THE RELATIONSHIP BETWEEN DOUBLE THERMAL INVERSIONS AND THERMAL BELT IN THE MT. YATSUGATAKE AREA, CENTRAL JAPAN

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Abstract We examined a thermal structure on the mountain slope over clean calm nights at the southern Mt. Yatsugatake. central Japan. Meteorological observations showed double thermal inversions over the slope. The upper one appeared between approximately 1800 m and 2000 m a.s.l. (1100 m and 1300 m from surface), and the lower one, between 700 m and 950 m a.s.l. (surface and 250 m from surface). Successive snapshots of a thermography showed horizontal bands of this upper inversion clearly. Radiosonde data in this field indicated that this thermal structure on the slope was associated with the thermo-dynamical processes in the atmospheric boundary layer: the upper inversion forced by the adiabatic warming by subsidence but the lower one forced by the radiative surface cooling.

Key words: double thermal inversions. thermal belt, sonde observation. adiabatic warming by subsidence flow, radiative surface cooling

1. Introduction

Many studies have reported the occurrences of the thermal belt on the middle slope of mountains at night whose temperature is higher than above and below the area. Gunji (1958) is one of the precedent studies in Japan which investigated the thermal belt. With the use of maximum and minimum thermometers, he showed that monthly mean temperature at thermal belt was 2℃ higher than that of basin surface in winter season at Mt. Tsukuba. Based on a dozen of observational studies. Yoshino (1975) summarized thermal belts as follows. (a) In most cases. the height of the center of the thermal belt on a slope appears at 200-300 m above the valley floor or mountain foot. (b) The horizontal position of the thermal belt depends on the cross section's shape of the valley. (c) During clear and calm nights, the thermal belt locates higher and a contrast of temperature is clearer. (d) The thermal belt is located higher in winter than in summer.

He also proposed a model of the cold air drainage and cold air lake including thermal belts (Yoshino 1982). According to his theory, the cold air drainage at the lower part of mountain slope generates a relatively warmer counter flow on the middle slope during the clear calm night. which produces high temperature belts (thermal belt) on the mountain slope.

Those results suggest that the altitude of thermal belts approximately coincide with that of the top of surface thermal inversions. Furthermore, Yoshino (1975) proposed other types of inversions such as the subsidence inversion and the frontal inversion that might be formed by the adiabatic warming of a layer of subsiding air in high pressure regions. In most cases, those are formed at higher altitudes than the surface inversion (Austin 1957). Ushiyama and Kitazawa (1997) compared the data of two stations which were located in 1720 m and 715 m a.s.l. (above the sea level) on the slope of northern area of Mt. Yatsugatake during winter season for five years. Despite of the difference of the altitude which was approximately 1000 m, 10% of total hours is occupied by the condition that temperature of mountainside (1720 m a.s.l.) was higher than that of flat area (715 m a.s.l.). They concluded this phenomenon was induced not only by surface inversion but also by subsidence and frontal inversion. In fact, we also found the high altitude thermal belt on the upper slope of Mt. Yatsugatake, based on temperature measurements and infrared thermal images (Tanaka 1993, 1995).

Actually, observational evidences are desired in order to clarify the thermal processes of these upper inversions in the atmosphere. Here we examine the relationship between the upper inversion in the atmosphere and the high-altitude thermal belt on the slope. The purpose of this paper is to provide a report of the meteorological observations to confirm the existence of high-altitude thermal belt on the slope and to discuss the thermal processes of high-altitude inversion. We will propose the results from an intensive observations at the southern slope of Mt. Yatsugatake, central Japan (Fig. 1), and show double thermal structures in the atmosphere that is associated with the two types of the thermal belt on the slope.

2. Meteorological observations and data

An intentional observation was carried out intensively from November 1 through 3 in 1997 at the southern area of Mt. Yatsugatake in central Japan. Study area and the detailed observational sites are shown in Fig. 1.

