Journal of the Meteorological Society of Japan, Vol. 75, No. 3, pp. 737–751, 1997

Airmass Transformation of the Yamase Air-flow in the summer of 1993

By Yasu-Masa Kodama,

Department of Earth Sciences, Faculty of Science, Hirosaki University, Hirosaki 036, Japan

(Manuscript received 19 August 1996, in revised form 21 April 1997)

Abstract

Yamase Air-Flow (YAF) is an outflow of the summertime maritime polar airmass over the North Pacific toward the San-Riku district of Japan (SRJ) and forms along the southern or southeastern edge of an anticyclone developed over the Okhotsk Sea (Okhotsk Sea high). In most summers, the Okhotsk Sea high appears intermittently, but the high and associated YAF persisted for an abnormally long period between mid July and mid August in 1993. Due to the continuous YAF, an abnormal low temperature accompanied with synoptic-scale (several or ten days) variation was observed in the SRJ during this period. We studied mechanisms of the AirMass Transformation (AMT) of the YAF in 1993 over the western North Pacific for both relatively warm and cool spells of the variation.

The temperature of the YAF at the coast of the SRJ varied over a narrow range around the offshore Sea Surface Temperature (SST). The temperature sometimes exceeded the SST plus 3°C only for a short period in the warm spells but never fell below the SST minus 3°C in the cool ones. Namely, the offshore SST controlled the lower limit of the YAF's temperature. The temperature variation was related to trajectories of air-parcels in the YAF over the western North Pacific. The YAF was directed southwestward toward the SRJ from Kuril Islands during the cool spells, while directed southwestward over the North Pacific and turned northwestward off the SRJ during the warm spells. Since SST gradient is large off the SRJ, the meridional direction of the YAF largely affected the AMT of the YAF. Trajectories of the YAF were related to the southeastward extension of the Okhotsk Sea high into the North Pacific, which was stronger in the warm spells.

During the cool spells, an atmospheric mixed layer accompanied with low-level clouds appeared in the YAF at the coast of the SRJ. The ocean supplied sensible heat of ~ 30 Wm^{-2} and latent heat of ~ 80 Wm^{-2} to the YAF on its way from the neighborhood of Kuril Islands to the SRJ. This heating compensated strong radiative cooling at the top of the low-level clouds (~ -70 Wm^{-2}) and kept the temperature of the YAF higher than the offshore SST minus 3°C.

During the warm spells, a stable layer attached to the sea surface accompanied with low-level clouds appeared in the YAF. Off the SRJ, the temperature of the YAF exceeded the offshore SST by several degrees and the YAF was cooled ($-10 \sim -20$ Wm^{-2}) and lost its moisture ($0 \sim -20$ Wm^{-2}) at its bottom. The low-level clouds also contributed to the cooling of the YAF through the radiative process (~ -70 Wm^{-2}). The cooling of the YAF on its way to the SRJ, however, sometimes may not have been enough to adjust its temperature to the SST when northwestward advection of the YAF off the SRJ was rapid or the radiative cooling was weakened by upper-level clouds.

Even during the cool spells, the AMT of the YAF was much weaker than that of the Asian winter monsoon breaking out over the Kuroshio area. In the AMT of the winter monsoon, radiative cooling at the top of the low-level clouds can be neglected in comparison with the dominant heat supply from the ocean. In the AMT of the YAF, on the other hand, the radiative cooling was comparable to the oceanic heating or cooling.

1. Introduction

When a cold airmass blows out over relatively warm ocean, the airmass is modified by sensible and latent heat supplied by the ocean. This process is AirMass Transformation (AMT) over the ocean. AMT of the Asian winter monsoon over the ocean around Japan is one of the most significant AMTs in the world. The temperature of the monsoon is much lower than the Sea Surface Temperature (SST) over the Kuroshio warm current, where the total heat flux attains ~ 800 Wm^{-2} when the monsoon is strong (Kondo, 1976; Nitta, 1976).

Although its extent and strength are limited, another AMT appears in summer over the western North Pacific when a polar maritime airmass blows out toward the northern part of Japan, especially the San-Riku district of Japan (SRJ), which is the Pacific side of the northern part of Honshu island, as shown in Fig. 1. The outflow of the airmass is not so continuous as that of the Asian winter monsoon. It occurs intermittently when an anticyclone of 1000 $\sim$ 2000 km scale appears around the Okhotsk Sea (Okhotsk Sea High; OSH) and a northeasterly or easterly blows over the western North Pacific toward the SRJ along the southeastern or southern edge of the OSH. In the SRJ, an on-shore wind originating in the polar airmass and cool and wet (cloudy or foggy) weather accompanied with the wind are generically called the 'Yamase'. In this paper, we thus define Yamase Air-Flow (YAF) by the northeasterly or easterly outflow of the polar airmass along the southeastern or southern edge of the OSH.

Although the OSH and associated YAF appear intermittently in most summers, they sometimes persist and cool and wet weather continues in the SRJ. In recent years, a persistent OSH and YAF were observed in the summers of 1980, 1988, and 1993. Especially, the YAF in 1993 was severest in the past 30 years. The mean temperature in the SRJ was 3 $\sim$ 7°C lower than the normal between mid July and mid August (Kanno, 1995). Rice crops over the SRJ were seriously damaged due to persistent cool, wet, and low-sunshine weather caused by the YAF. The Yamase in 1993 affected the food policy of Japanese government and aroused many meteorologists' interest in Japan. Tentative results of many studies on the Yamase were published in the Extended Abstract of Yamase Symposium -'93 Yamase and its surroundings- (Kawamura (ed.), 1995).

According to back trajectory analysis for the YAF in 1993 performed by Takai *et al.* (1996), the birthplace of the YAF is the subpolar portion of the North Pacific to the north of 45°N including the Okhotsk Sea and Bering Sea where SST remains $\sim$10°C during the summer. The north-south gradient of SST over the North Pacific is strong to the south of 45°N and SST attains 15°C$\sim$20°C off the SRJ at 40°N. Since the temperature of the airmass almost follows the SST over the birthplace (Kudoh, 1984; Kato, 1985; Kodama and Yamamoto, 1990), the airmass is modified by sensible and latent heat over the warmer ocean to the south of 45°N before reaching the SRJ (Kudoh, 1984; Ninomiya and Mizuno, 1985). During this process, an Atmospheric Mixed Layer (AML) associated with low-level clouds appears in the YAF. Radiative cooling at the top of the clouds together with bottom heating by the ocean develop the AML (Urano, *et al.*, 1990). The AML is, however, much thinner ($\sim$1000 m) than that of the winter monsoon ($\sim$3000 m) around Japan, because the AMT is much weaker for the YAF (Ninomiya and Mizuno, 1985). The AMT of the YAF is related to the agricultural damage in the SRJ, because the AMT controls most characteristics of the YAF observed in the SRJ, namely, its temperature, wetness, and low-level clouds which largely diminish sunshine.

The study area of the previous efforts on the AMT of the YAF (Kudoh, 1984; Ninomiya and Mizuno, 1985; Urano *et al.*, 1990) was confined to the off-shore ocean of the SRJ. Moreover, they dealt only with events when a cool northeasterly YAF was observed. Recently, Tsuboki and Kimura (1995) studied the AMT of the YAF in 1993 using a regional numerical model. Although they extended the study area to the western North Pacific, they investigated only events of a cool northeasterly YAF. Activity of the YAF shows synoptic time-scale (several to ten days) variation and the direction of the YAF is not only northeasterly but southeasterly at the coast of the SRJ (Inoue, 1992). Since the meridional gradient of SST is large off the SRJ, the north-south direction of the YAF may strongly affect the AMT of the YAF.

In this study, we investigate the AMT of the YAF in the summer of 1993. Different from the previous studies, we extend the study area to the western North Pacific to deal with the whole portion of the YAF, and the study period to about one month to detect synoptic time-scale variation of the YAF. Poor observational coverage over the western North Pacific may be an obstacle to the performance of this study. We use atmospheric objective analysis and SST data of the JMA (Japan Meteorological Agency), in which relatively dense ship observations over the western North Pacific are reflected. Although satellite observations may largely develop in the near future (Kawamura, 1995), we cannot yet evaluate heat fluxes over the ocean using only satellite data.

