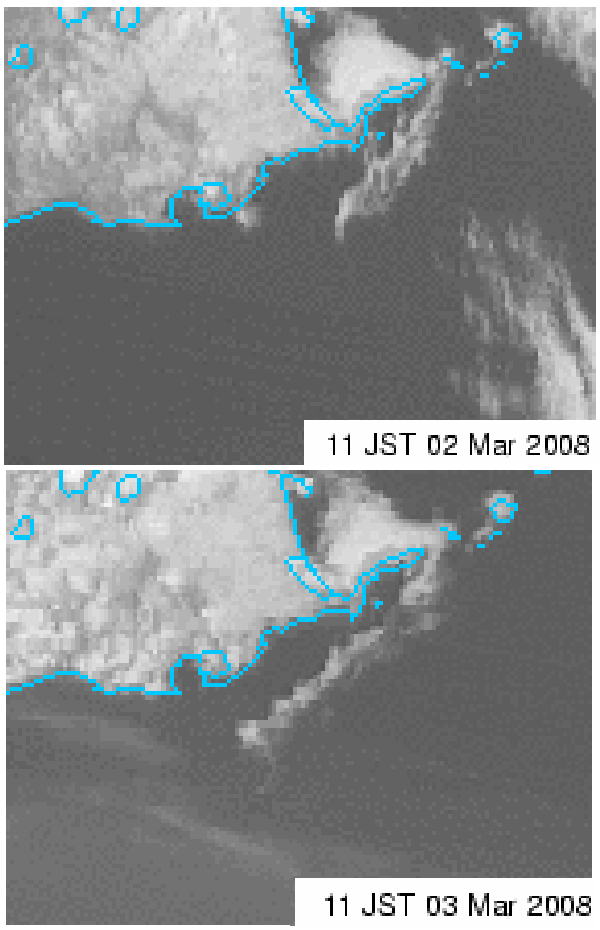

Fig. 10 Sea-ice conditions off the southeastern coast of Hokkaido at 11 in Japan Standard Time on 2 (upper panel) and 3 (lower panel) March 2008, observed by Multi-functional Transport Satellite (MTSAT)-1R

.

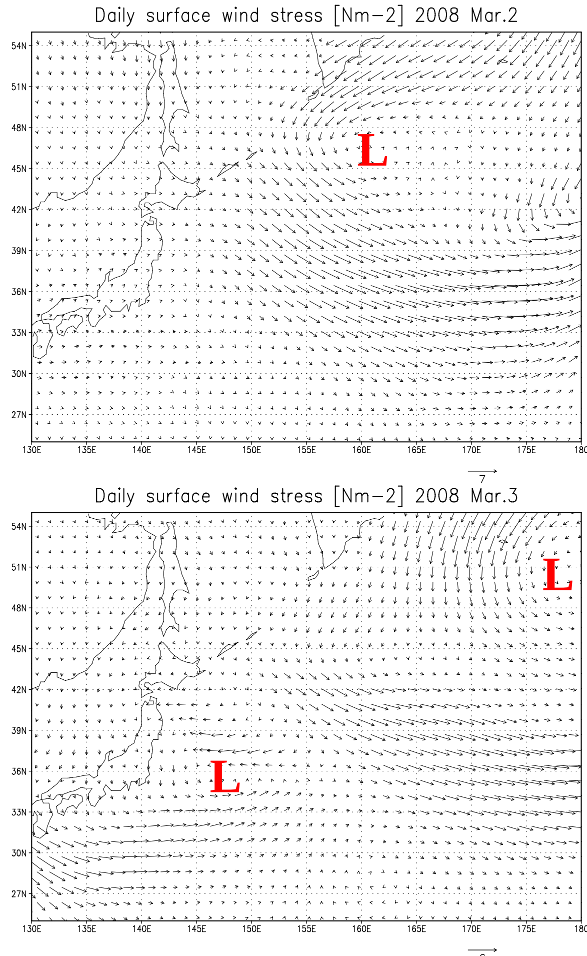

Fig. 11 Daily surface wind stress over the northwestern North Pacific and the adjacent seas on 2 (upper panel) and 3 (lower panel) March 2008 from JRA-25. Unit is N/m^2.

