Daytime Boundary Layer Evolution in a Deep Valley. Part I: Observations in the Ina Valley

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ABSTRACT

The development process of the daytime boundary layer under fair weather and weak synoptic wind conditions was observed in the Ina Valley, a deep two-dimensional valley in Japan. The daytime boundary layer over the bottom of the valley consisted of two sublayers. The lower sublayer is a turbulent mixed layer that reached to heights of 500–1000 m above the surface. The upper sublayer is formed by the local subsidence, which is part of the thermally induced cross-valley circulation, remaining a slightly stable stratification during the daytime. The specific humidity did not become vertically uniform in the upper sublayer due to the weakness of the turbulent mixing.

The heating rate of the boundary layer was larger over the valley bottom while smaller over the mountainous areas. The observed results suggest that the thermally induced cross-valley circulation (i.e., upslope flow along the side slopes) plays a role in the heat transport from the mountainous regions to the central part of the valley. The structures of the boundary layer obtained during these observations were also consistent with previous results observed in other basins and valleys.

The cross-valley circulation prevailed until the early afternoon. However, an up-valley wind along the valley developed during the late afternoon and continued to flow until midnight. The intensity of the up-valley wind increased with increasing the thermal contrast between the coastal and inland regions in central Japan.

1. Introduction

Over flat, horizontally uniform terrain, the convective boundary layer (CBL) develops due to the sensible heating from the surface during the daytime under fair weather conditions. The potential temperature in the CBL is vertically uniform due to the strong turbulent mixing, which is a characteristic of the daytime planetary boundary layer (PBL) over flat terrain. Over complex terrain such as mountainous areas, however, the formation and structure of the daytime PBL strongly depend on the thermally induced local circulations that develop under fair weather conditions.

Over the last several years, many studies have examined the daytime PBL evolution over complex terrain. Whiteman (1982), Müller and Whiteman (1988), and Sakiyama (1990) observed the development of the daytime boundary layer in mountain valleys, indicating that local subsidence plays an important role in the breakup of the temperature inversion and the formation of the CBL. Local subsidence is associated with a compensating current of the upslope flow along the side slopes, and it was also found in the daytime heating process of a three-dimensional basin (Kondo et al. 1989). In the study they found that adiabatic heating due to local subsidence intensifies the atmospheric heating over the basin bottom and causes the development of a deep CBL in the afternoon. The larger atmospheric heating rate over the basin bottom was also confirmed by a heat budget analysis of the daytime PBL over central Japan (Kuwagata et al. 1990a,b). Whiteman (1990) summarized recent investigations of thermally developed wind systems in complex mountainous terrain, while also discussing the role of the thermally induced wind in the heat transfer of the PBL over complex terrain.

The depth of the basins and valleys, which have been examined in these previous studies, are in the range of approximately 500–1000 m. In the present study, however, the structure of the daytime PBL is investigated over a two-dimensional deep

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valley, having a depth of over 2000 m, by means of observations in the Ina Valley in Japan. The study examines the relationship between the PBL structure and the thermally induced local circulation. First, the outline of observations are described in section 2. The observed structure of the PBL and the role of the thermally induced cross-valley circulation are discussed in section 3. In section 4, the role of the thermally induced circulation along the valley, which developed in the late afternoon, is also discussed.

2. Observation

The development process of the daytime PBL was observed in the Ina Valley, a deep two-dimensional valley in Japan. Figure 1 shows the location and the topography of the Ina Valley, one of the deepest and largest valleys in Japan. The elevation of the bottom of the valley (the valley bottom) is around 500–600 m MSL, while the mountain ridges on both sides reach altitudes of around 3000 m MSL. The altitude of the highest mountain of the eastward mountain ridge (the Akaishi Mountains) is 3192 m MSL, with that of the westward mountain ridge (the Kiso Mountains) being 2956 m MSL. The depth of the valley, which is the difference between the valley bottom and the top of the mountain ridges, ranges from 2000 to 2500 m. The width of valley is about 40 km, and the length of the valley about 100 km. Both sides of the mountains facing the valley are covered by forest except for the higher regions, greater than 2500 m MSL. The ground surface of the valley bottom mostly consists of paddy fields and other cultivated fields.

Observation sites are indicated by the letters A, B, and C in Fig. 1c. Site A (Iijima) is the base site, located near the valley bottom at an altitude of 690 m MSL. At this site, both surface and upper-air meteorological data were gathered. The upper-air data were taken by means of rawinsonde and pilot balloon observations. Sites B and C are located on the westward mountain side slope at altitudes of 1695 and 2645 m MSL, respectively, where the surface pressure and air temperature were measured. The location of site C is close to the top of the mountain ridge.

The observations were conducted over 4 days, 12 May and 1–3 June 1992, under fair weather conditions. During the observation periods, Japan was under the influence of a large traveling anticyclone, and the synoptic winds were weak.