2. Data and study period

We utilize twice-daily (9 and 21, Japan Standard Time; JST=UTC+9) polar-stereo projected objective analysis data of the JMA during the summer of 1993, when a strong YAF frequently appeared. The data are composed of two types as follows: One is 'Japan area objective analysis data' with fine resolution (40 km at 60°N) and narrow coverage, and the other is 'Asian objective analysis data' with coarser resolution (150 km at 60°N) and wider coverage. The latter is used only outside the region of coverage of the former. The outer boundary of the former is shown in Fig. 1.

Daily surface observations at Hachinohe (40.5°N, 141.5°E), Miyako (39.6°N, 141.0°E), and Ofunato (39.1°N, 140.5°E) are utilized to detect activity of

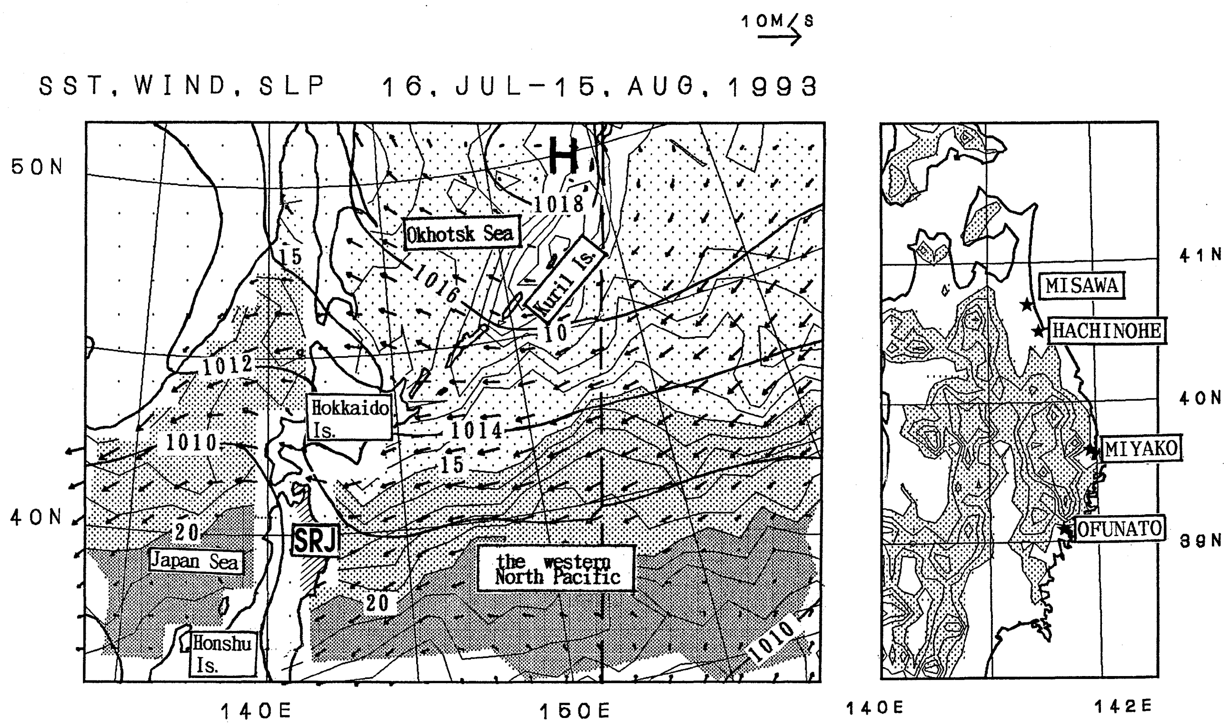

Fig. 1. Left panel: Distributions of SST (thin contours), sea-level wind (vectors), and sea-level pressure (thick contours) averaged between July 16 and August 15 in 1993. The contour intervals of SST and sea level pressure are 1°C and 2 hPa, respectively. A hatched area corresponds to the San-Riku district of Japan (SRJ). A vertical dashed line indicates the outer boundary of 'Japan area objective analysis data'. Right panel: Topography around the SRJ and the location of the four observation stations (⋆) along the coast of the SRJ. The contour interval of height is 200 m and areas higher than 200 m are shaded.

the YAF. To show vertical structure of the YAF, twice daily (9 and 21, JST) aerological observations at Misawa (40.7°N, 141.4°E) are used. These stations are located along the coast of the SRJ, as shown in Fig. 1. Ten-day mean 1° lat. ×1° lon. grid SST data over the western North Pacific compiled by the JMA are utilized to describe SST distribution. In this paper, daily mean is calculated on JST bases (0∼24, JST).

3. The YAF in the 1993 summer

3.1 Characteristics observed at the surface

Figure 1 shows distributions of SST, sea surface wind (10 m height), and sea-level pressure averaged between 16 July and 15 August, 1993. This almost corresponds to the period when the severe YAF continuously appeared, as shown later. The YAF over the North Pacific toward the SRJ was a part of an anticyclonic circulation around the OSH which almost continuously covered the Okhotsk Sea and a part of the western North Pacific. Except over the Japan Sea, the north-south SST gradient was large to the south of 45°N, while SST was almost uniformly 10°C∼12°C to the north of 45°N except along the Kuril islands where SST was low (∼7°C). SST was lower off the SRJ than over the North Pacific of the same latitude due to intrusion of cold Oyashio water toward the SRJ (*e.g.*, Sekine, 1988). To the east of Japan, the YAF crossed the SST contours at a low angle toward the warmer area. This suggests heating of the YAF by the ocean. As shown later, however, the YAF sometimes changed its direction northwestward off the SRJ and crossed the contours toward the colder area, namely, the YAF was cooled by the ocean.

Figure 2 shows day-to-day variations of several meteorological elements observed at the coast of the SRJ together with the SST off the SRJ between July and August of 1993. As stated by Kanno (1995), low air-temperature 3∼7°C less than the normal continued between the second decade of July and the second decade of August (upper panel of Fig. 2). Within this period, an easterly (the YAF) was continuously observed except after 12 August, when wind direction was unstable due to the passage of cyclones over the SRJ (not shown). We thus define the Yamase period of 1993 as between 11 July and 11 August.

Anomalous low-temperature during the Yamase period was accompanied by significant temperature variation on the synoptic time scale. Namely, the YAF was relatively warm both in 23∼31 July and

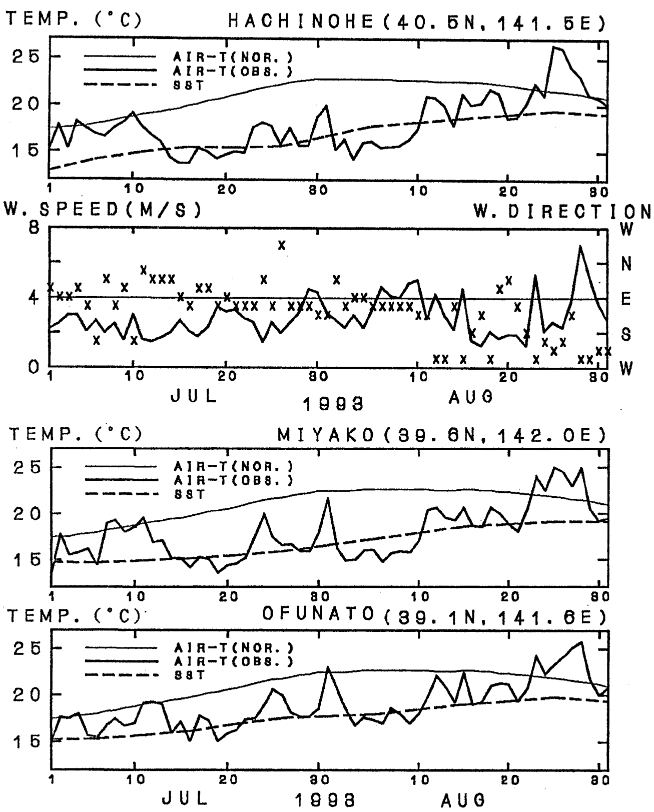

Fig. 2. Top panel: Variations of daily-averaged air temperature observed at Hachinohe (40.5°N, 141.5°E) in the northern part of the SRJ (thick solid line) and of SST off Hachinohe at (40.5°N, 142.5°E) (thick dashed line) in July and August, 1993. The thin solid line indicates the normal seasonal variation of air temperature at Hachinohe averaged between 1961 and 1990. Second panel: Same as the top panel, except for daily mean wind speed (solid line) and most frequent wind direction (×) observed at Hachinohe. Third and bottom panels: Same as the top panel, except at Miyako (39.6°N, 142.0°E) in the central part of the SRJ and with SST at (39.6°N, 143.0°E) and at Ofunato (39.1°N, 141.6°E) in the southern part of SRJ with SST at (39.1°N, 142.6°E), respectively.

on 11 August and relatively cool in the other periods. Moreover, the temperature of the YAF oscillated within a range of the offshore SST plus/minus 3°C. Although the temperature sometimes exceeded the SST plus 3°C for a short period, for example 24 July at Miyako and 31 July at Miyako and Ofunato, it never fell below the SST minus 3°C. In other words, the offshore SST controlled the lower limit of the YAF's temperature at the coast of the SRJ.