Figure 2 is a schematic diagram of this observation system. The observation points are on the slope from Mt. Amigasa (2524 m a.s.l.), the southeastern peak of Mt. Yatsugatake, to the Kamanashi river (approximately 700 m a.s.l.) which is the lowest point of this profile.

Radiosondes (JWA-94W developed by Meisei Electric Co., Ltd.), observed three meteorological variables (pressure, temperature and relative humidity) from the ground surface (700 m a.s.l.) to approximately 10 000m a.s.l. Its observational time interval was every 0.5 seconds. At night, radiosondes were launched nine times on November 1-2, and ten times on November 2-3, respectively.

Towersonde (Tether Multi sonde developed by Atmospheric Instrumentation Reserch, Inc.) took five meteorological variables (wind direction, wind speed, air pressure, air temperature, and relative humidity) from the ground surface (1100 m a.s.l.) to approximately 1900 m a.s.l. Its observational time interval was approximately 20 minutes,

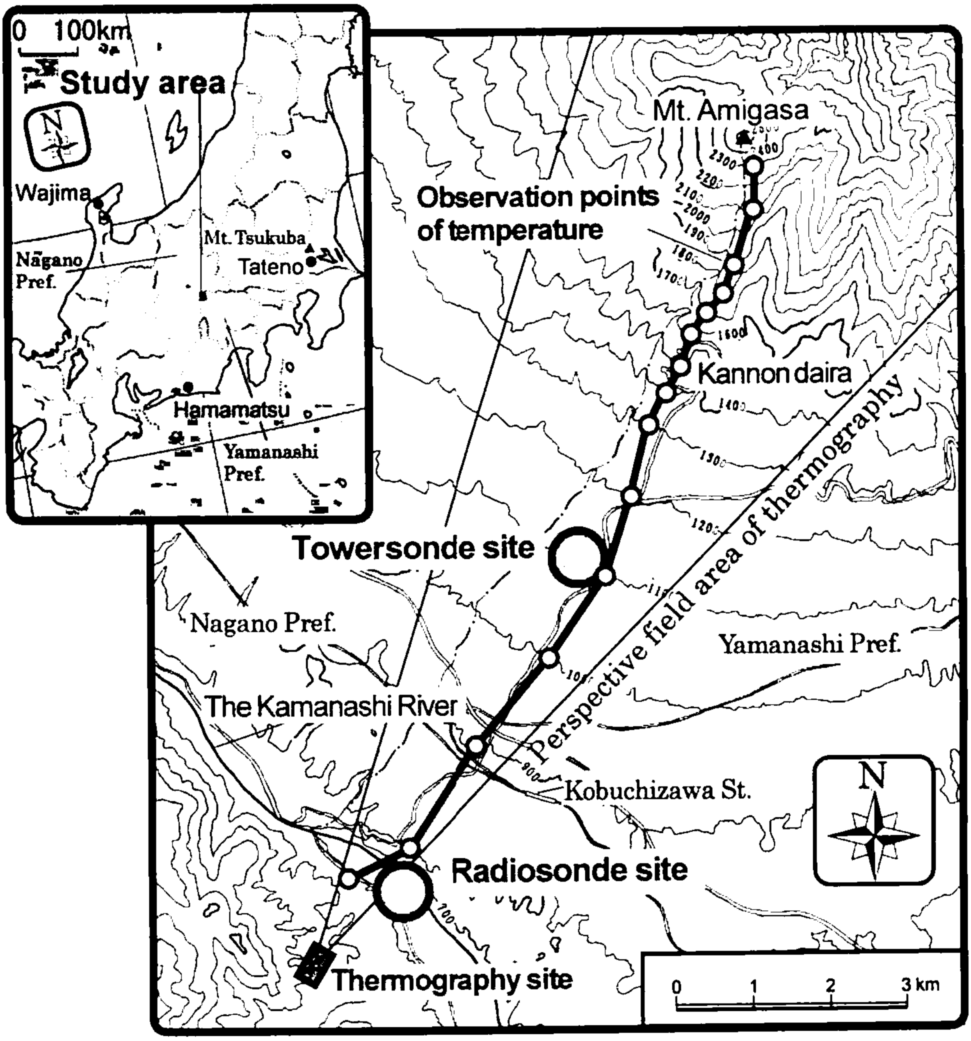

Fig. 1 Study area and observational sites
Thick line corresponds to the mountain slope in Fig. 2.