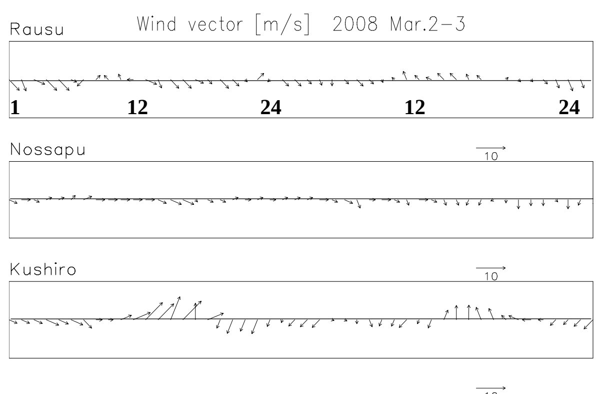

Fig. 12 Wind vectors for each hour at observational station in Rausu town, Nossapu Cape and Kushiro city on 2 and 3 March 2008. Northerly wind is shown as downward. Unit is m/s.

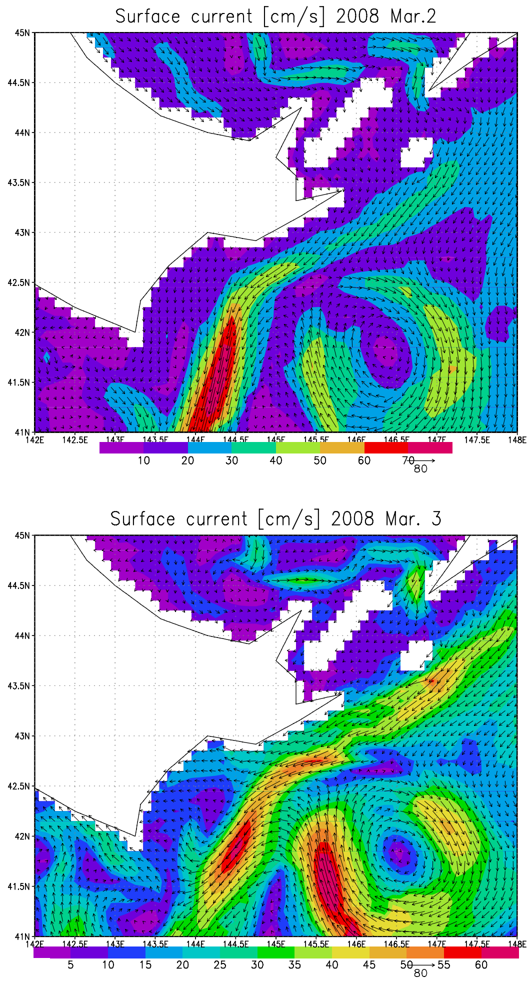

Fig. 13 Daily surface current around eastern Hokkaido on 2 (upper panel) and 3 (lower panel) March 2008 from MOVE/MRI.COM-WNP. Unit is cm/s.

6. Sea-ice drift reaches the shores of southeastern Hokkaido around Kushiro

Sea ice drifted off the southeastern coast of Hokkaido from the Goyoumai Pass to the eastern coast of Tokachi District on 7 to 9 March 2008. Figure 14 shows sea-ice bands and streams floating in this region, as observed by MTSAT-1R. Parts of the floating sea ice reached the southeastern coast of Hokkaido and the shores around Kushiro on 8 March 2008.