The relationship between the YAF's temperature and the offshore SST can be confirmed in other summers of 1980 and 1988 when a continuous YAF appeared (Fig. 3). In the 1980 summer, the OSH and YAF were almost continuously observed during July and August, except 19~25 July when the OSH disappeared. Within the period when the YAF appeared, the temperature of the YAF changed around the offshore SST, except 11 and 13 July when the temperature exceeded the SST by ~4°C at several stations. In the 1988 summer, the OSH and YAF almost continuously appeared in July. Within the period, the temperature of the YAF changed around the offshore SST except 9 July at Miyako and 15 July at Hachinohe when the temperature exceeded the SST by ~4°C.

Temperature of the polar airmass is around 10°C over its birthplace, the subpolar portion of the North Pacific (Kodama and Yamamoto, 1990), and lower than that of the YAF at the SRJ. Therefore, the lower limit of the YAF's temperature controlled by the offshore SST indicates that the YAF was heated by the ocean before reaching the SRJ to be of temperature above the SST minus 3°C. We will discuss on this process again in Section 5.

3.2 Vertical structure

The upper panel of Fig. 4 shows the daily variation of potential temperature profile observed at Misawa, just 30 km to the north of Hachinohe (Fig. 1), between 10 July and 15 August. Shading indicates wet layers defined by the difference between air temperature and dew point less than 2.5°C. The lower panel of Fig. 4 shows the daily position of the surface front (solid lines) and the center of surface cyclones (marked '×') along 140°E. The location of the SRJ is indicated by hatching.

During the Yamase period between 11 July and 11 August, the wet layer was confined below ~850 hPa level, except for periods in 11~19 July and between 25 July and 1 August. The upward development of the wet layer in these periods was ascribed to synoptic disturbances, because several weak cyclones passed the SRJ during the former period and stationary fronts appeared over the southern part of the SRJ during the latter period, as shown in the lower panel of Fig. 4. During these periods, the YAF around the SRJ should be strongly affected by these disturbances.

In 20~24 July and 2~11 August, the wet layer was shallow. In these periods, both surface fronts and extratropical cyclones were located to the south of the SRJ except in 2~4 August and on the afternoon of 11 August when cyclones appeared (Fig. 4) around the SRJ. However, direct influence of the cyclone in 2~4 August seems to be negligible because the cyclone was weak and stagnated over Japan Sea, and its cloud area did not extend to the SRJ according to satellite images (not shown). On the af-

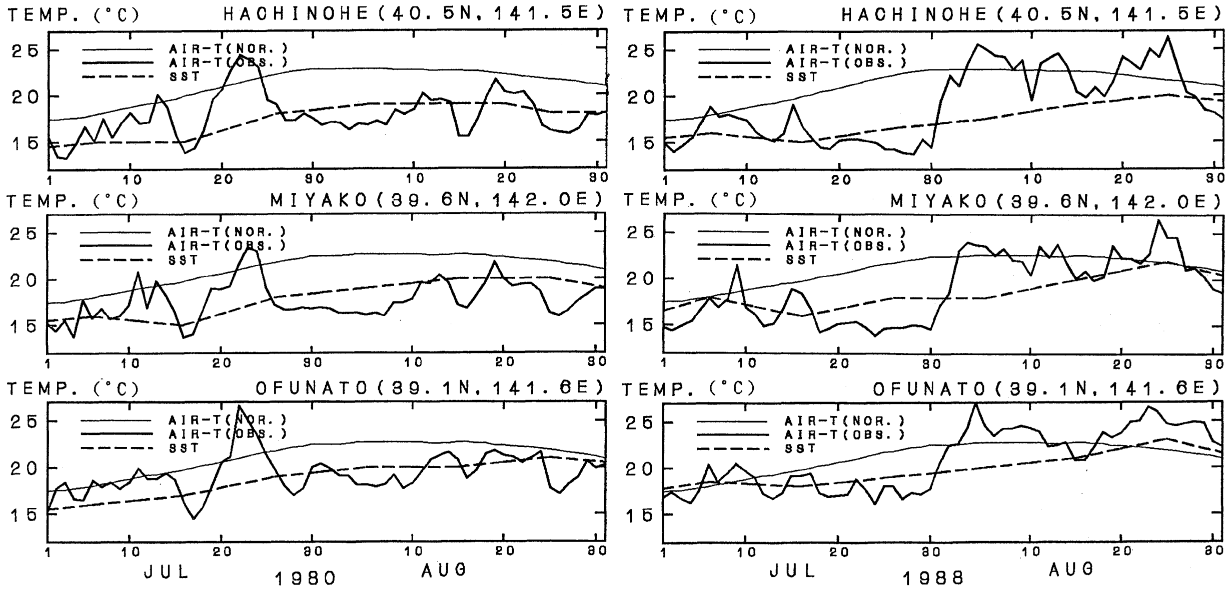

Fig. 3. Same as the top, third and bottom panels of Fig. 2, except in the summers in 1980 (left panels) and in 1988 (right panels).

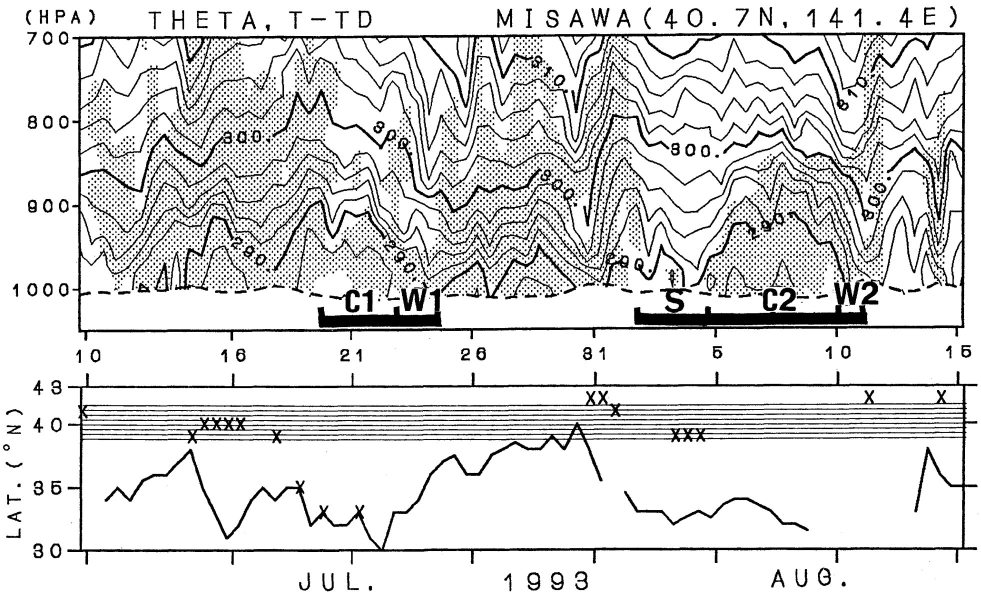

Fig. 4. Upper panel: Daily variation of potential temperature profile observed at Misawa (40.7°N, 141.4°E) between 10 July and 15 August, 1993. Shading indicates the wet layer where temperature minus dew point is less than 2.5°C. Periods for the cool and warm spells and for Spell-S (see text) are also shown. Lower panel: Daily position of the surface front (solid lines) and centers of surface cyclones (marked '×') along 140°E. Hatching indicates the location of the SRJ. If there were fronts or cyclones not at 140°E but at any places between 137°E and 143°E, the latitudes of these disturbances are shown.

ternoon of 11 August, on the other hand, influence of the cyclone may have been strong in spite of the shallow wet layer, because the cyclone passed the SRJ with an increase in its strength (not shown).