however it fluctuated by condition of electric wave. The interval was, therefore, not constant. At night, towersonde moored three times in November 1-2, and five times in November 2-3, respectively, which took three to four hours for each observation. The horizontal distance of two sonde sites is 4860 m and the difference of relative heights is 400 m. Towersonde is a kind of kite-balloon system developed by Atmospheric Instrumentation Research, Inc., U.S.A., which is able to observe five meteorological variables at different heights simultaneously.

Thermography (JTG-6300 developed by Japan Electron Optics Laboratory Co., Ltd.)

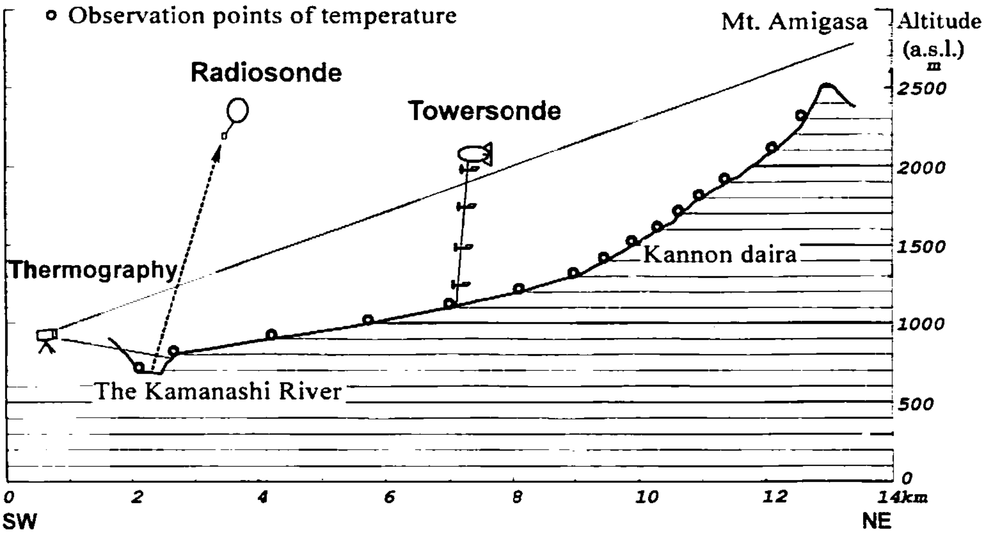

Fig. 2 Schematic diagram of this observation

took infrared thermal images (radiative surface temperatures), every one-minute interval. The range of wavelength is between 8 and 13 micrometer which corresponds to the infrared thermal band. The area between two lines in Fig. 1 indicates a perspective range from the infrared thermography.

Surface air temperatures were observed by Micro Data Loggers (developed by IBC Co., Ltd.) with radiation shields at 100-200 m altitude interval on the slope. Its observational time interval is four minutes.

Aerological observations by rawinsondes operated by Japan Meteorological Agency are also carried out at 9:00 and 21:00 JST (Japan Standard Time) every day. Hereafter, JST is adopted as the time descriptions. It takes five meteorological variables which are the same as towersonde observation at the southern area of Mt. Yatsugatake. Aerological stations of Hamamatsu (47681: station index number of World Meteorological Organization) and Tateno (47646) are near this study area, therefore we used these station data at 9:00, November 2 in 1997. The distance is, however, over 130 km between the study area and Hamamatsu, the nearest aerological station (Fig. 1). Data set is derived from "temperature and relative humidity significant level" reported in Aerological Data of Japan, November in 1997, published by Japan Meteorological Agency.