During this period, the atmospheric pressure field featured a low pressure in central Okhotsk Sea and a high pressure south of Hokkaido, causing westerly to south-southwesterly winds off the southeastern coast of Hokkaido as shown in Fig.15. Figure 16 shows the wind vectors for each hour at observational stations in Rausu town, Nossapu Cape and Kushiro city from 7 to 9 March 2008. Westerly to south-southwesterly winds

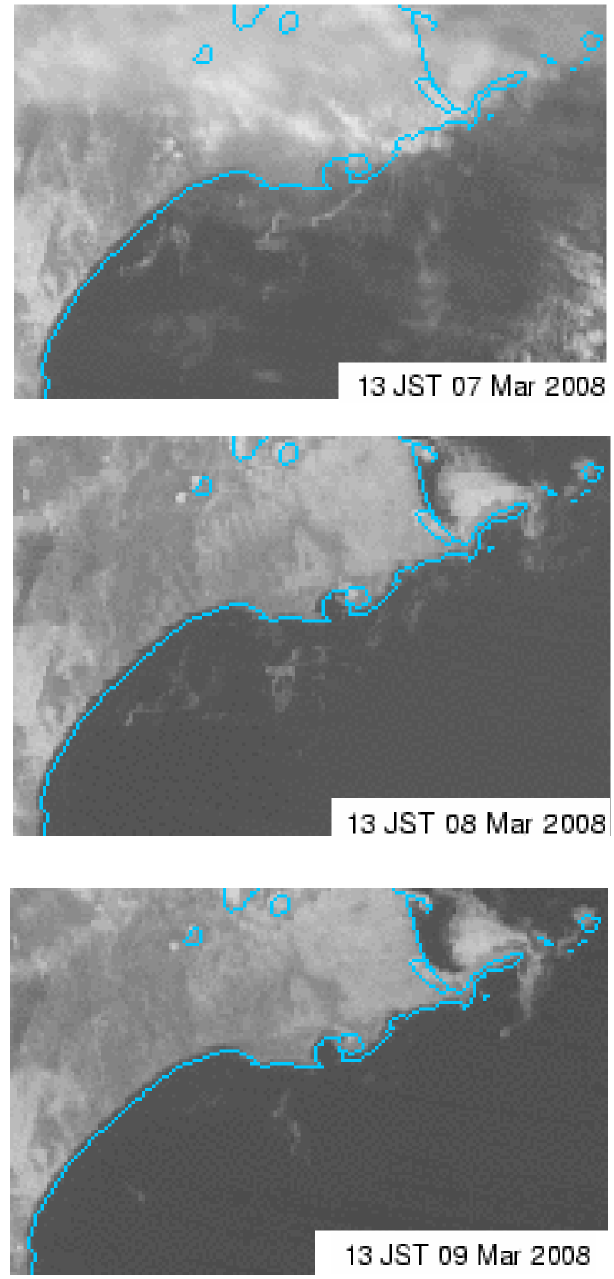

Fig. 14 Sea-ice conditions off southeastern coast of Hokkaido at 13 in Japan Standard Time on 7 (top panel), 8 (middle panel) and 9 (bottom panel) March 2008, observed by Multi-functional Transport Satellite (MTSAT)-1R.

were observed at stations in Nopssapu Cape and Kushiro city for three days, with speeds of 3 to 18 cm/s.

The Coastal Oyashio Current is estimated to have weakened to less than 10 cm/s (see Fig.17), while the Oyashio Current and anti-cyclonic eddy are