To study the AMT of the YAF, we exclude from the Yamase period those periods when a strong influnce of the disturbances on the YAF in SRJ was expected, namely 11∼19 July, between 25 July and 1 August, and on the afternoon of 11 August. After that, we selected two relatively cool and two relatively warm spells from the residual periods by referencing Fig. 2 and Fig. 4: Spell-C1 and Spell-C2 are cool periods in 20∼22 July and between 5 and the morning of 10 August, respectively. Spell-W1 and Spell-W2 are warm periods in 23∼24 July and between the noons of 10 and 11 August, respectively.

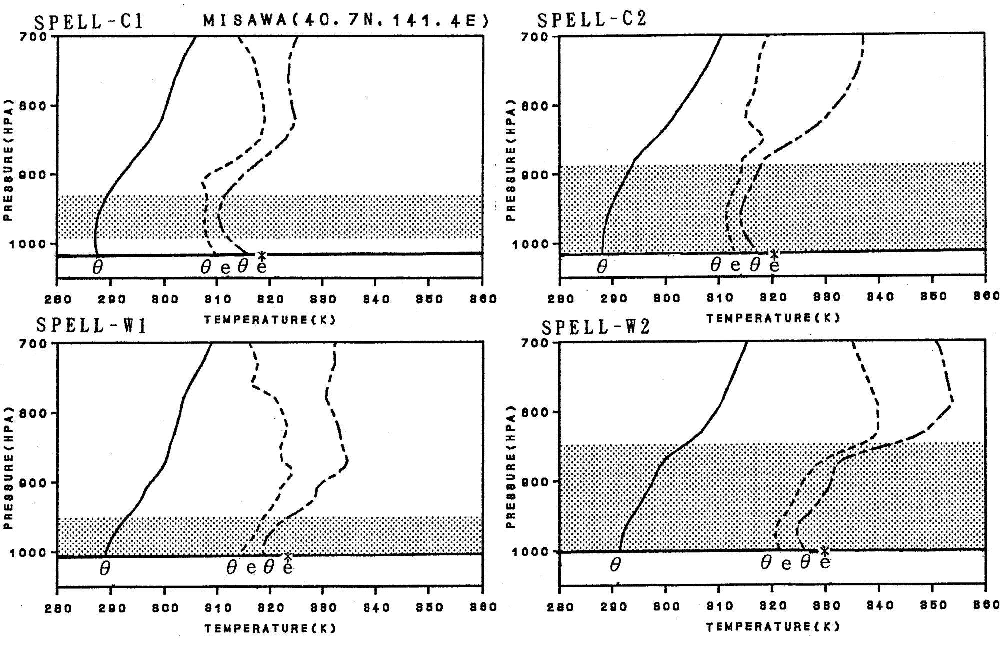

Fig. 5. Profiles of potential temperature (solid line), equivalent potential temperature (dashed line), and saturated equivalent potential temperature (dash-dotted line) averaged for the two cool spells (upper panels) and two warm ones (lower panels). Shading indicates the wet layer where temperature minus dew point is less than 2.5°C.

Characters C and W in labels symbolize cool and warm, respectively. The boundary of Spell-C2 and Spell-W2 is the noon of 10 August, because the temperature of the YAF in the SRJ started to increase after that noon (not shown). We also define Spell-S (Special) by 2∼4 August when the YAF was as cool as in the cool spells. We distinguish this period because the AMT of the YAF in Spell-S was very different from those in the other spells, which will be shown in Section 4. The periods of each spell are shown in the upper panel of Fig. 4.

Figure 5 shows profiles of potential temperature, equivalent potential temperature, and saturated equivalent potential temperature averaged for each spell except Spell-S. Shading indicates the wet layer where the difference between air temperature and dew point is less than 2.5°C.

There was a distinct difference in stratification of the YAF between the cool and warm spells. In the cool spells, a significant AML, which was characterized with constant equivalent potential temperature in the wet layer and constant potential temperature in the dry layer, appeared below the ∼900 hPa level. The AML was nearly saturated, especially in its middle and upper portions, which indicates the existence of low-level clouds in the layer. In the warm spells, on the other hand, a layer of absolute stability, where saturated equivalent potential temperature increased with height, appeared between the surface and the 900∼850 hPa level. The wet (cloudy) layer attached to the surface existed at the bottom of the stable-layer in Spell-W1 and in the whole stable layer in Spell-W2.

The YAF was accompanied by low-level clouds both in the cool and warm spells. Since there was no wet layer, *i.e.*, cloud free, in the troposphere above the low-level cloud layers (not shown), strong radiative cooling would have occurred at the top of the low-level clouds remarked upon by Urano *et al.* (1990). The relationships among the AMT, vertical structure, and radiative cooling of the YAF will be discussed in Section 5.

4. Trajectories of the YAF

To detect the areas where the YAF was transformed, we evaluate 2-dimensional backward trajectories of air parcels in the YAF. Trajectories are calculated at every hour using hourly interpolated wind at 10 m height above the sea surface derived from the twice-daily objective analysis data. The height of wind for determining the trajectories should be a stirring level which represents vertically averaged air motion of the YAF. However, the objective analysis data have only a few levels (surface, 925 hPa, and 850 hPa) in the lower troposphere, and top of the YAF is sometimes lower than the 925 hPa level (Ninomiya and Mizuno, 1985; Kanno, 1995). We thus utilize wind data at the surface (10 m height) for the analysis. Although the wind speed at the surface should be smaller than the vertically averaged speed of the YAF in many cases, evaluated trajectories are useful to detect the outline of the YAF's

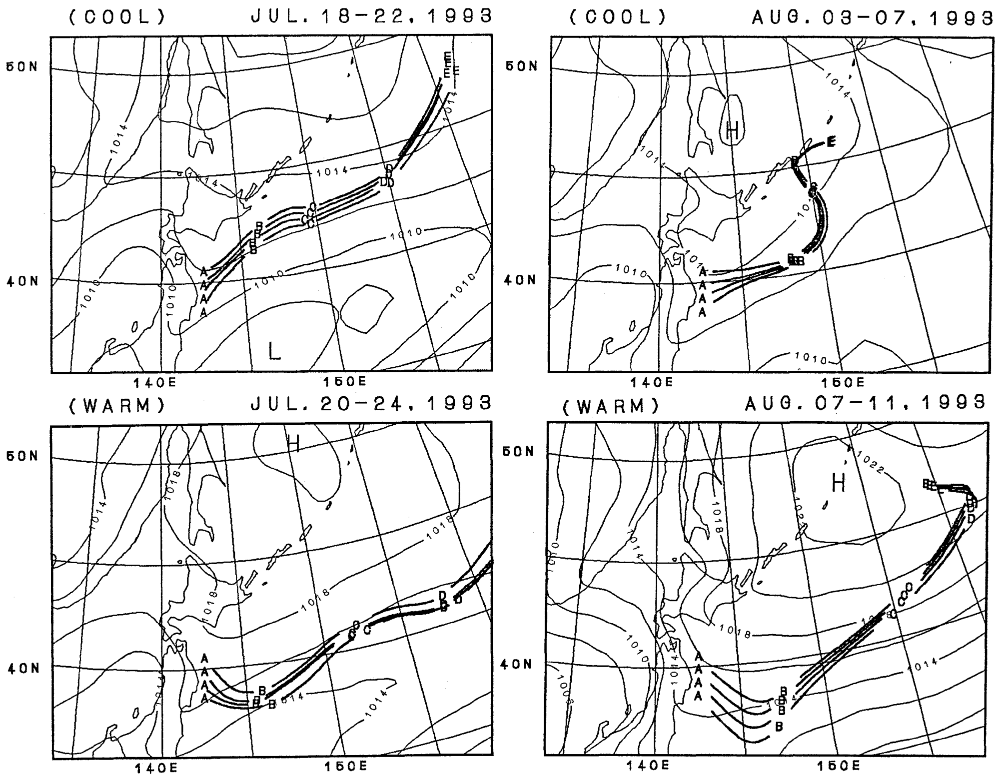

Fig. 6. Backward trajectories of four air parcels at the sea surface aligned off the SRJ during the 4-day period shown in each panel. Symbols of 'A' show starting positions of the parcels. 'B', 'C', 'D', and 'E' indicate the positions of the parcels for one, two, three and four days previous, respectively. Sea-level pressure averaged for the period is also shown. Upper panels are for the cool spells and lower ones are for the warm spells.

advection.