On the night of November 1 through 2 in 1997, the central Japan was covered with a synoptic anticyclone as shown in Fig. 3 (Japan Weather Association, 1998). The weather was almost fine over this night.

3. Results from intensive observations

First, we will show infrared thermal and visible images in Fig. 4, which were taken

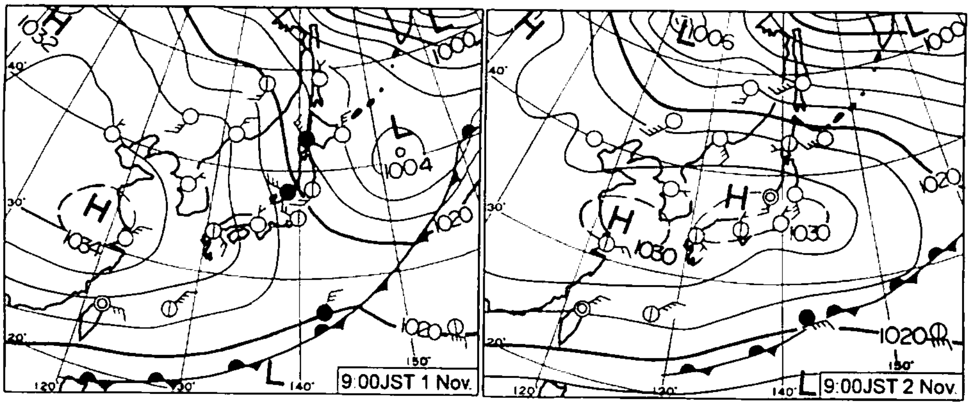

Fig. 3 Synoptic weather chart of surface at 9:00 JST (00Z GMT), November 1 and 2, 1997 (Japan Weather Association, 1998)

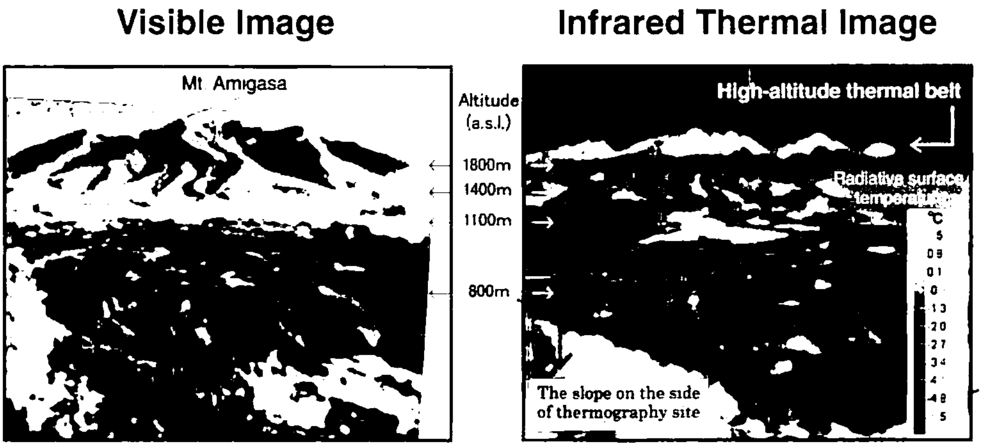

Fig. 4 Visible image (left panel) and thermal image (right panel) of the southern area of Mt. Yatsugatake at 4:00 JST on November 2, 1997

by the infrared thermography from the opposite mountain slope at 4:00, November 2 in 1997, when a thermal contrast on the slope was mostly developed. Infrared thermal image and visible image indicate the same perspective field area. In the visible image, topographic feature can be well captured. In the infrared thermal image, it is found that a brighter zone exists at the top of mountain over 1800 m a.s.l., where surface temperature is higher than lower altitudes. This horizontal zone of high temperature, which is called the high-altitude thermal belt on the slope, is sharply isolated from the lower surface, the zone of colder temperature. The surface temperature is approximately 0.5℃ at around 2000 m a.s.l. in the high-altitude thermal belt, whereas it decreases to -2.0℃ at around

1800 m a.s.l.