3. The cross-valley circulation

a. Thermal structure of the PBL over the valley bottom

Figure 2 shows the daily time variations of the potential temperature and specific humidity profiles at site A (Iijima). In all cases, the daytime PBL consisted of two sublayers and had a total depth of 1500–2500 m. The lower sublayer corresponds to the turbulent mixed layer, which remained under heights of 1000 m from the surface, even during the afternoon. On the other hand, the upper sublayer maintained a stable stratification during the daytime and gradually warmed with time. As will be discussed in section 3c, the upper sublayer is created by the adiabatic heating due to the local subsidence, which is part of the thermally induced cross-valley circulation.

The time variation of the specific humidity was rather complicated compared with that of the potential temperature. The specific humidity in the lower sublayer was vertically uniform, while that in the upper sublayer did not become vertically uniform, even during the late afternoon, due to the weakness of the turbulent mixing. The specific humidity in the lower sublayer tended to be invariant with time or to decrease during the daytime, while that in the upper sublayer tended to increase during the daytime. Further, small maximum peaks in the specific humidity existed in the upper sublayer during the afternoon. These characteristics are closely related to the water vapor transport due to the thermally induced circulation in the valley (see section 3c).

The two-layer structure of the PBL was also observed at the basins or valleys that have depths of less than 1000 m (Whiteman 1982; Kondo et al. 1989). In those cases, the upper sublayer merged with the lower turbulent mixed layer until the late afternoon, resulting in a deeper CBL over the valley bottom. In the present case of a deep valley, however, the upper sublayer remained with a slightly stable stratification during the daytime and did not merge into the lower turbulent mixed layer, even in the late afternoon.

b. Heating rate of the PBL

Table 1 lists the daytime mean heating rate Q_s of the PBL at the valley bottom (site A), calculated from two upper-air data, observed around 0500 JST (near sunrise) and 1600 JST. The main source of heating the PBL is the sensible heat flux H from the ground surface, and the value of H depends mainly on the intensity of solar radiation, temperature, humidity, and the conditions of ground cover. In the previous study (Kuwagata et al. 1990b), the daytime mean value of H was estimated as around 200 W m^{-2} in the Ina Valley under fair weather conditions during the early summer season. On the other hand, the heat advection due to the large-scale (synoptic) flow also influences the heating rate of the PBL. The observed values of Q_s considerably exceed 200 W m^{-2}, even when the heating due to the synoptic subsidence was weak (corresponding to the cases of 12 May and 3 June when the potential temperature profiles above the PBL were almost invariant during the daytime). These results suggest that the PBL over the valley bottom is heated not only by the sensible heat from