Similar back trajectory analysis was done for the YAF in 1993 by Takai *et al.*, (1996) using ECMWF (European Center of Medium range Weather Forecasting) objective analysis surface wind data. Their study aimed to detect the birthplaces of the YAF and our study aims to show the difference in trajectories of the YAF between the warm and cool spells.

Figure 6 shows the backward trajectories for four air-parcels aligned off the SRJ for each spell. In each panel, starting positions for the backward trajectories of the parcels are shown by 'A' and we trace back each of them into the past. 'B', 'C', 'D', and 'E' represent positions of the parcels for one, two, three and four days previous, respectively. Each panel also shows the sea-level pressure field averaged for each 4-day period. Although the warm spells were one or two-days long, the analysis was done for 4-day periods ending on the last date of the spells so as to show behavior of the YAF off the SRJ in the warm spells.

Off the SRJ, the YAF was directed southwestward and came from around Kuril islands in the cool spells, as shown by Kudoh (1984), while it was directed southwestward over the western North Pacific far from the SRJ but turned northwestward off SRJ in the warm spells. Similar results were obtained for the other days of each spell (not shown). Previous studies discussed the relationships between direction and temperature of the YAF observed at the coast of the SRJ (*e.g.*, Rikiishi and Iida, 1990). However, the YAF at the coast is strongly affected by the topography of the SRJ (*e.g.*, Inoue, 1992), where mountains with several-hundred-meter heights extend to the coast (Fig. 1). Kawamura (1995), using sea-surface wind data observed by a satellite- mounted scattrometer, showed that the YAF was steered by the mountains of the SRJ from ~100 km off the coast. Actually the most frequent wind direction was ESE at Hachinohe, which is parallel to the edge of the mountain area of the SRJ (Fig. 1), both in the cool and warm spells (Fig. 2). The clear relationships between temperature and trajectories of the YAF are found for the first time in this study. Since the north-south SST gradient is strong off the SRJ, the meridional direction of the YAF's trajectory may change the AMT of the YAF significantly. This process will be discussed in Section 5.

Differences in trajectories were clearly related to the synoptic situation. During the cool spells, the OSH stagnated over the Okhotsk Sea with its center around the northern or western part of the sea.

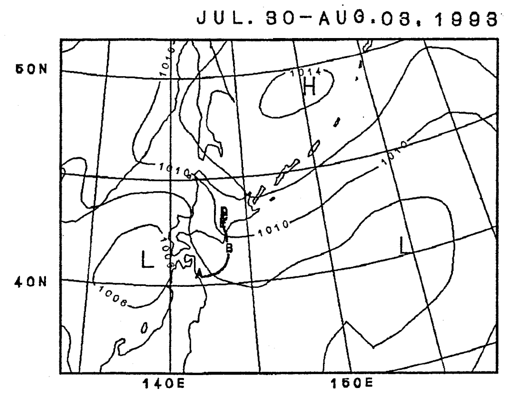

Fig. 7. As in Fig. 6, but for the air parcel which reached Misawa in Spell-S when a cool but dry and shallow AML of the YAF was observed.

Extension of the OSH toward the Pacific was weak and the YAF was southwestward along the southeastern edge of the OSH. In the warm spells, on the other hand, the OSH changed its center southeastward to around Kuril islands and extended toward the western North Pacific. The YAF was northwestward off the SRJ along the periphery of the OSH. Therefore, the temperature of the YAF at the SRJ was related to the extension of the OSH toward the western North Pacific.

Figure 7 shows the backward trajectory for an air-parcel near Misawa in Spell-S. In this period, the parcel came from Hokkaido island and its path length and duration over the sea were very short. Although the YAF was as cool as in the cool spells (Fig. 2), the YAF was dry and its AML was shallow (Fig. 4), different from the cool spells. The unique stratification in Spell-S suggests that long-path advection of the YAF over the ocean is necessary to make a wet and well-developed AML of the YAF.

5. AMT of the YAF

5.1 Evaluation of the AMT of the YAF

The AMT is composed of heating and moistening processes. We evaluate oceanic heating and moistening of the YAF by calculating upward sensible and latent heat fluxes at the sea surface over the western North Pacific, and also evaluating heating of the YAF by longwave and shortwave radiation processes.

Figure 8 shows large-scale distributions of surface air temperature, sea-air temperature difference, sensible heat flux, and latent heat flux for each spell. The fluxes are evaluated from the daily-averaged objective analysis and SST data using the bulk formulae by Kondo(1975), in which the fluxes are determined from wind speed and specific humidity at the sea surface and sea-air temperature difference, and then averaged for each spell. Since wind fields did not largely change within each spell (not shown), we can detect the outline of the AMT by searching the fluxes along the trajectories of the YAF, which are shown in Fig. 6 and schematically presented in the upper panels of Fig. 8. The fluxes averaged over the sea off the SRJ are shown in Table 1 for each spell, although the fluxes for the cool spells are determined not from Fig. 8 but based on a theoretical consideration discussed later in Section 5.2.

Radiative heating shown in Table 1 is evaluated for the atmospheric boundary layer in the YAF, which corresponds to the AML or the stable layer observed during the cool spells and warm spells, respectively (Fig. 5). To evaluate the radiative heating, we supposed the following: 1. Clouds can exist only in the wet layers shown in Fig. 5 and not in the troposphere above the 700 hPa level. 2. Clouds are blackbody for longwave radiation and their absorption coefficient for shortwave radiation is 10 % (after Stephens, 1978). 3. Daily-averaged downward shortwave radiation is $\sim$400 Wm^{-2} at the top of the clouds (by referencing clear-sky shortwave radiation observed at the surface in the SRJ (not shown)). 4. Heating by shortwave absorption in cloud-free atmosphere can be neglected. 5. Heating through radiative energy exchange between the sea surface and the bottom of clouds can be neglected.

Heating by long-wave radiation is evaluated by applying the Yamamoto's radiation chart (Yamamoto, 1952) to twice-daily sounding data at Misawa and then averaging for each spell. Since Misawa faces the North Pacific and the influence of the land surface on the soundings is weak, we can get an approximation of radiative heating of the YAF over the ocean from the observations at Misawa. Calculation is done for the following three cases: 1. The wet layers being cloud-free. 2. The layers being 100 % covered with low-level clouds. 3. Same as Case 2, except for 50 % cloud cover. Here, short-wave absorption by the low-level clouds was supposed to be 40 Wm^{-2} and 20 Wm^{-2} , when 100 % and 50 % covered with low-level clouds, respectively.

Table 1 shows the heating rate of the boundary layer determined from the evaluated radiative heating and the heat fluxes. However, latent heat flux is excluded from the calculation when it is negative, because negative latent heat flux contributes not to the cooling of the atmosphere but to the heating of ocean when moisture is condensed at the sea surface. The results shown in Table 1 are evaluated under the assumption that the cloudiness was 50 % in the wet layers, which is the most plausible condition. Using GMS (Geostationaly Meteorological Satellite) cloud images, Takai (1996) showed that low-level clouds under a clear sky appeared off the SRJ in $\sim$50 % of the Yamase period in 1993 summer.