Figure 5 shows a vertical profile of air temperature, relative humidity, potential temperature, and specific humidity at 4:00 (accurately 3:57:00 at 700 m a.s.l. through 4:08:14 at 2600 m a.s.l.) on November 2, 1997. Radiosonde observations show two inversion layers from the temperature profile (left panel) at around 2000 m a.s.l. and 950 m a.s.l., respectively. The altitude of the upper one corresponds to that shown in the infrared thermal images on the slope (Fig. 4). On the other hand, the lower one has several characteristics of the thermal belt of Yoshino (1975). A temperature inversion of upper one reaches 4.3℃ between 1800 m and 2000 m a.s.l., while lower one, 3.2℃ between the ground surface and 950 m a.s.l.

The profiles of relative humidity, specific humidity and potential temperature also show different properties between upper and lower inversions (Fig. 5). In the lower part of the upper inversion, both relative humidity and specific humidity decrease rapidly as the altitude increases. Relative humidity is less than 10% above 2000 m a.s.l. in contrast to high humidity below 1800 m a.s.l. From surface to 2000 m a.s.l. large gradient of potential temperature exists. Namely, this part is occupied by stable air mass. On the contrary, gradient of potential temperature is small in the upper part, which shows the existence of unstable air mass.

Figure 6 shows a time-altitude diagram of temperature (hatches) and horizontal wind velocity (arrows) measured by the towersonde system from 2:00 to 5:30, on

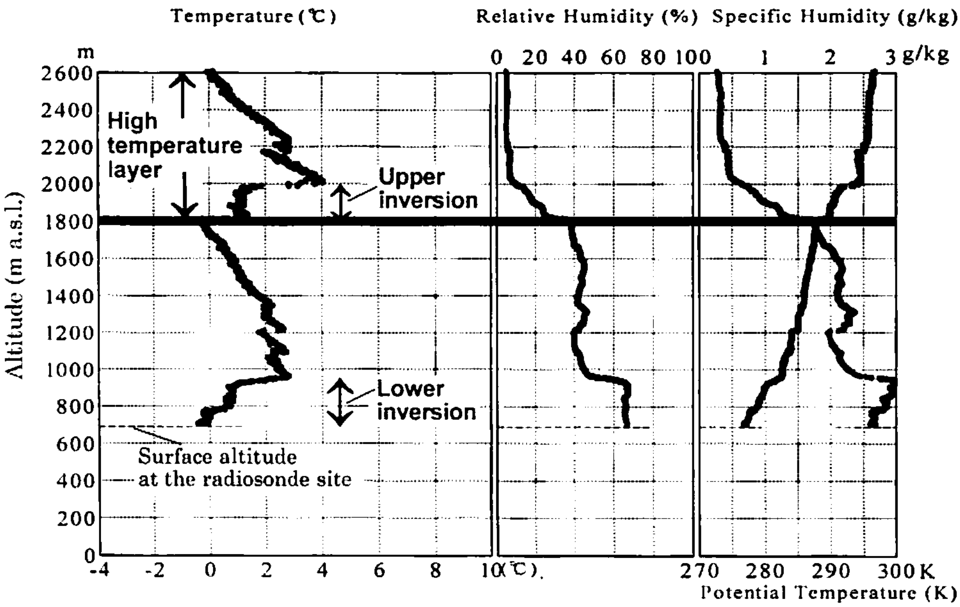

Fig. 5 Vertical profiles of temperature, relative humidity, potential temperature, and specific humidity measured by radiosonde on the southern area of Mt. Yatsugatake (radiosonde site) at 4:00 JST on November 2, 1997