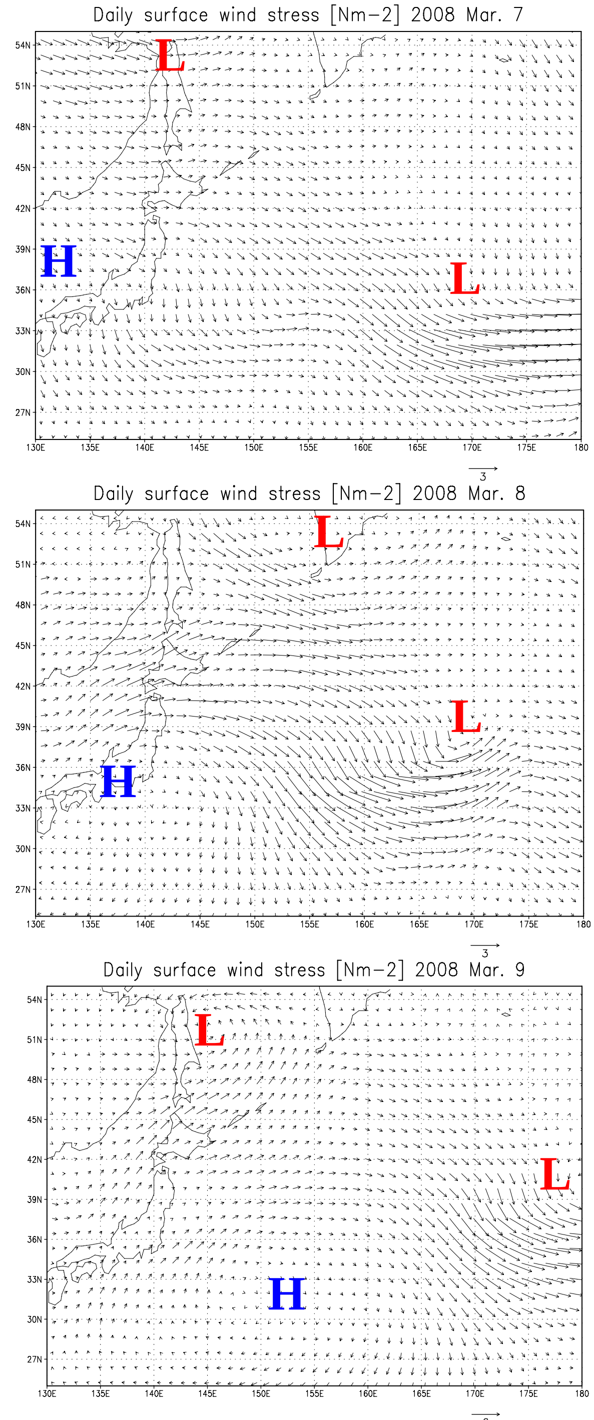

Fig. 15 Daily surface wind stress over the northwestern North Pacific and its adjacent sea on 7 (top panel), 8(middle panel) and 9 (bottom panel) March 2008 from JRA-25. Unit is N/m^2.

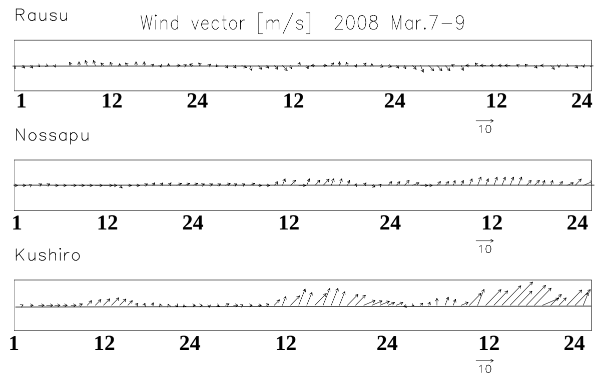

Fig. 16 Wind vectors for each hour at observational station in Rausu town, Nossapu Cape and Kushiro city on 7 to 9 March 2008. Northerly wind is shown as downward. Unit is m/s.

represented as stronger currents over the continental slope. The direction of the Coastal Oyashio Current is off shore south of Kushiro, which is opposite to that of sea-ice drift toward the shore around Kushiro. Based on atmospheric and oceanic reanalysis data, a possible factor for sea-ice reaching the shores of the southeastern coast of Hokkaido around Kushiro on 8 March 2008 is a strong westerly to south-southwesterly wind, lasting for several days near the coast.

7. Discussion

The path of sea-ice drift along the Coastal Oyashio Current is clearly observed by MTSAT-1R. Sea ice melts during the drift and, as Ohtani (1989) mentions, acts as a freshwater source for the Coastal Oyashio water which is cold and has low-salinity. Nakamura et al. (2003) and Kono et al. (2004) studied the Coastal Oyashio by model simulation and successfully reproduced the Coastal Oyashio Current, consistent with the sea-ice path identified in the present study. Sea-ice drift from the Sea of Okhotsk to the Coastal Oyashio region through the Nemuro Strait is direct evidence supporting the mixing process presented by Oguma et al. (2008) from isotopic tracers.