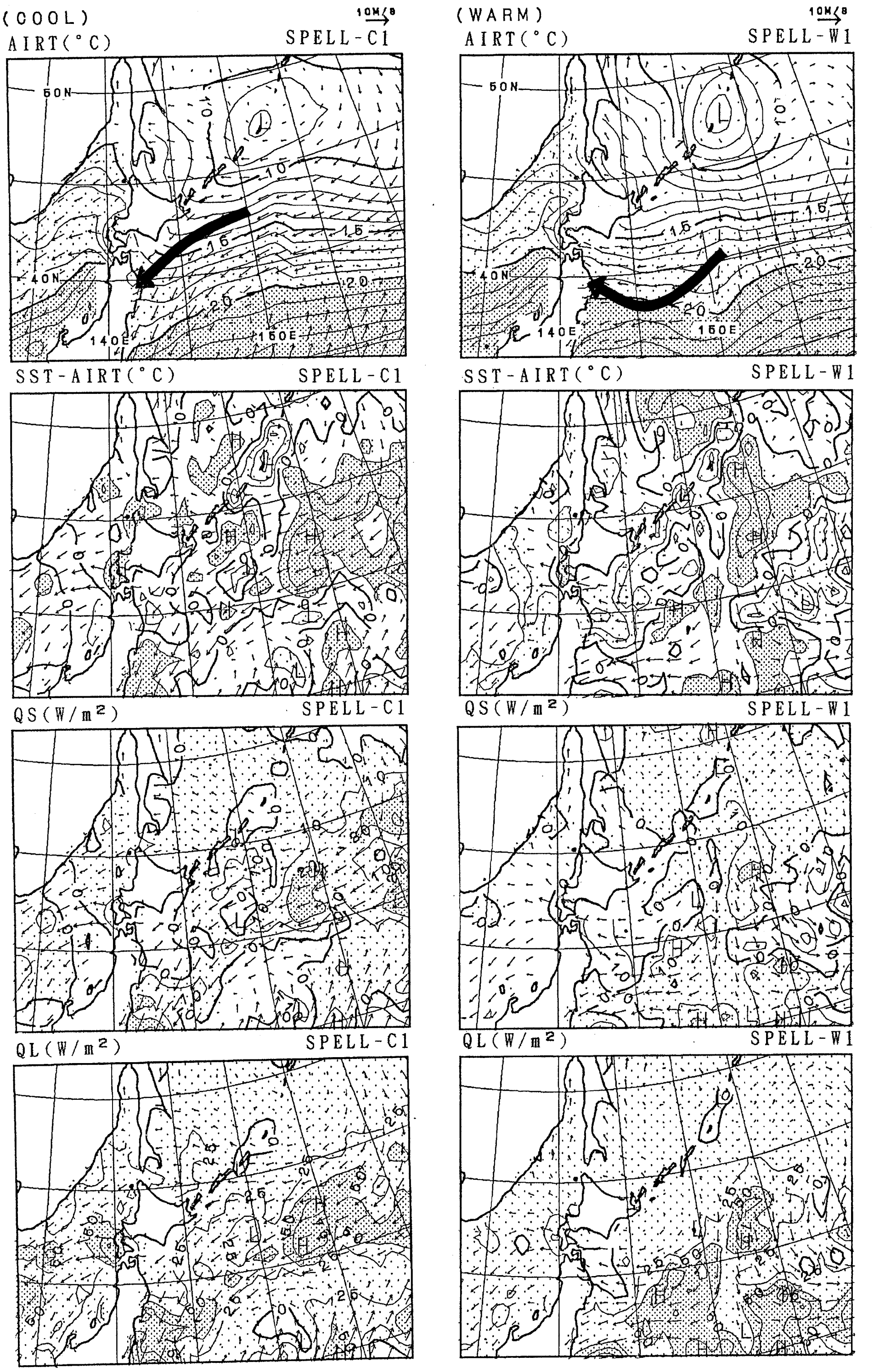

Fig. 8. Large-scale distributions of surface air-temperature (top panels), SST minus air-temperature (second panels), sensible heat flux (third panels), and latent heat flux (bottom panels) averaged for each spell. Vectors in each panel indicate averaged surface wind fields. Thick arrows shown in the top panels indicate the trajectories of the YAF in each spell. The contour interval is 1°C in the top panels. The interval is also 1°C and thick (thin) shading indicates more (less) than 1°C (−1°C) in the second panels. The contour interval is 10 $\mathrm{Wm^{-2}}$ and thin (thick) shading indicates more than 0 $\mathrm{Wm^{-2}}$ (20 $\mathrm{Wm^{-2}}$) in the third panels. The contour interval is 25 $\mathrm{Wm^{-2}}$ and thin (thick) shading indicates more than 0 $\mathrm{Wm^{-2}}$ (50 $\mathrm{Wm^{-2}}$) in the bottom panels.

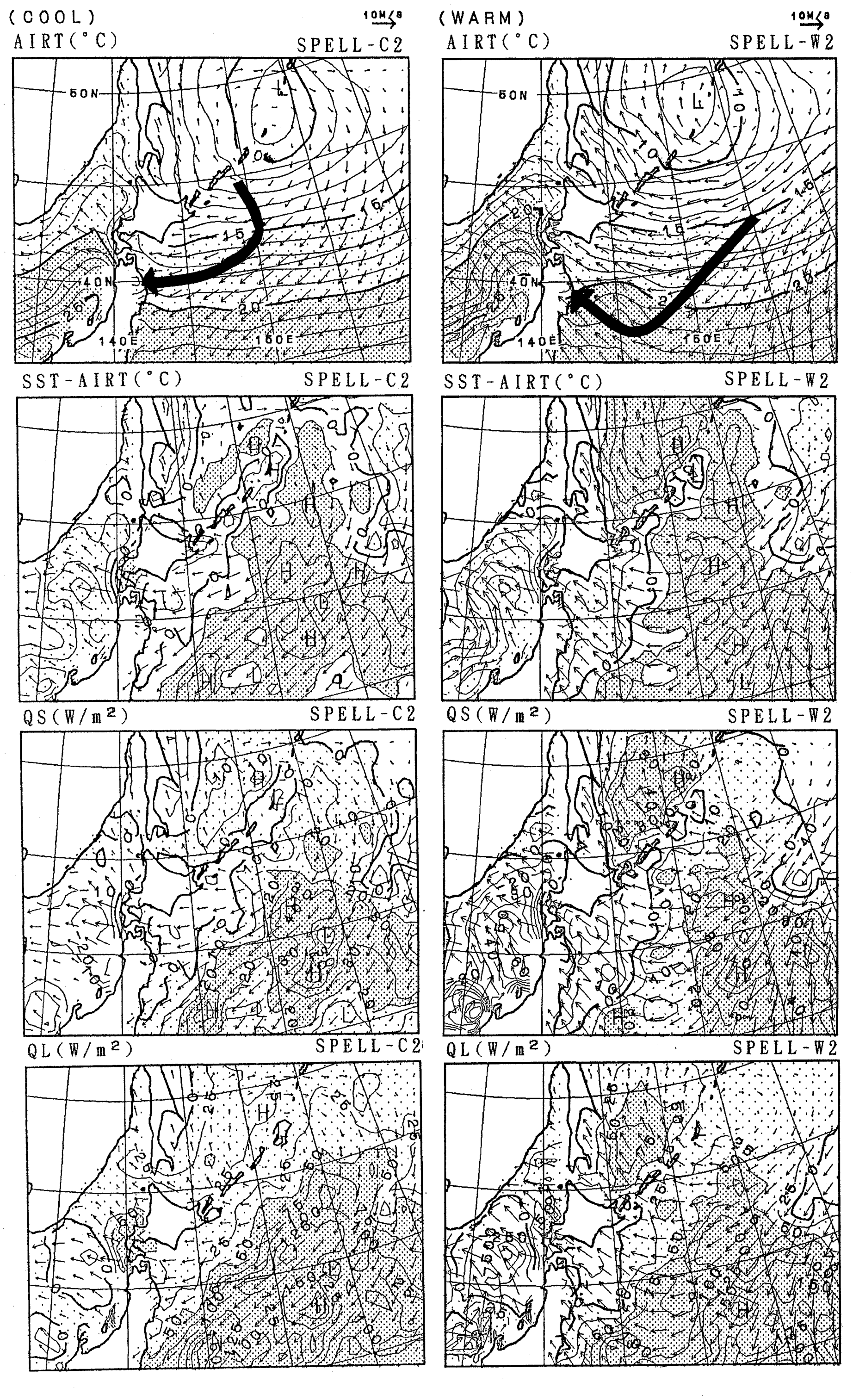

Fig. 8. (Continued)

5.2 Characteristics in the cool spells

During the cool spells, the YAF was directed southwestward between Kuril islands and the SRJ. Along the course, SST was 1~2°C higher than the air temperature and sensible and latent heat fluxes were upward (0~20 Wm^{-2} and 20~70 Wm^{-2}, respectively) except off the SRJ, where the air temperature was nearly equal to the SST and heat fluxes were small (Fig. 8). The small sea-air temperature difference is, however, doubtful in spite of a relatively low SST off the SRJ due to the intrusion of cool Oyashio water. This is because the

Table 1. Estimated heat fluxes at the sea surface and radiative heating within the boundary layer of the YAF off the SRJ averaged for the each spell. The vertical position of the boundary layer, top height of low-level clouds and evaluated heating rate of the layer are also shown. Heat fluxes evaluated for the AirMass Transformation Experiment (AMTEX) performed for the Asian winter monsoon over the Kuroshio area are listed after Kondo (1976) for comparison.

