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AIR MASS TRANSFORMATION OVER THE SEA OF JAPAN DURING COLD-AIR OUTBREAKS REVEALED BY AIRCRAFT OBSERVATIONS

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1. INTRODUCTION

In winter, when cold-air masses break out from a cold continent, air mass transformation occurs on a warm sea surface. The Sea of Japan, one of the typical regions of air mass transformation, is characterized by the intense horizontal gradient of the sea surface temperature SST (1 °C /100km), which causes the large temperature difference downstream between the air mass and SST. So far, the thermodynamic developments of the mixed layer with shallow convection and cloud structures (e.g. cloud streets), which are related to the large amount of sensible and latent heat fluxes from the sea surface to the atmosphere have been investigated by many researchers (e.g. Ninomiya 1975; Asai and Nakamura 1978).

The intense of continental cold-air mass strongly affects not only the development of boundary layer and clouds but also the sea surface cooling and amount of the resultant dense water. Therefore, investigating the relationship between the coldness of air mass and turbulent heat fluxes, in particular, at the upstream region, is indispensable to understanding the atmospheric and oceanic impacts of cold-air outbreaks. Considering the large air-sea temperature difference near the upstream coast, the transports of heat and moisture are quite important for the boundary layer development and initiation of cloud formation. In this study, in order to clarify the dynamic and thermodynamic structure of the boundary layer and its development in upstream region, we carried out aircraft observations near the coast of eastern Siberia in January and February 2001 for the first time.

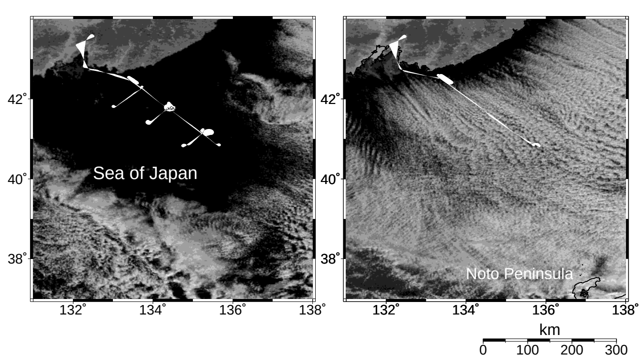

Figure 1: GMS visible imageries on 29 January (left panel) and 03 February 2001 (right panel) near the coast of eastern Siberia. The flight patterns of the IL-18 are also shown by white lines.

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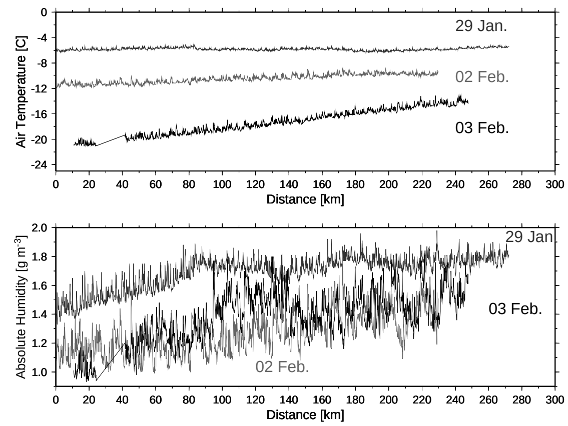

Figure 2: Horizontal distributions of the air temperature (upper panel) and absolute humidity (lower panel) at the lowest flight level in each case.

2. AIRCRAFT OBSERVAIONS

The aircraft observations were conducted during the cold-air outbreaks on 29 Jan., and 2 and 3 Feb., 2001, using a Russian research aircraft ILYSHIN-18 (IL-18). The aircraft was equipped with gust probes to measure wind speed, wind direction, air temperature, humidity, dew point temperature, absolute humidity and pressure with 1-Hz and 20-Hz sampling frequencies. Furthermore, the aircraft IL-18 was equipped with instruments to measure all components of the radiation budget, liquid water content and cloud droplet concentration.

Two flight patterns of the aircraft IL-18 were carried out. One is oriented parallel and normal to the mean wind, and consisted of vertical profile soundings and horizontal legs placed at various levels depend on the depth of the mixed layer (left panel in Figure 1). The other one has four measuring level flights with 300 km horizontal length (200, 400, 1500 and 2800 m above the sea level) parallel to the northwesterly wind direction (right panel in Figure 1). At starting and end points of each flight, we did vertical soundings of the wind direction, wind speed, air temperature and dew point temperature.