Besides present-day sea-ice and Coastal Oyashio water conditions mentioned above, Last Glacial Maximum (LGM) conditions of sea ice and water are also important for the study of the sensitivity of sea ice and water in the environment. Ikehara (2003) and Sakamoto et al. (2005) reconstructed the history of sea ice in the Japan Sea and the Sea of Okhotsk, respectively. Sea ice might extend to lower latitudes in LGM. Oba (2006) reconstructs sea surface temperature

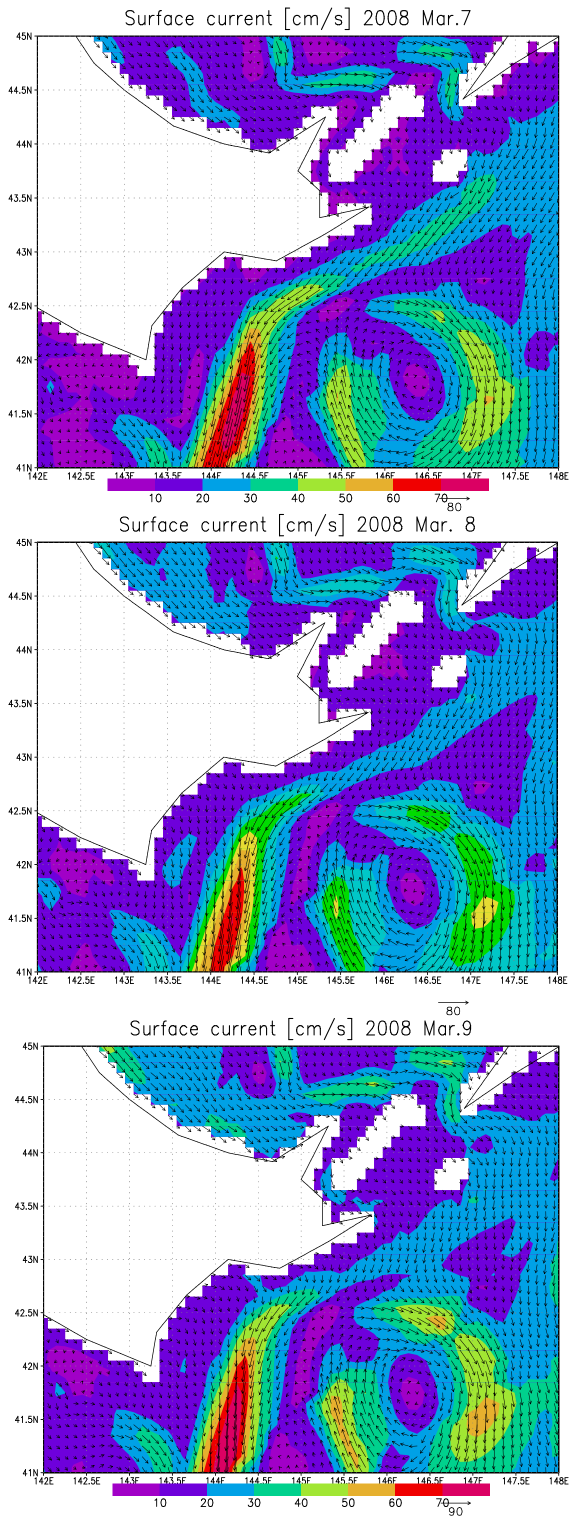

Fig. 17 Daily surface current around eastern Hokkaido on 7 (top panel), 8(middle panel) and 9 (bottom panel) March 2008 from MOVE-MRI.COM-WNP. Unit is cm/s.

temperature (SST) in western North Pacific and estimates SST to be about 20 degree lower in the LGM over the present-day Kuroshio extension region, which suggests that sea-ice drifted to lower latitudes along currents with eddies and streamers off the eastern coast of Honshu, the central island of Japan.