	Heat Flux at sea Surface		Radiative Heating within the Boundary layer			Boundary Layer		
	S.H. Flux	L.H. Flux	Cloud free	50 % Cloudiness	100 % cloudiness	Layer	Cloud top	Heating Rate (C=50 %)
Yamase(Spell-C1)	~30 Wm^{-2}	~80 Wm^{-2}	~ −10 Wm^{-2}	~ −70 Wm^{-2}	~ −130 Wm^{-2}	1020~900 hPa	~930 hPa	~ 3°C/day
Yamase(Spell-C2)	~30 Wm^{-2}	~80 Wm^{-2}	~ −10 Wm^{-2}	~ −70 Wm^{-2}	~ −140 Wm^{-2}	1020~880 hPa	~890 hPa	~2.5°C/day
Yamase(Spell-W1)	~ −10 Wm^{-2}	~ 0 Wm^{-2}	~ −10 Wm^{-2}	~ −70 Wm^{-2}	~ −140 Wm^{-2}	1010~880 hPa	~950 hPa	~ −6°C/day
Yamase(Spell-W2)	−10 ~ −20 Wm^{-2}	~20 Wm^{-2}	~ −10 Wm^{-2}	~ −70 Wm^{-2}	~ −140 Wm^{-2}	1010~850 hPa	~850 hPa	~ −5°C/day
AMTEX(Spell-Cold)	~200 Wm^{-2}	~500 Wm^{-2}						
AMTEX(Spell-Warm)	~ 20 Wm^{-2}	~ 80 Wm^{-2}						

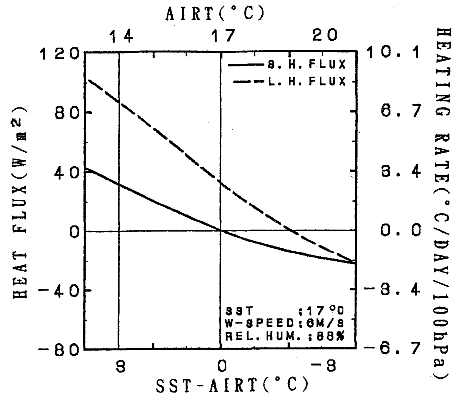

Fig. 9. Dependence of sensible heat flux (solid line) and latent heat flux (dashed line) on sea-air temperature difference. SST, wind speed, and relative humidity are fixed to be 17°C, 6 ms^{-1}, and 88 %, respectively. The bulk formulae by Kondo(1975) are utilized to estimate the fluxes.

air-temperature of the objective analysis data disagreed with the observation at the coast of the SRJ. For example, the daily mean air temperature observed at Hachinohe (air temperature around Hachinohe derived from the objective analysis data) during Spell-C1 and Spell-C2 was ~14°C (~17°C) and 15°C (~18°C), respectively (upper panels of Fig. 2 and Fig. 8). The objective analysis data shows an air temperature ~3°C lower than the observation. Kudoh (1984) and Kimura (1995) showed a narrow (~100 km-width) cool air intrusion of the YAF along the coast of the SRJ. Such a fine air-flow structure may not be fully represented in the objective analysis data.

Figure 9 shows the dependency of the heat fluxes on the sea-air temperature difference evaluated by the bulk formulae by Kondo(1975). Here, the surface wind speed, SST, and relative humidity are fixed to be 6 ms^{-1}, 17°C, and 88 %, respectively, which were typical values observed off the northern part of the SRJ in the cool spells (not shown). If the surface air temperature decreased to 14°C as the observations, namely, 3°C lower than the SST, the sensible and latent heat fluxes off the SRJ would increase to be ~30 Wm^{-2} and ~80 Wm^{-2}, respectively. The YAF, therefore, seems to be heated throughout its way between Kuril islands and the SRJ. Table 1 thus shows these amounts for the cool spells.

As shown in Table 1, the radiative cooling (~ −70 Wm^{-2}; 50 % cloudiness supposed) in the boundary layer was canceled by the oceanic heating. The excess heat supply was ~40 Wm^{-2} if all of the latent heat was released in the AML; this can warm the boundary layer at a rate of 2.5~3°C/day.

This rate is consistent with the observed warming of the YAF from 13°C around Kuril islands to 17°C along SRJ per two days (*cf.*, top panels of Fig. 6 and Fig. 8) and is enough to keep the YAF's temperature higher than the offshore SST minus 3°C.

The process of the AMT of the YAF during the cool spells is consistent with the observed stratification of the YAF. The well developed and nearly saturated AML of the YAF (Fig. 5) can be maintained by oceanic heating and moistening at the bottom and radiative cooling at the top.

5.3 Characteristics in the warm spells

During the warm spells, the YAF was directed southwestward over the Pacific far from the SRJ and turned northwestward off the SRJ (Fig. 6). Before its turn, the YAF was cooler than the SST and heated by the ocean (Fig. 8). In this process, an AML of the YAF should appear as in the cool spells. After its turn, the YAF was warmer than the SST by ~2°C off the SRJ (Fig. 8), where both sensible and latent heat fluxes were downward ($-10 \sim -20$ Wm^{-2} and $0 \sim -20$ Wm^{-2}, respectively) (Fig. 8). Namely, the YAF was cooled and lost its moisture through condensation. Since the surface air temperature derived from the objective analysis data agreed with the observation at the coast of the SRJ (not shown), the evaluated fluxes shown in Fig. 8 are reliable.

Since low-level clouds appeared in the stable layer, strong radiative cooling would occur at the top of the clouds. This radiative cooling (~ -70 Wm^{-2}) together with the oceanic cooling ($-10 \sim -20$ Wm^{-2}) can refrigerate the YAF strongly. The cooling seemed to extend vertically throughout the stable layer by turbulent mixing.

Figure 8 indicates that the cooling of the YAF occured only over a narrow area off the SRJ to the south of Hokkaido island and the YAF passed the area only for a half or one day, by referencing to the back trajectories (Fig. 6). In this study, the sea-air temperature difference off the SRJ did not exceed 3°C either in Spell-W1 and -W2; namely, the YAF' temperature almost followed the offshore SST. As shown in Table 1, the estimated cooling rate of the boundary layer was 5~6°C/day and almost agreeded with the temperature change along the YAF's path, *i.e.*, ~2°C per half a day, estimated from Fig. 6 and Fig. 8. However, if the northward advection of the YAF off the SRJ was rapid or radiative cooling at the top of the low-level clouds was diminished by upper-level clouds, the temperature of the YAF might hardly follow the SST decrease and sea-air temperature difference would be large. This is a possible explanation of why temperature of the YAF at the coast of the SRJ sometimes largely exceeded the offshore SST.

The process of the AMT of the YAF during the warm spells was consistent with the observed vertical structure of the YAF. A stable layer attached to the sea surface (Fig. 5) could be maintained by the oceanic cooling at the bottom of the YAF.

5.4 Comparison to the AMT of the Asian winter monsoon

Table 1 also shows typical heat fluxes of the AMT of the Asian winter monsoon over the East China Sea evaluated by Kondo (1976). Due to the synoptic time-scale variation of the monsoon outflow, the temperature over the East China Sea changes appreciably. Heat fluxes for the monsoon are shown for both its relatively cold and warm spells.

The heat fluxes for the YAF in the cool spells were much smaller than those for the winter monsoon in its cold spells and comparable to those in its warm spells. Thus the AMT was much weaker for the YAF than for the winter monsoon, as stated by Ninomiya and Mizuno(1985). During the warm spells of the YAF, the heat fluxes were downward; this situation does not appear continuously for the winter monsoon.

Although low-level clouds under a clear sky also appear in the monsoon outflow over the ocean (Takeda *et al.*, 1979), Table 1 does not include radiative atmospheric heating evaluated for the Asian winter monsoon, because there have been no reports on it. However, strong radiative cooling cannot appear in the winter monsoon, because the upward radiation at the cloud-top should be smaller for the winter monsoon due to lower cloud-top temperature than for the YAF. As a conclusion, radiative cooling is not important for the AMT of the winter monsoon, in which the oceanic heating is much stronger than the radiative cooling, but is important for the AMT of the YAF, in which the oceanic heating is not strong.