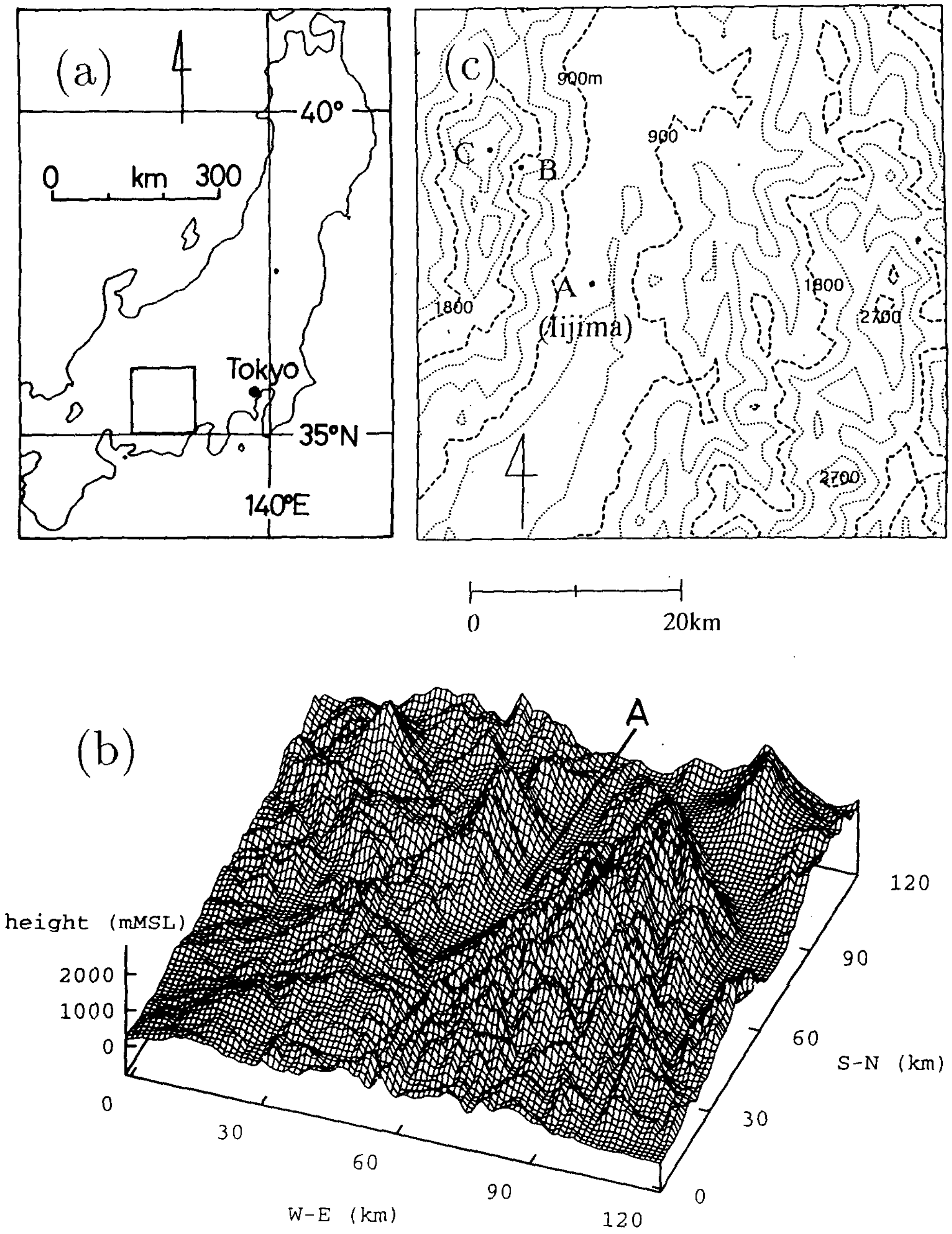


FIG. 1. (a) Map of a part of Japan showing the location of the Ina Valley (indicated by the square). (b) Three-dimensional illustration showing the Ina Valley, corresponding to the area enclosed by the square in (a). (c) The locations of the observational sites A, B, and C; also shown are contours of elevation above mean sea level with a 300-m interval.

the ground surface but also by the heat advection due to the local circulation.

Figure 3a shows the diurnal variation of air temperatures at sites A (solid line) and C (dot–dash line), while Fig. 3b shows the diurnal variation of surface pressure deviations at sites A (solid), B (dotted), and C (dot–dash). The solid squares in Fig. 3b are the atmospheric pressure deviations above the valley center at an altitude that is the same as site C (2645 m MSL).

According to the hydrostatic equation, the surface pressure decreases nearly proportional to the PBL heating rate if the atmospheric pressure at a certain level above the PBL is invariant during daytime (Kuwagata et al. 1990a). The surface pressure at the valley bottom (site A) had a large diurnal variation, the depression reaching about 3–4 hPa during the daytime. However, the diurnal variations of surface pressure were small over the mountainous areas (sites B