In any epoch, whether the present day, the LGM or in a future global warming world, sea-ice trajectory can be expressed by Newton's second law of motion with Corioli's force. Wind and current induce air and water drag and work as a driving force for sea-ice drift. Sea-ice trajectory observed in the present study should be expressed by forces from both the wind and current. By solving the momentum equation of sea ice, its trajectory can be represented and the driving force on it analyzed, as Smith (1993), Bigg et al. (1997), Matsumoto (1997) and Gladstone et al. (2001) have done for icebergs.

8. Summary

The path of sea-ice drift from the Sea of Okhotsk to the Pacific Ocean during late February to early March, 2008 is investigated and the dominant forcing factors of the drift are detected for four sea-ice drift events, which are (1) southward sea-ice drift in the Nemuro Strait on 25 February, (2) sea-ice drift along the Oyashio Current on 28 to 29 February, (3) sea-ice drift along the Coastal Oyashio Current on 2 to 3 March and (4) Sea-ice drift reaching the shores of the Pacific coast of southeastern Hokkaido around Kushiro on 7 to 9 March.

As summarized in Fig.18, wind data observed at Nossapu Cape and Rausu town reveal that north-northwesterly to northwesterly wind with speeds of 5 to 10 m/s drove sea surface ice and water southward on 25 February all day long.The sea-ice outflow from the Nemuro Strait through the Goyoumai Pass to the Pacific Ocean resulted in a distinct southwestward drift of sea ice against west-northwesterly to southwesterly winds of speeds 2 to 8 m/s, which suggests that the Oyashio Current is a possible factor for the southwestward drift of sea ice on 28 to 29 February.

In the case of Okhotsk sea-ice flow into the Pacific Ocean through the Goyoumai Pass on 2, 3, 7, 8 and 9, the path of sea-ice drift was near the coast along the Coastal Oyashio Current. Sea ice reached Tokachi District and parts of them reached the shores of the Pacific coast of southeastern Hokkaido around Kushiro city on 8 March due to westerly to south-southwesterly winds with speeds of 3 to 18 m/s. These winds started on 7 March and continued for three days.

It has been shown that the Goyoumai Pass and the Coastal Oyashio Current are key factors in the drift of Okhotsk sea ice in the Pacific. Based on the present research, our proposal for future work is to study the role of Okhotsk sea-ice drift through gateways such as the Soya Strait, the Nemuro Strait and the Goyoumai Pass which links the Sea of Okhotsk to the Japan Sea and the Pacific Ocean. We hope to use satellite sea-ice data, ocean and atmosphere reanalysis data and a sea-ice trajectory model for analysis of sea-ice drift driving forces and sea-ice rafted material fluxes.