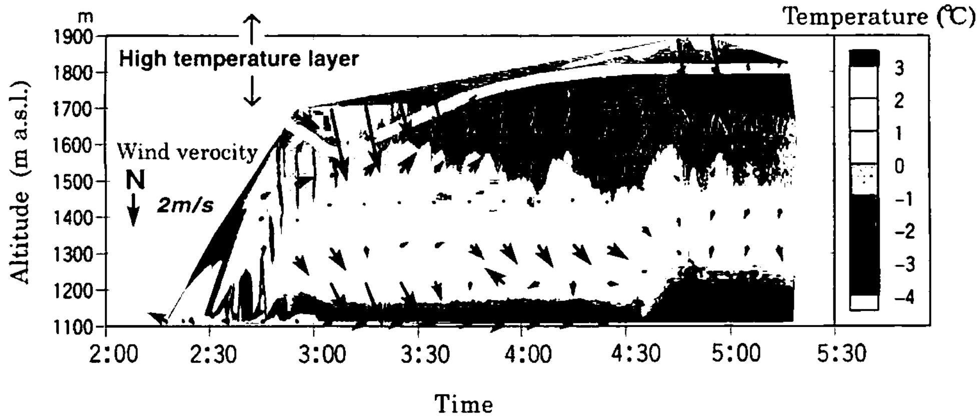

Fig. 6 Time-altitude diagram of temperature (hatches) and horizontal wind velocity (arrows) measured by the towersonde system at the southern area of Mt. Yatsugatake, November 2, 1997
The downward arrow indicates the northerly wind.

November 2, 1997. In this figure, downward arrows indicate northerly wind, and wind velocities are 10 minutes vector averages. Strong northerly wind blew 4.9 m/s at 4:45, and 5.9 m/s at 4:55 appeared at around 1900m a.s.l. Similar northerly appeared at around 1700 m a.s.l. from around 3:00 to 3:30. At the same time, a weak southerly is found below the strong northerly wind layer. A rapid increase of wind velocity occurs as the temperature inversion develops. At the same altitude, the decrease of the relative humidity is observed by the radiosondes. Therefore this strong wind layer would correspond to the high temperature layer detected by the radiosonde data. The lower boundary, superimposed in Fig. 6, appears at 1600 m to 1800 m a.s.l.

Table 1 shows an example of various meteorological variables and calculated values in three vertical points around the high temperature layer observed by the towersonde. These are 10 minutes averages over 4:50 through 5:00, when the top sensor of towersonde reaches the highest altitude in this night, and it was raised above the lower limit of the high temperature layer. This table shows that the high temperature layer was formed by the warm air advection from the north, and that a lower limit of the high temperature layer has not only a large gradient of temperature and humidity but also of wind direction and wind speed.

The vertical temperature profiles at the southern area of Mt. Yatsugatake at 4:00 is displayed in the left panel of Fig. 7. Note that radiosonde data are not observed just at 4:00, since it takes over ten minutes from surface to 2600 m a.s.l. Towersonde profile is based on the measurement at 4:50 through 5:00. Despite of the height difference of both sonde sites, lower limit of the high temperature layer appeared at the same altitude of 1800 m a.s.l. This means that upper temperature inversion appeared at the same altitude for the two different sonde sites. In other words, it is independent of the relative height from the surface of the mountain slope.

Table 1 An example of meteorological values and calculated data around the lower limit of high temperature layer obtained by towersonde observation
Ten minutes averaged data from 4:50 to 5:00, November 2, 1997 are shown.