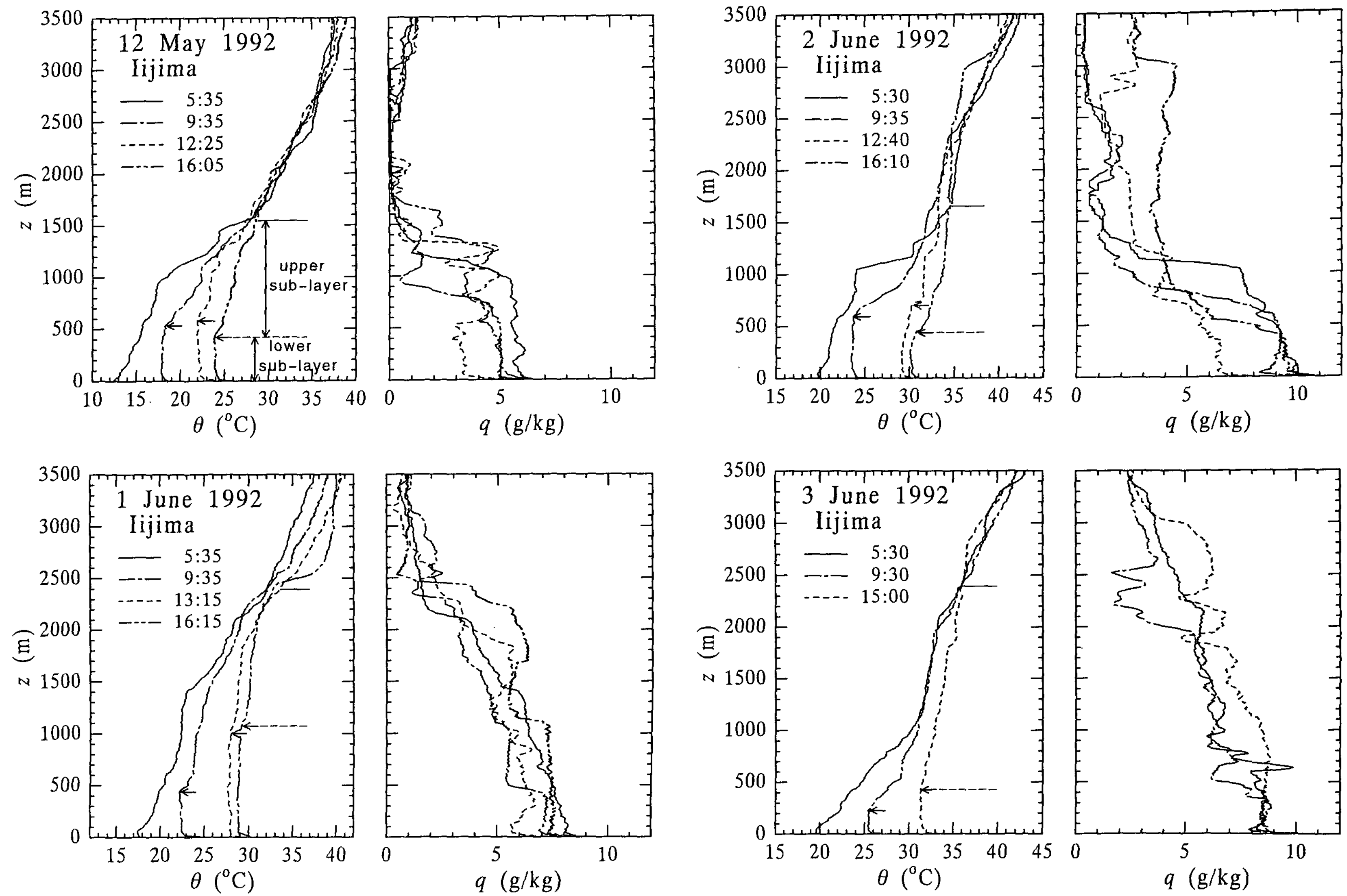


FIG. 2. Daily time variations of the potential temperature (left) and specific humidity (right) profiles at site A (Iijima). The tops of the turbulent mixed layer (lower sublayer) are indicated by arrows and those of the PBL by bars. Time corresponds to Japan standard time (JST).

TABLE 1. The daytime mean PBL heating rate Q_s at the valley bottom (site A). The values of the depth of the PBL z_h were estimated from the time variation.

Date	Q_s (W m^{-2})	z_h (m)
12 May 1992	312	1550
1 June 1992	379	2400
2 June 1992	304	1650
3 June 1992	270	2400
Mean	316	

and C). The diurnal variation of atmospheric pressure observed at an elevated point above the valley center by the rawinsonde exhibited the same features as that at site C, as long as the altitude of the point was at the same level as site C. The larger decrease of surface pressure at the valley bottom corresponds to the larger daytime PBL heating rate, while the smaller pressure decrease in the mountainous areas corresponds to the smaller PBL heating rate in that region. The larger daytime increase of temperature at site A and smaller one at site C also correspond to the difference in the daytime PBL heating rate between both areas. These results imply that heat transport occurred from the mountainous regions to the central part of the valley during the daytime.

c. Mechanism of the cross-valley circulation

The thermally induced circulation in the valley was investigated using a two-dimensional numerical model by Kimura and Kuwagata (1995). The study suggests that the upper sublayer of the PBL observed in the Ina Valley is created by the adiabatic heating due to local subsidence. The result of this numerical study is briefly discussed with the respect to the PBL structure observed in the Ina Valley.

The local subsidence over the valley bottom is part of the cross-valley circulation. Figure 4 shows a schematic illustration of the cross-valley circulation. The cross-valley circulation can be divided into four parts, the upslope flow along the side slopes, the counter-upslope flow in the upper level, the strong upward flow over the mountain ridge, and the weak downward flow (subsidence) over the valley bottom (Kimura and Kuwagata 1995).

The driving force of the cross-valley circulation is the nonuniform horizontal temperature field, with the circulation playing a role in the heat transport from the mountainous regions to the central part of the valley. The wind tends to adjust the potential energy to minimum values so that the potential temperature field in the valley becomes nearly horizontally uniform in the late afternoon. Local subsidence heating over the valley bottom contributes to part of this heat transport system. Owing to this circulation, the daytime PBL heating rate increases over the valley bottom while it becomes negative over the mountainous areas (Kimura and Kuwagata 1995). The PBL heating rates observed in this present study (section 3b) are in accordance with the heat transport due to the cross-valley circulation discussed above.