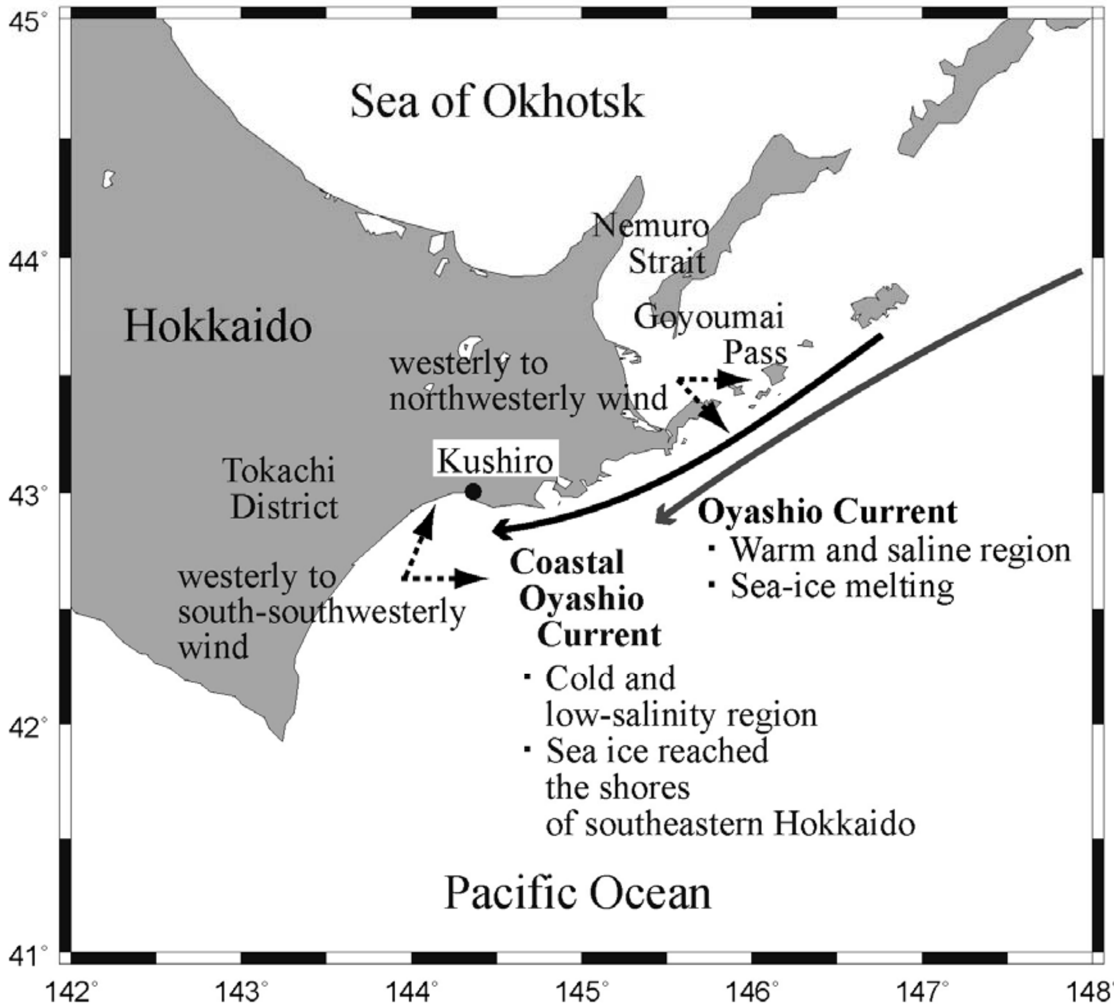

Fig. 18 Schematic view summarizing our findings. Winds in the Goyoumai Pass and off the coast of Kushiro are key factors for sea-ice spreading into the Pacific from the Nemuro Strait and reaching the shores around Kushiro off Tokachi District, respectively. The Coastal Oyashio Current is a key factor for west-southwestward sea-ice drift from the south of Goyoumai Pass to the east of Tokachi District along the southeastern coast of Hokkaido.

Acknowledgement

We wish to thank Dr. Makoto Kashiwai for recommending us to present our research at the 4th PICES Workshop on the Okhotsk Sea and Adjacent Waters. We also appreciate Mrs. Yukiko Suda's assistance in preparing this paper. The research was partially supported by a grant from the Ministry of Education, Culture, Sports Science and Technology, Grant-in-Aid for Scientific Research No.20540433.

References

Akagawa, M. 1959. On the Melting of Pac-Ice Field. *Kenkyu Jihou.*, **11**: 921-932 (in Japanese with English abstract).

Akagawa, M. 1964. On the Drifting of Pac-Ice in the Pacific Ocean off Hokkaido. *Bull. of the Hakodate Marine Observatory.*, **11**: 50-65 (in Japanese with English abstract).

Bigg, G.R., Wadley, M.R., Stevens, D.P. and Johnson J.A. 1997. Modelling the dynamics and thermodynamics of icebergs. *Cold Regions Science and Technology*, **26**: 113-135.

Gladstone, R.M., Bigg, G.R. and Nicholls K.W. 2001. Iceberg trajectory modeling and meltwater injection in the Southern Ocean. *J. Geophys. Res.*, **106**(C9):19903-19915.

