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ESTIMATION OF SURFACE HEAT FLUX BASED ON RADIOSONDE OBSERVATION IN THE SOUTHWESTERN PART OF THE SEA OF OKHOTSK UNDER ICE-COVERED CONDITION

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1. INTRODUCTION

The Sea of Okhotsk is extensively covered with sea ice during winter. Recently, Honda et al. (1999) showed that the Okhotsk sea-ice cover anomalies bring about significant large-scale atmospheric responses not only around the Sea of Okhotsk but also downstream towards North America, using an atmospheric general circulation model. This remote response is caused by anomalous turbulent heat flux off the ice-edge over and around the Sea of Okhotsk associated with sea-ice extent anomalies. Several observational studies have estimated the turbulent heat fluxes of sensible and latent heat in other marginal ice zone, but few measurements have existed in wintertime ice-covered conditions in the Sea of Okhotsk.

In order to estimate the turbulent heat fluxes in the Sea of Okhotsk covered with sea ice, and to investigate processes of the boundary-layer modification over there when the cold air outbreaks occur, atmospheric observation using rawinsondes in the southwestern Sea of Okhotsk was performed from late January to early February in 1998 (Iwamoto et al., 2001).

2. OBSERVATION

Cold-air outbreaks are intermittent southward cold advections from eastern Siberia. In order to investigate the air mass modification along the directions of the cold-air advection, we developed three rawinsonde stations (two land-based and one shipboard) along mean wind directions for the climatic mean winter monsoon around the southwestern part of the Sea of Okhotsk (Fig. 1) in the winter of 1998. One land-based station is Yuzhno-Sakhalinsk (hereafter YS), a Russian meteorological observatory, which is located upstream of the winter monsoon in the observational area. Another land-based station is temporally developed at Shari, the Okhotsk coast of Hokkaido (hereafter SH). SH is located downstream of the winter monsoon passing over YS. The ice breaker *Soya*, which belongs to Japan Coast Guard, patrols the Sea of Okhotsk off Hokkaido during the arrival period of sea ice every year. We developed the shipboard station on the *Soya* (hereafter SO) during her cruise.

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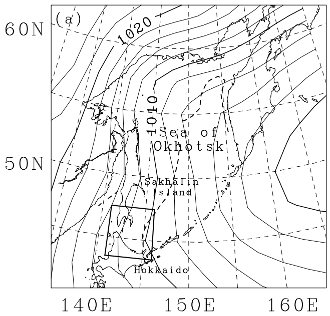

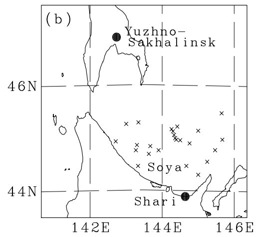

Fig. 1: Location map of (a) the Sea of Okhotsk and of (b) the observational area. Solid lines in (a) indicate mean sea level pressure (hPa) in January for 1967-1997. Mean sea-ice edge for the end of January (1979-1998), which is indicated by 40% ice concentration, is shown by dashed lines. Solid circles and crosses in (b) represent land-based stations and ship-based station on the ice breaker *Soya* (SO), respectively.

3. RESULTS & DISCUSSION

During our observation, the sea-ice coverage between Sakhalin and Hokkaido increased considerably by advection associated with the continual northerly wind near the surface. At the beginning, the mean sea-ice concentration around the southwestern Sea of Okhotsk was 45-50%. By the end of our observation, the area was mostly covered with sea ice, and the mean ice concentration increased up to 71%.

3.1 *Mixed Layer Development*

We performed a backward trajectory analysis from SH, using wind data at 925 hPa of the Europian Centre for Medium-Range Weather Forecasts (ECMWF) analyses, and obtained nine cases that the air mass at YS

Table 1: Average sea ice concentration in the southwestern part of the Sea of Okhotsk, top of the mixed layer (p_{top}), calculated net radiative flux (F_{rad}), and estimated turbulent heat flux of sensible and latent heat (F) in each case.