On the other hand, water vapor is transported from the central part of the valley to both mountainous side regions due to the cross-valley circulation, resulting in latent heat accumulating over the mountain ridge. The specific humidity in the daytime PBL does not become vertically uniform due to this water vapor transport (Kimura and Kuwagata 1995). In Part II, the heat and

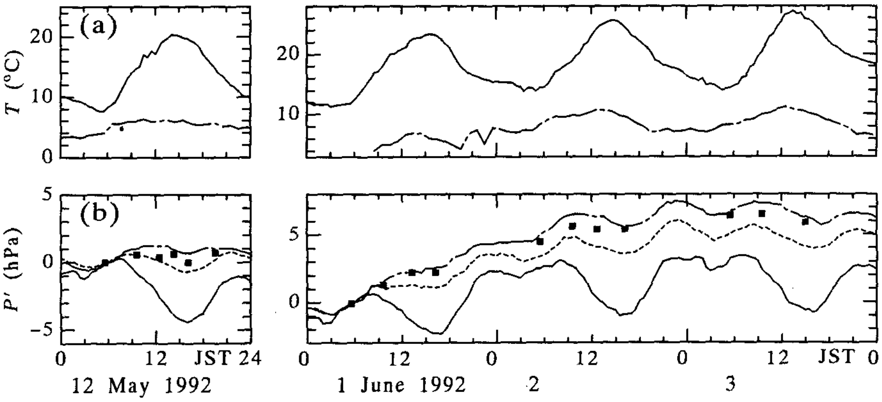


FIG. 3. (a) Diurnal variation of air temperatures at sites A (solid line) and C (dot–dash line). Data were measured at 3.7 m above the ground at site A and at 1.5 m at site C. Data at site C were supplied by the Chuoh Alps Kanko Company Ltd. (b) Diurnal variation of surface pressure deviations P' at sites A (solid), B (dotted), and C (dot–dash). The solid squares are the atmospheric pressure deviations above the center of the valley floor at the same altitude as site C. Here, $P' \equiv P - P_{\text{base}}$, where P_{base} is the pressure at 0600 JST 12 May or 3 June 1992.

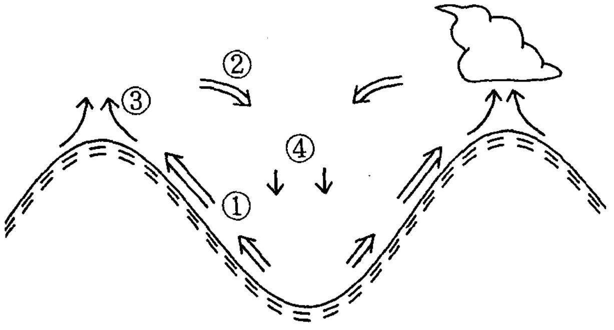


FIG. 4. Schematic illustration showing the daytime cross-valley circulation, where 1 is the upslope flow, 2 the counter-upslope flow, 3 the strong upward flow, and 4 the weak downward flow (subsidence). The figures are designed according to the results of the numerical simulation conducted by Kimura and Kuwagata (1994).

water vapor transport in the Ina Valley due to the cross-valley circulation will be further investigated using the two-dimensional numerical model.

4. The circulation along the valley

Figure 5 shows time–height cross sections of the horizontal wind vectors at site A for the 4 days. In all cases, the upper-level synoptic wind was weak, with the wind speeds in the layer between 1500 and 3000 m above the ground being less than 10 m s^{-1} during the daytime. The lower-level wind speeds, below 1500 m, were also weak until around noon. That is, it can be expected that the cross-valley circulation prevailed until the early afternoon. However, the northward up-valley wind along the valley occurred around noon, up to heights of approximately 800–1400 m by the late afternoon. The maximum wind speeds in the layer of the up-valley wind ranged from 7 to 15 m s^{-1} during the late afternoon.

The diurnal variations of specific humidity and wind speed at site A are shown in Fig. 6. The surface wind speed at the valley bottom remained weak during the morning hours but became stronger in the afternoon. This somewhat stronger wind corresponds