Location	Altitude	Air temperature	Relative humidity	Wind speed	Wind direction	Specific humidity	Potential temperature
Units	m a.s.l.	℃	%	m/s	degree	g/kg	K
In the high temperature layer	1893.4	0.7	28.9	5.9	347.5	1.4	290.3
At the lower limit of the high temperature layer	1808.9	-1.7	55.8	0.7	312.4	2.3	286.8
Under the high temperature layer	1713.8	-1.2	64.2	1.5	227.7	2.7	286.4

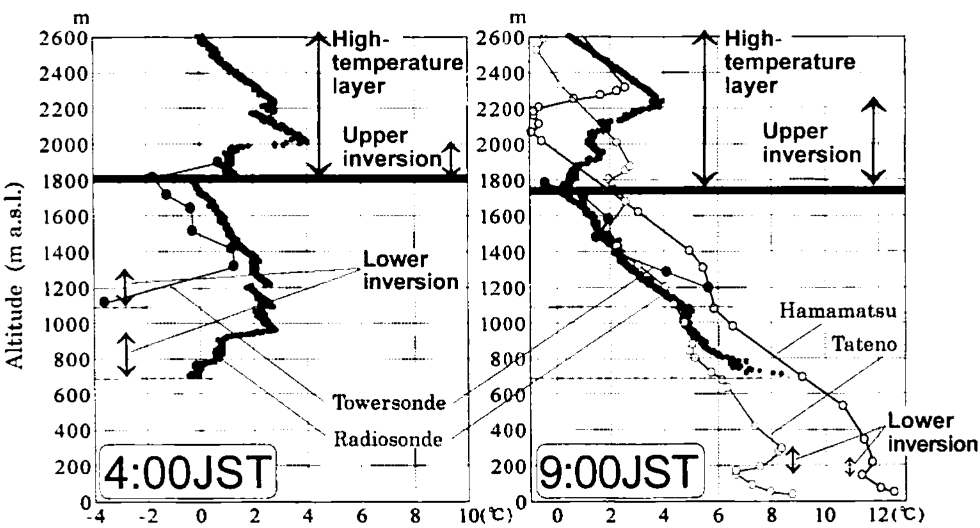

Fig. 7 Vertical temperature profiles at the southern area of Mt. Yatsugatake (radiosonde site and towersonde site) at 4:00 JST and 9:00 JST, November 2, 1997
Also shown are the profiles of Hamamatsu and Tateno (aerological observation sites) at 9:00 JST, November 2, 1997.

4. Discussion

We will compare three vertical profiles such as radiosonde, towersonde and rawinsonde by the aerological observation. Note that Fig. 7 does not show the profile of just 9:00, namely, radiosonde data at Mt. Yatsugatake are obtained from 8:58:52 (surface) to 9:07:23 (2600 m a.s.l.). Because the aerological observation begins 30 minutes before 9:00 and 21:00 in principle (Japan Meteorological Agency 1995), towersonde profile of 10 minutes mean from 8:25 to 8:35 is calculated, and the vertical temperature profiles on the study area were compared with those at Hamamatsu and Tateno (Fig. 7). A local maximum is found at 9:00 in both radiosonde observations at the study area (2234 m a.s.l.) and at Hamamatsu (2311 m a.s.l.), simultaneously. The difference of temperature inversion at the high temperature layer is 4.2℃ and 3.6℃, respectively. It should be noted that the upper temperature inversion occurs in the same altitude, and the difference of temperature is almost same, although the distances between two sites are over 130 km. A rapid decrease of humidity at the temperature inversion was also observed at Hamamatsu. Therefore these results indicate that the high temperature layer would be an anticyclonic-scale phenomenon.

In relation to this phenomenon, Suzuki and Kawamura (1995) analyzed temperature inversion up to 300hPa over Japan using aerological observation data. In this study, high frequency peaks of inversions were shown around 950hPa, 750hPa and 300hPa. They suggested the peak around 750hPa was considered to be emerged in conjunction with winter monsoon or subsidence flow in anticyclone.

