5.7

ROLE OF SEA-ICE IN THE AIR MASS TRANSFORMATION OVER THE SOUTH-WESTERN REGION OF THE SEA OF OKHOTSK DURING COLD AIR OUTBREAKS

*Jun Inoue[1], Meiji Honda[2] and Masayuki Kawashima[1]
[1]Inst. Low Temperature Science, Hokkaido Univ., Sapporo, Japan
[2]Inst. Global Change Research, Frontier Research System for Global Change, Tokyo, Japan

1. INTRODUCTION

In winter, when cold air masses break out from a continent or sea-ice, air mass transformation occurs over the ocean covered with sea-ice. The Sea of Okhotsk, which is well known as one of the southernmost seasonal ice regions in the Northern Hemisphere, is characterized by low sea surface temperature (SST) and sea-ice. For better understanding of the air-ice-sea interaction of the Sea of Okhotsk, it is important to estimate the surface turbulent heat fluxes over the ice-covered condition. The main purpose of this study (Inoue et al. 2001) is to investigate the air mass transformation during cold-air outbreak events by estimating averaged turbulent heat fluxes based on two indirect methods using in-situ observational data and the sounding data observed around the southwestern Sea of Okhotsk.

2. DATA

Figure 1 shows our observational / analysis area. During the period from 26 January to 11 February 1998, we launched the GPS (Global Positioning System) sondes at Shari, Wakkanai and Yuzhno-Sakhalinsk are the operational sounding stations. The data are available at every 6 hours (00, 06, 12 and 18 UTC) for Shari and Yuzhno-Sakhalinsk and every 12 hours for Wakkanai (00 and 12 UTC). The maritime meteorological data (i.e. air temperature, wind velocity, humidity, cloud amount and shortwave radiation) and sea-ice data were obtained by the ice-breaker "SOYA" which cruised around the southwestern Sea of Okhotsk from 4 - 11 February. Ice thickness was monitored by a downward-looking video camera mounted at the side deck of the ship. We obtained 2016 samples of ice thickness. Three cold-air outbreak events for a few days were captured during the observation. We decided the analysis periods (cases-A, -B and -C) by considering the observed winds and surface weather maps. In case-C, maritime meteorological data observed on the SOYA are available.

3. METHODS

The atmospheric heat budget formulation and notations used in the present analysis are basically the same as those in Ninomiya (1975). We obtained the mean vertical velocity from the equation of mass continuity averaged over the analysis area. The equations of heat and moisture continuity in the p-coordinate,

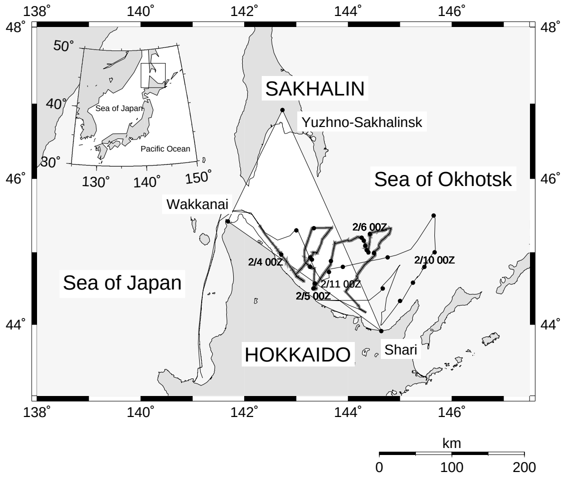

Figure 1: Locations of aerological stations (closed circles) and the cruise course of the "SOYA" (solid line). The white triangle area denotes the area where heat budget calculations are made using the upper air soundings at three stations (Shari, Wakkanai and Yuzhno-Sakhalinsk). Maritime meteorological and sea-ice data observed on the "SOYA" during 4 - 7 February 1998 (thick lines) are used for calculation in the thermodynamic equilibrium model of ice.

averaged over a certain area, are

$$\frac{d\overline{T}}{dt} + \frac{\partial}{\partial p}\overline{\omega' T'} = Q_R + \frac{L}{C_p} m \qquad (1)$$

$$\frac{d\overline{q}}{dt} + \frac{\partial}{\partial p}\overline{\omega' q'} = -m \qquad (2)$$

where Q_R is the cooling rate due to the net radiative process, m the net condensation rate, L the latent heat release of condensation, and $\overline{\omega' T'}$ and $\overline{\omega' q'}$ the sub-grid scale eddy transport of heat and moisture, respectively. The sum of turbulent sensible and latent heat fluxes $FSH + FLH$ from the sea or ice surface to the top of the mixing layer is evaluated by the integration of Eqs. (1) and (2):

$$FSH + FLH = \frac{1}{g}\int_{p_{top}}^{p_{srf}} C_p\left(\frac{d\overline{T}}{dt} - Q_R\right) + L\frac{d\overline{q}}{dt}dp. \qquad (3)$$

The other method used in the present analysis is basically the same as that described in Toyota *et al.* (2000). Heat budgets are calculated by the following equation,

$$FSH + FLH + FSW + FLW + FCI = 0 \qquad (4)$$

* *Corresponding author address*: Jun Inoue,
Inst. of Low Temp. Science, Hokkaido Univ., Sapporo 060-0819, Japan; e-mail: inoue@lowtem.hokudai.ac.jp

FSH, FLH, FSW, FLW and FCI on the left hand side of Eq. (4) are the sensible heat flux, latent heat flux, short wave radiation, long wave radiation and conductive heat flux, respectively. This equation means that FSH, FLH, FSW, FLW and FCI are balanced at the surface of the sea-ice. Each flux was calculated samely as Toyota *et al.* (2000) by using the meteorological and ice thickness data.