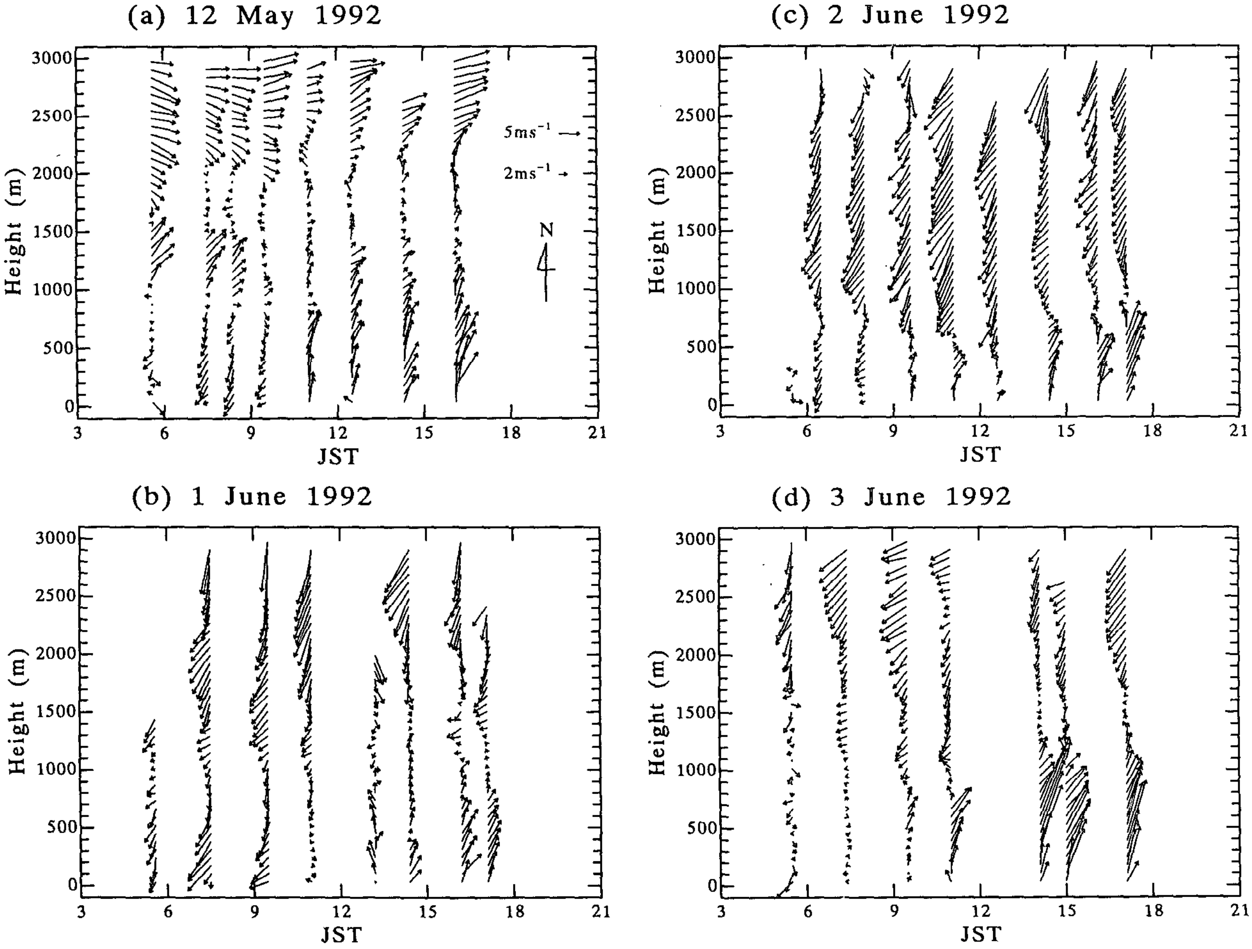


FIG. 5. Time–height cross sections of the horizontal wind-vectors at site A, for (a) 12 May, (b) 1 June, (c) 2 June, and (d) 3 June 1992.

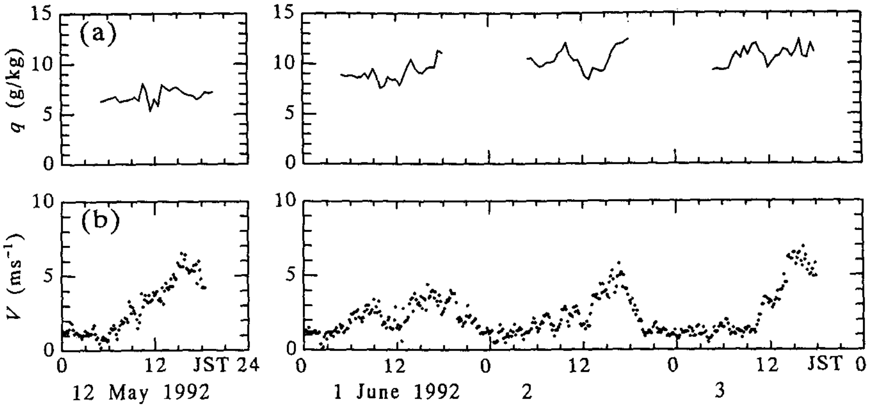


FIG. 6. (a) Diurnal variation of specific humidity at site A measured at 0.9 m above the ground. (b) Diurnal variation of wind speed at site A measured at 4.0 m above the ground.

to the northward up-valley wind along the valley and continued to flow until midnight. On the other hand, the specific humidity reached a minimum value around noon and then increased after the onset of the up-valley wind.