6. Conclusions

In the summer of 1993, the YAF continued for an abnormally long period between mid July and mid August accompanied with synoptic time-scale (several or ten days) temperature variations. We compared characteristics of the YAF between the relatively cool and warm spells and studied their relationships to synoptic situations and YAF's trajectories over the western North Pacific. Finally, we discussed the process of the AMT of the YAF over the ocean quantitatively for the cool and warm spells. The main results are summarized as follows:

1. Due to the continuous YAF, cool weather with temperature 3~7°C lower than the normal was observed in the SRJ between 11 July and 11 August in 1993. Within this period, the temperature of the YAF varied over a norrow range around the SST off the SRJ with a synoptic time-scale. The relatively cool YAF continued for several days and the rel-

atively warm YAF appeared consequently for only a few days. The temperature of the YAF sometimes exceeded the offshore SST plus 3°C for a short period but never fell below the SST minus 3°C. Namely, the lower limit of the YAF's temperature was controlled by the offshore SST.

2. Trajectories of the YAF over the western North Pacific were different between the cool and warm spells of the YAF. The YAF was directed southwestward toward the SRJ from around Kuril islands during the cool spells, while during the warm spells it was directed southwestward over the ocean far from the SRJ but turned northwestward off the SRJ. The difference in trajectories was related to the southward extension of the OSH, which was stronger in the warm spells.

3. During the cool spells, a well developed AML with tops at ~900 hPa appeared in the YAF observed in the SRJ. The AML was accompanied by low-level clouds with tops at ~900 hPa. The YAF was supplied sensible heat of ~30 Wm^{-2} and latent heat of ~80 Wm^{-2} from the ocean off SRJ. This heating compensated strong radiative cooling at the top of the low-level clouds (~ −70 Wm^{-2}) and kept the temperature of the YAF greater than SST minus 3°C. Both the oceanic heating at the bottom and radiative cooling at the top developed the AML of the YAF.

4. During the warm spells, a stable-layer with tops at 850~900 hPa attached to the sea surface appeared in the YAF. Low-level clouds attached to the surface existed in the layer. The stable layer was maintained by cooling by the ocean (−10 ~ −20 Wm^{-2}) off the SRJ, where SST was several degrees lower than the air temperature. Radiative cooling at the top of the low-level clouds (~ −70 Wm^{-2}) also contributed to the cooling of the layer. Cooling of the YAF was significant only over a narrow area off the SRJ where the YAF passed within a half or one day. The cooling should be weakened if another cloud-deck exists above the stable layer and diminished the radiative cooling. The YAF in the SRJ was sometimes much warmer than the offshore SST, because the YAF reached the SRJ before adjusting the SST when its northwestward advection was rapid off the SRJ or its radiation cooling was weak.

5. In Spell-S, the YAF in the northern part of the SRJ was cool but only a weak and dry AML was observed, different from the cool spells. In this spell, the YAF in the northern part of the SRJ were advected not from the North Pacific but from Hokkaido island and their path length over the ocean was very short. This suggests that long path-length advection over the ocean is necessary to maintain the wet AML of the YAF observed in the cool spells.

6. Even during the cool spells, the AMT of the YAF was much weaker than those of the winter monsoon outflow over the Kuroshio area. In the AMT of the winter monsoon, radiative cooling at the top of the low-level clouds is negligible compared with the dominant heat supply from the ocean. In the AMT of the YAF, on the other hand, the radiative cooling was comparable to the oceanic heating or cooling.

Tsuboki and Kimura (1995) performed a numerical experiment for an event when a relatively cool YAF was observed in 1993 summer. They evaluated that the sensible and latent heat fluxes off the SRJ were 20~40 Wm^{-2} and ~100 Wm^{-2}, respectively. Their results are somewhat larger but consistent with our estimation for the cool spells.

Difference in the AMT process between the cool and warm spells may change the characteristics of the low-level clouds in the YAF. In the cool spells, the clouds appear in a well developed AML, where the liquid water content generally increases with height (Slingo *et al.*, 1982). Therefore the bottom of the clouds is apt to be detached from the surface. Actually, the wet layer was detached from the surface in Spell-C1 (Fig. 5) and there were no fog reports at any of the three stations at the coast of the SRJ (Hachinohe, Miyako, and Ofunato) during the cool spells (not shown). In the warm spells, on the other hand, we can expect the clouds to be attached to the sea surface and maintained by the oceanic cooling. Actually, the wet layer was attached to the surface (Fig. 5) in the warm spells, although there were no fog reports at the three stations (not shown).

The YAF in the SRJ is sometimes affected by cyclones or fronts passing the SRJ and by clouds in the upper or middle troposphere which accompany them (Inoue, 1992). As shown in Fig. 4, a wet layer sometimes extended upward beyond the boundary layer of the YAF under the influence of these disturbances. Such cases were not studied in this paper but are worth studying because the upper-level clouds strongly diminish the radiative cooling of the YAF and affect the process of the AMT.

Heat fluxes at the sea surface and the radiation processes contributed to the AMT of the YAF, and they offset each other in the cool spells. The AMT of the YAF was maintained by a subtle balance of them in the spells. To evaluate the AMT of the YAF more precisely, special observations of the YAF off the SRJ are desired to get higher quality data-sets than the data we utilized here.

We found out that southward extension of the OSH can change characteristics of the YAF observed at the coast of the SRJ. Our knowledge of mechanisms to determine the horizontal extension and temporal variation of the OSH is insufficient. Further studies are expected on these problems to improve the prediction of YAF observed in the SRJ.

Acknowledgment

The author would like to thank Numerical Prediction Division, Maritime Meteorological Division, and Long-range Forecast Division of Japan Meteorological Agency for providing the data. Discussions on the Yamase in 1993 summer with Prof. H. Kawamura and Dr. T. Hayasaka of Center for Atmospheric and Oceanic Studies, Tohoku Univ., Drs. H. Kanno and T. Kuwagata of Tohoku National Agricultural Experiment Station, and Mr. H. Takai and Mr. H. Yamamoto of Japan Weather Association were very helpful. Thanks are also extended to the editor and the two anonymous reviewers for valuable comments.

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1993年夏季のヤマセ気流の気団変質

児玉安正
(弘前大学理学部地球科学科)

ヤマセ気流は、オホーツク海高気圧の南ないしは南東の縁にそって、北太平洋で発達した寒帯気団が三陸地方に向かって吹き出すものである。通常、オホーツク海高気圧とそれに伴うヤマセ気流は、夏季に間欠的に現れるのみであるが、1993年の夏季には、それらが7月中旬から8月中旬まで持続した。持続的なヤマセ気流のため、三陸地方では異常な低温が総観規模の時間スケールの気温変動を伴いながら続いた。本研究では、気温変動の相対的な高温期と低温期の両方について、1993年のヤマセ気流の北西太平洋上における気団変質のメカニズムを調べた。

三陸地方沿岸で観測されるヤマセの気温は、沿岸のSSTを短期間3°C以上上回ることはあったが、SSTを3°C以上下回ることはなかった。つまり、SSTは気温の下限を決めていた。ヤマセ気流の気温変化は北西太平洋上のヤマセ気流の流跡線と関係していた。三陸地方に達するヤマセ気流の空気塊は、低温期には千島列島方面から南西進し、高温期には日本の東方海上から北西進してきていた。三陸沖ではSSTの南北傾度が大きいので、ヤマセ気流の南北方向の向きの変化は、その気団変質に大きな影響を与えていた。流跡線の違いには、オホーツク海高気圧の北太平洋への張り出しの強弱が関係していた。

低温期には、三陸地方で観測されるヤマセ気流には下層雲を伴った大気混合層が発達した。千島列島から東北地方にいたる海上で、ヤマセ気流は海から顕熱と潜熱をそれぞれ~ 30 Wm^{-2}、~ 80 Wm^{-2}受取り、これによる加熱は下層雲による~ 70 Wm^{-2}の放射冷却を打ち消して、気温をSST–3°C以上に保っていた。

高温期には、三陸地方のヤマセ気流には下層雲を伴った海面に接地する安定層が発達した。東北北部の沿岸域ではSSTが気温より低く、ヤマセ気流は、顕熱と潜熱をそれぞれ10 ~ 20 Wm^{-2}、0 ~ 20 Wm^{-2}失っていた。下層雲による放射冷却もヤマセ気流の冷却に寄与していた。しかし、三陸地方沿岸域での気流の北上が非常に速い場合や、上層雲によって放射冷却が弱められる場合には、ヤマセ気流の気温低下がSSTの低下に追いつかない可能性がある。

ヤマセ気流の気団変質は低温期であっても、冬季アジアモンスーンが黒潮域に吹き出す際に比べてきわめて弱かった。冬季モンスーンの気団変質では下層雲の放射冷却は海面の熱フラックスに比して無視できるが、ヤマセの気団変質では熱フラックスと同程度で重要である。