We can recognize that the lower temperature inversion has a local maximum temperature between 200 m and 300 m a.s.l. at 9:00 in the aerological data of Hamamatsu (211 m a.s.l.) and Tateno (290 m a.s.l.). These altitudes are corresponding to those of thermal belt which appears on the mountain slope around Kanto plain, central Japan. Kondoh *et. al.* (1992) showed this fact by the analysis of the thermal band of the thematic mapper of the LANDSAT-5. Gunji (1957) and Yoshino (1961) also show the thermal belt at 200 through 300 m a.s.l. on the slope of Mt. Tsukuba, 19 km north of Tateno aerological station. On the other hand, in the study area at 4:00, the lower temperature inversion appears between 200 m and 250 m in a relative height from the surface in either of radiosonde and tower sonde observations. These results show that the thermal belt depends on surface altitude because it is formed by surface inversion from radiative cooling and local circulation. In contrast, the altitude of high temperature layer in the top of upper inversion, which is associated with the high-altitude thermal belt, appears broadly at the same altitude in different sites in the central Japan.

5. Concluding Remarks

Figure 8 is a schematic diagram of the meteorological observations which summarizes most results in the study area. The horizontal line at 1800 m a.s.l. shows the lower limit of the high temperature layer. The high temperature layer, which is characterized by warm and dry air flows with strong winds, appears above this altitude. On the contrary, it is relatively cool and moist below the lower limit of the high temperature layer. The dot-curved line above a few hundred meters on the slope shows upper limit of the surface inversion layer. The thermal belt appears at this height.

Finally, we summarize concluding remarks:

1. The high-altitude thermal belt, which appeared at the southern slope area of Mt. Yatsugatake, is formed in the high temperature layer that is associated with subsidence inversion of anticyclones.

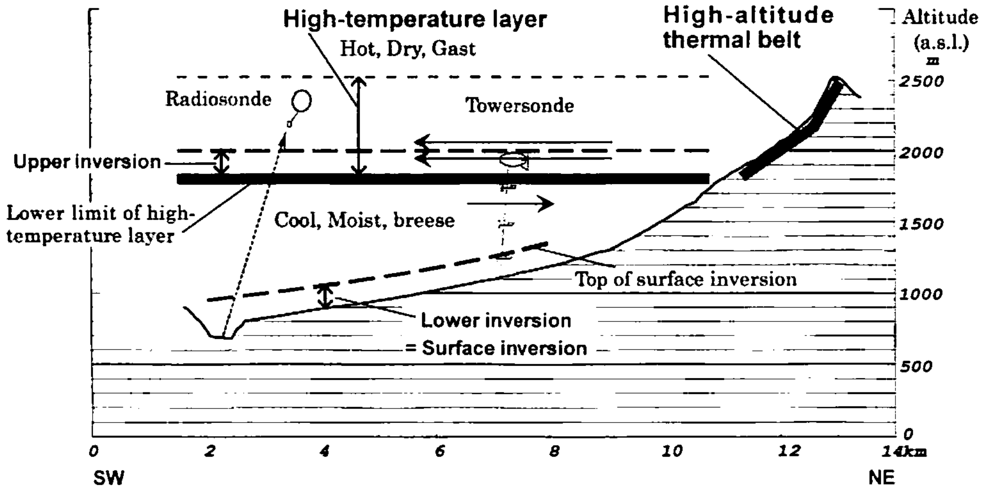

Fig. 8 Schematic diagram of the result of this observation, and a conceptual model of the occurrence of the high-altitude thermal belt

2. The temperature inversion and the rapid humidity decrease are simultaneously found in the same altitude at the aerological observation in Hamamatsu and at radiosonde measurements at the southern slope area of Mt. Yatsugatake.
3. The formation process for the high temperature layer is different from those for the thermal belt. The main factor for the high temperature layer (high-altitude thermal belt) formation is attributed to the subsidence flow in the travelling anticyclone, whereas the low-altitude thermal belt is formed by the surface inversion from radiative cooling and local circulation.

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