Case	1	2	3	4	5	6	7	8	9
Time at SH (UTC)	26Jan 18	29Jan 00	29Jan 06	01Feb 00	06Feb 21	10Feb 18	10Feb 21	11Feb 00	11Feb 03
Started at	YS	YS	YS	YS	YS	SO	SO	YS	SO
Sea-ice Cover (%)	45	48	46	49	62	65	65	65	71
p_{top} (hPa)	780	870	870	840	850	965	920	945	955
F_{rad} (Wm^{-2})	-30	-20	-20	-20	-20	-20	-20	-10	0
F (Wm^{-2})	210	110	100	140	120	100	100	60	30

(or SO) moved to SH. Then, considering the time lag for the advection between two stations in each case, we compared their vertical profiles of equivalent potential temperature (Fig. 2). The mixed layer, which is caused by heat supply from the ocean, developed at SH. The top of the mixed layer has descending tendency with time. Hereafter, these nine cases are named as *case 1*, *2*, $\cdots$, and *case 9*, respectively.

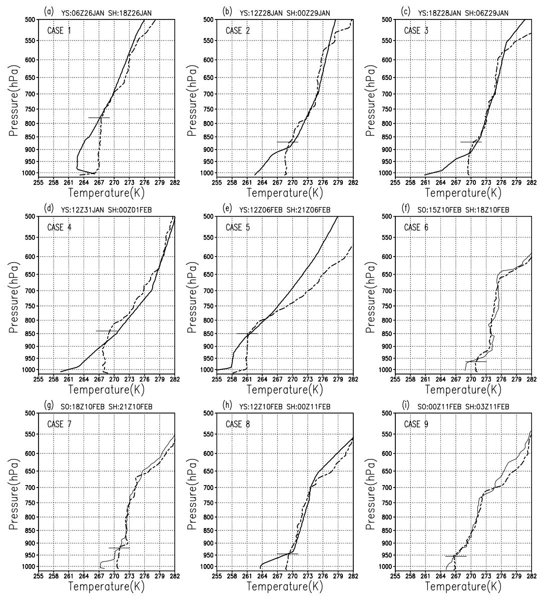

Fig. 2: Vertical profiles of equivalent potential temperature at YS (thick solid line), SO (thin solid line), and SH (dashed line). Horizontal thin lines denote the top of the mixed layer.

3.2 *Surface Heat Flux*

The heat and moisture supply should reflect the moist static energy h of the air mass. When the air mass at YS moves to SH, the air-mass modification occurs in the layer between the lower boundary, p_{low} (we take 1000 hPa as p_{low} in all cases), and the top of the mixed layer at SH, p_{top}, and the total increment of the moist static energy, ΔH, is represented as follows:

$$\Delta H = -\int_{p_{low}}^{p_{top}} \frac{1}{g} \left(h_{SH} - h_{YS} \right) dp, \qquad (1)$$

where subscripts denote the stations. The total energy increment is mainly due to the sensible and latent heat fluxes and the radiation effect. So, we extract the turbulent fluxes (F) by removing the effect of radiative flux (F_{rad}), that is,

$$F = \frac{\Delta H}{\Delta t} - F_{rad}, \qquad (2)$$

where Δt is the time lag for the air mass advecting between the stations. To estimate the F_{rad}, a one-dimensional radiative model was used.

Table 1 shows the obtained turbulent heat fluxes. They gradually get smaller with time during our observational period, corresponding to the descending tendency of the mixed layer height of SH. This tendency may reflect the insulating effect of the heat transfer associated with the upward trend of the sea ice concentrations. The effect of the radiation process becomes gradually weaker, and its relative role on the mixed layer development becomes also small.

4. SUMMARY

Rawinsonde observation was performed in the southwestern part of the Sea of Okhotsk during winter in 1998 to estimate the turbulent heat fluxes over the ice-covered ocean. Associated with cold air outbreaks, cold and stable air mass at the upstream station (YS or SO) was modified through heat flux release from warm ocean surface. As a result, the mixed layer characterized by neutral stability was observed at the downstream station (SH), and its height gradually decreased through our observational period. Correspondingly, significant reduction of the turbulent fluxes of sensible and latent heat was also confirmed. Both decreases may reflect the increase of the insulative effect of the sea ice on heat transfer between the atmosphere and ocean.

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