4. RESULTS

In the atmospheric heat budget analysis, we decided the top of mixing layer as the level at which the heating rate becomes zero. Table 1 shows thus-decided top of the mixing layer and the sum of sensible and latent heat fluxes in each case obtained by using Eq. (3). The estimated total sensible and latent heat fluxes are -50, -56 and -117 W m^{-2} in cases-A, -B and -C, respectively. A significant difference is not found between cases-A and -B, as expected from the fact that the sea-ice area in our analysis domain does not dramatically increase in a week and their intensity of cold-air outbreaks are almost same. In contrast, in case-C, the turbulent heat flux is twice as large as those in other two cases, although the sea-ice concentration is almost similar. The difference mainly reflects the intensity of cold air mass (colder 3.5 K below the 800 hPa level).

Table 1: The height of the mixing layer and turbulent heat fluxes (negative upward) estimated for three cases.

Case	Top of Mixing Layer	FSH + FLH
A	890 hPa	-50 W m^{-2}
B	925 hPa	-56 W m^{-2}
C	835 hPa	-117 W m^{-2}

Figure 2-a shows the surface temperature as a function of the sea-ice thickness at 10 cm intervals (H_i=5, 15, 25, 35, ... cm). Estimated T_S decreases with increase of sea-ice thickness. Estimated T_S decreases with increase of sea ice thickness. However, T_S is approximately regarded as -8 $\sim$ -10°C where the thickness is more than 15 cm.The turbulent heat fluxes calculated by substituting thus-obtained T_S as a function of ice thickness using the daily mean (3- 7 February) meteorological data (Fig. 2-b). Clearly, the turbulent heat flux decreases as sea-ice thickness increases. For open water (H_i=0 cm) and nilas (H_i=5 cm), the sum of the turbulent heat fluxes is remarkably larger than that of thicker ice. Under cold-air outbreak conditions, in which air temperature generally becomes lower than sea-ice surface temperature, the flux is always upward whether the sea-ice is thick or not. Figure 2-c shows the frequency of the open water and ice thickness obtained by video analysis. In the sea-ice area which covers 70% of the observational area, relatively thin (10$\sim$40 cm) sea-ice is dominant. Figure 2-d shows the area-weighted turbulent heat flux for the individual ice thickness. More than half of the upward net turbulent heat flux comes from the open water area (-47 W m^{-2}). The sum of the turbulent heat flux over the sea-ice area reaches -34 W m^{-2}. Thus, the total turbulent heat flux over the whole analysis area is estimated to be -81W m^{-2}.

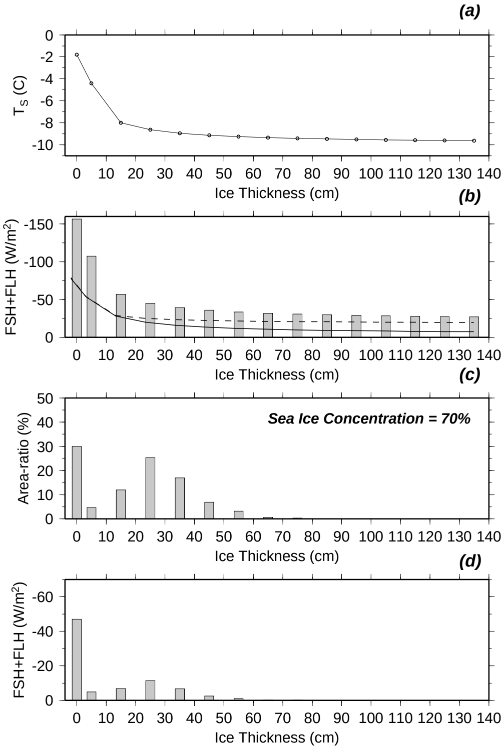

Figure 2: (a) surface temperature T_S, (b) turbulent heat fluxes as a function of sea-ice thickness, (c) area-ratio of sea-ice thickness, and (d) area-weighted turbulent heat flux as a function of ice thickness are shown. Solid and dashed lines in (b) are sensible and latent heat fluxes, respectively.

5. CONCLUSION

The two indirect estimates of the total sensible and latent heat fluxes over the southwestern Sea of Okhotsk are approx. 100 W m^{-2} from the ocean to the atmosphere even under the intense cold-air outbreak period (case-C). The difference in the heat fluxes between case-C (100 W m^{-2}) and both of cases-A and -B (50 W m^{-2}) does not come from the change in sea-ice cover, but the coldness of the air mass. These values are much smaller than those in open water areas, which means that the sea-ice works, as a whole, as an insulating material on the heat transfer between ocean and atmosphere. Nevertheless, the result from the bulk method suggests that a non-negligible amount of upward turbulent heat flux from the ice surface through the inside of sea-ice exists during cold-air outbreaks, and contributes to ice growth at the bottom of the sea-ice.

REFERENCES

Inoue, J., M. Honda and M. Kawashima, 2001: Air mass transformation processes over the southwestern region of the ice-covered Sea of Okhotsk during cold air outbreaks, *J.Meteor.Soc.Japan*, **79**. (in press)

Ninomiya, K., 1975: Large-scale aspects of air-mass transformation over the East China Sea during AMTEX '74. *J.Meteor.Soc.Japan*, **53**, 285-303.

Toyota, T., T. Kawamura and M. Wakatsuchi, 2000: Heat budget in the ice cover of the Southern Okhotsk Sea derived from in-situ observations. *J.Meteor.Soc.Japan*, **78**, 585-596.