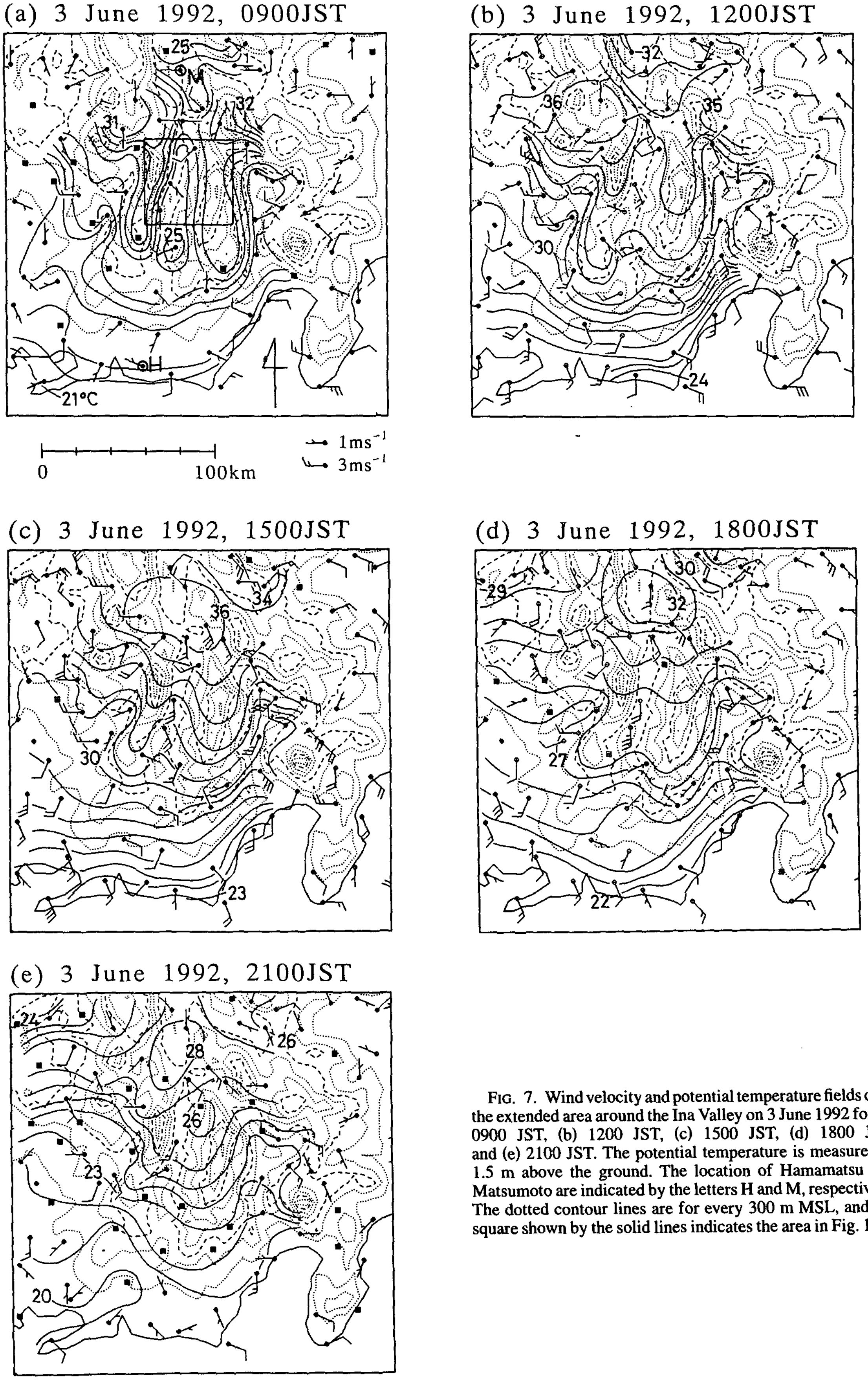
Figure 7 shows the wind velocity and potential temperature fields over the extended area around the Ina Valley on 3 June 1992, analyzed from data acquired by the Automated Meteorological Data Acquisition System of the Japan Meteorological Agency. The prevailing northward wind in the In a Valley is separated from the sea breeze over the coastal area. The afternoon potential temperatures are higher over the inland areas than over the coastal area of central Japan. According to this horizontal thermal contrast, a daytime thermal low should develop over central Japan (Kuwagata and Sumioka 1991).

As described in section 3b, the surface pressure decreases during the daytime nearly proportional to the PBL heating rate. Thus, the horizontal pressure difference between the coast and inland increases with increasing the thermal contrast between both areas. Table 2 reveals the relationship between the intensity of the up-valley wind and the horizontal pressure gradient over central Japan for the 4 days of observations. Here, $V_{\max}$ is the maximum wind speed at site A (recorded around 1600 JST for all cases), z_v the height to which the up-valley wind penetrates around 1700 JST at site A, and ΔP the horizontal pressure difference at the 610 m MSL between the coast and inland at 1500 JST [$\Delta P \equiv P_H - P_M$, where P_H is the upper-level pressure at Hamamatsu, and P_M the surface pressure at Matsumoto]. The values of $V_{\max}$ and z_v increase with increases in ΔP. Although the mechanism of the up-valley wind in the Ina Valley is not presently fully known, the intensity of the up-valley wind increased with increasing the thermal contrast between coastal and inland regions over central Japan. The numerical simulation also predicts that the thermally local flow from coastal plain to inland basin is induced by the thermal contrast between both areas in the late afternoon (Kimura and Kuwagata 1993).