3. DOWNSTREAM MODIFICATION

Downstream development of the boundary layer represented by the air temperature and absolute humidity at the lowest flight level in each case, is presented in Figure 2. On 3 Feb., the air temperature near the Siberian coast was the coldest in all measurements, which expects the greatest air-sea temperature differences (about 20 °C). Clearly, the increase of the air temperature from upstream to downstream region (about 6 °C) was also

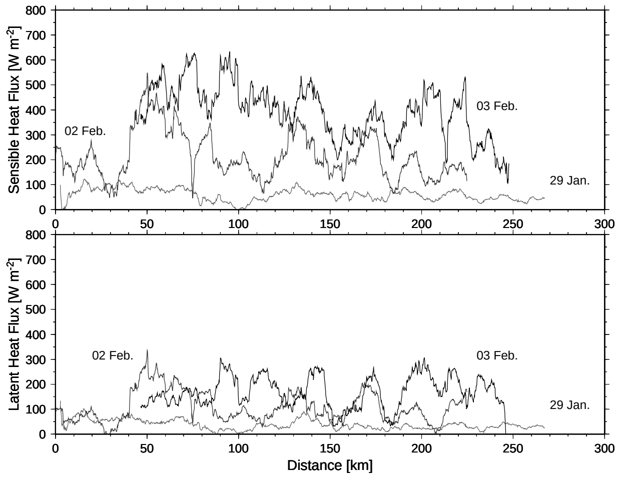

Figure 3: Horizontal distributions of sensible (upper panel) and latent (lower panel) heat fluxes at the lowest level in each case.

the largest. On the other hand on 29 Jan., the air temperature was almost constant within 300 km at the lowest flight level. These results suggest that the amount of heat fluxes from the sea surface are related with the coldness of the air mass. Consequently, we can see the quite different distribution of clouds in each day (Figure 1).

4. TURBULENT HEAT FLUXES

All measurements of the turbulence should be made on the horizontal flight path with a constant velocity and without any change of rolling and heading. All turbulent fluctuations were measured for the frequency range from 0.06 Hz to 8 Hz. For the aircraft IL-18, the frequency range corresponded to the scale range from 20-30 m to 1.5-2.0 km. The constant components, linear and parabolic trends, were removed from the series of wind speed, air temperature and air humidity. The main method for defining the turbulent fluxes of momentum, sensible heat and latent heat is the eddy correlation method with the averaging period of 100 seconds.

Figure 3 shows the horizontal distribution of the sensible and latent heat fluxes in each case. Sensible heat flux decreases from upstream region to downstream in each case, in particular, the trend of the coldest case (3 Feb.) shows the steep decrease because the large air-sea temperature difference induced the large amount of upstream turbulent heat fluxes. On the other hand, the amount of latent heat flux is half as much as that of sensible heat flux in each case. However, it keeps almost constant downstream, which means that the role of latent heat flux in the air mass transformation becomes relatively large in downwind region.

Vertical distributions of the sensible and latent heat fluxes, which are calculated by cross-wind flight legs on 29 Jan. and 2 Feb., are presented in Figure 4. The flight legs at 200 m, 500m and higher than 1000 m correspond to below cloud base, near cloud base and near cloud top, respectively. In the sub-cloud layer, the sensible heat flux profiles are significantly different not only between the upstream and downstream region but also between the two cases. In both cases, the sensible heat flux profile is characterized by negative slope from surface to cloud top,

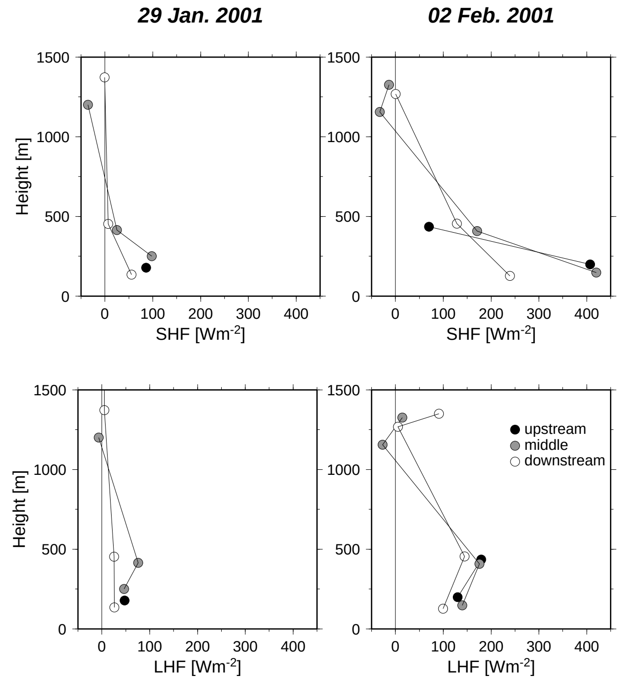

Figure 4: Vertical distributions of sensible and latent heat fluxes on crosswind flight legs on 29 Jan. and 2 Feb. Black, gray and white circles denote the upstream, middle and downstream legs, respectively.

starting at a large positive value near warm sea surface, and becoming negative near the top of the mixed layer. In case of 2 Feb., the negative heat flux is prominent at the top of the mixed layer in the middle and downstream leg due to the entrainment. In addition, the latent heat flux increases slightly with height in the sub-cloud layer, suggesting a net drying of the mixed layer.

5. CONCLUSIONS

The results of the aircraft observations over the Sea of Japan showed a relationship between the coldness of a continental air mass and the turbulent heat fluxes near the eastern part of Siberian coast. The range of the amount of turbulent heat flux near the coast was quite large (900 $\sim$ 200 W m^{-2}) between three cases which associated with the condition of cold-air outbreaks. The development of boundary layer and resultant clouds were closely connected by the horizontal and vertical changes of turbulent heat fluxes.

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