Ikehara, K. 2003. Late Quaternary seasonal sea-ice history of the north-eastern Japan Sea. *J. Oceanogr.*, **59**: 585-593.

Ishikawa, I., Tsujino, H., Hirabara, M., Nakano, H., Yasuda, T. and Ishizaki, H. 2005. Meteorological Research Institute Community Ocean Model (MRI.COM) Manual. *Technical Reports of the Meteorological Research Institute*, No.47: p189 (in Japanese).

Kono, T., Foreman, M., Chandler, P. and Kashiwai, M. 2004. Coastal Oyashio South of Hokkaido, Japan. *J. Phys. Oceanogr.*, **34**: 1477-1494.

Matsumoto, K. 1997. Modeled glacial North Atlantic ice-rafted debris pattern and its sensitivity to various boundary conditions. *Paleoceanography*, **12**(2): 271-280.

Nakamura, T., Awaji, T., Toyoda, T. and Ishikawa, Y. 2003. Coastal Oyashio in a North Pacific Simulation Experiment. *Bull. on Coastal Oceanogr.* **41**(1): 13-22 (in Japanese with English abstract).

Nakano, H., Hirabara, M., Tsujino, H. and Motoi, T. 2008. Development of a global ocean model with the resolution of 1°x1/2° and 1/8°x1/12°.*CLIVAR Exchanges*, **13**(1):11-13.

Oba, T. 2006. Paleoenvironmental changes in the Japan Sea and off Kashima over the Last 150 kyr based on Oxygen and Carbon isotopes of Foraminiferal tests. *J. Geography*, **115**:652-660.

Oguma, S., Ono, T., Kusaka, A., Kasai, H., Kawasaki, Y. and Azumaya, T. 2008. Isotopic Tracers for Water Masses in the Coastal Region of Eastern Hokkaido. *J. Oceanogr.*, **64**: 525-539.

Ohtani, K. 1989. The role of the Sea of Okhotsk on the formation of the Oyashio water. *Umi to Sora*, **65**(2): 63-83 (in Japanese with English abstract)

Onogi, K., Tsutsui, J., Koide, H., Sakamoto, M., Kobayashi, S., Hatsushika, H., Matsumoto, T., Yamazaki, N., Kamahori, H., Takahashi, K., Kadokura, S., Wada, K., Kato, K., Oyama, R., Ose, T., Mannoji, N. andTaira, R. 2007. The JRA-25 Reanalysis. *J. Meteor. Soc. Japan*, **85**: 369-432.

Sakamoto, T., Ikehara, M., Aoki, K., Iijima, K., Kimura, N., Nakatsuka, T. and Wakatsuchi, M. 2005. Ice-rafted debris (IRD)-based sea-ice expansion events during the past 100kyrs in the Okhotsk Sea. *Deep-Sea Res. II*, **52**: 2275-2301.

Smith, S.D. 1993. Hindcasting iceberg drift using current profiles and winds. *Cold Regions Science and Technology*, **22**: 33-45.

St. Laurent, L., Simmons, H. L.and Jayne, S.R. 2002. Estimating tidally driven mixing in the deep ocean. *Geophys. Res. Lett*., doi:10.1029/2002GL015633.

Tsujino, H. and Fujii, Y. 2007. Improved representation of currents and water masses in the upper layer of the North Pacific Ocean in eddy-resolving OGCMs. *CLIVAR Exchanges*, **12**(3): 19-21.

Uda, M. and Watanabe, N. 1936. *Kagaku*, **6** (5): 192-193 (in Japanese).

Uda, M. 1943. *Seppyou*, **5**(2): 43-47.(in Japanese).

Usui, N., Ishizaki, S., Fujii, Y., Tsujino, H., Yasuda, T. and Kamachi, M. 2006. Meteorological Research Institute multivariate ocean variational estimation (MOVE) system: Some early results. *Adv. Space Res.*, **37**: 806-822.