The advection of cold, moist air due to the up-valley wind results in the cooling and humidifying of the PBL in the Ina Valley during the evening hours. Figure 8 shows the time variations of the potential temperature (left) and specific humidity (right) profiles at site A during the late afternoon of 12 May 1992. Although the potential temperature was almost invariant from 1415 to 1605 JST, the layer below 2000 m was cooled from 1605 to 1930 JST. The specific humidity in this cooled layer abruptly increased during the same period. The increase in the surface pressure at the valley bottom (site A) from 1700 to 2100 JST corresponds to the cooling of the PBL, which can be partly attributed to the cold-air advection by the up-valley wind (see Fig. 3b). As described above, the structure of the PBL in the Ina Valley was affected by the up-valley wind in the late afternoon.

TABLE 2. The relationship between the intensity of the up-valley wind and the horizontal pressure gradient. Here, $V_{\max}$ is the maximum wind speed at site A (4.0 m above the ground, recorded around 1600 JST for all cases.), z_v the height to which the up-valley wind penetrates around 1700 JST at site A, and ΔP the horizontal pressure difference at 610 m MSL between coast and inland at 1500 JST ($\equiv P_H - P_M$, where P_H is the upper level pressure at Hamamatsu, P_M the surface pressure at Matsumoto). The locations of Hamamatsu and Matsumoto are indicated by letters H and M in Fig. 7a, and the value of P_H is estimated from aerological data by interpolating linearly in time.

Date	$V_{\max}$ (m s^{-1})	z_v (m)	ΔP (hPa)
12 May 1992	6.5	1400	5.9
1 June 1992	4.0	800	3.6
2 June 1992	5.8	800	4.3
3 June 1992	6.9	1350	4.9


(a) 3 June 1992, 0900JST

(b) 3 June 1992, 1200JST

(c) 3 June 1992, 1500JST

(d) 3 June 1992, 1800JST

(e) 3 June 1992, 2100JST

FIG. 7. Wind velocity and potential temperature fields over the extended area around the Ina Valley on 3 June 1992 for (a) 0900 JST, (b) 1200 JST, (c) 1500 JST, (d) 1800 JST, and (e) 2100 JST. The potential temperature is measured at 1.5 m above the ground. The location of Hamamatsu and Matsumoto are indicated by the letters H and M, respectively. The dotted contour lines are for every 300 m MSL, and the square shown by the solid lines indicates the area in Fig. 1c.

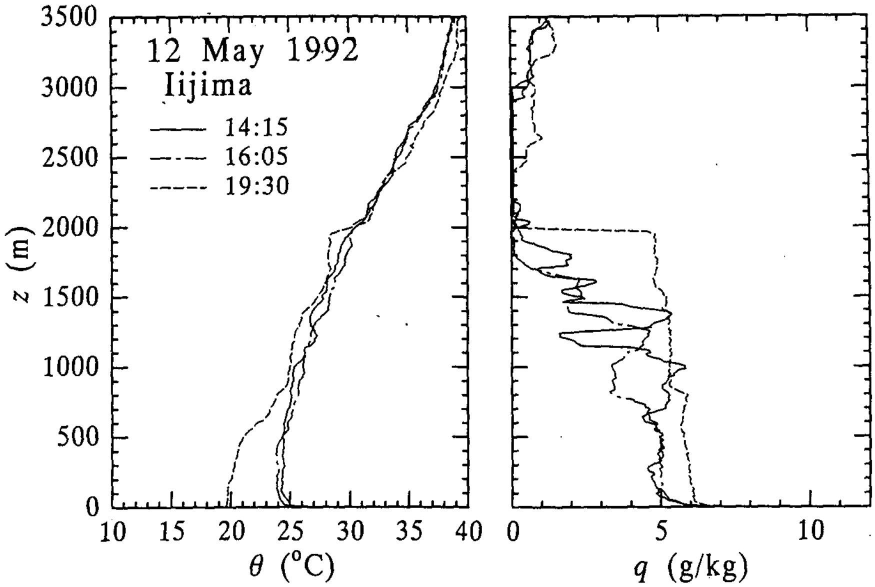


FIG. 8. The variations of the potential temperature (left) and specific humidity (right) profiles at site A (Iijima) during the late afternoon of 12 May 1992.

5. Summary

The development process of the daytime PBL was observed in the Ina Valley, a deep, two-dimensional valley in Japan, under fair weather and weak synoptic wind conditions. The results can be summarized as follows:

1) The daytime PBL over the valley bottom consisted of two sublayers. The lower sublayer is the turbulent-mixed layer, which was formed up to heights of less than 1000 m from the surface. The upper sublayer is created by the local subsidence, which is part of the thermally induced cross-valley circulation.

2) Although the upper sublayer was heated over time, it maintained a slightly stable stratification during the daytime. The specific humidity within the PBL, therefore, did not become vertically uniform, even in the late afternoon, due to the weakness of the turbulent mixing.

3) In the Ina Valley, the PBL heating rate was larger over the valley bottom, while smaller over the mountain ridge regions. The observed results suggest that the thermally induced cross-valley circulation, represented by the upslope flow along the side slopes, plays a role in the heat transport from the mountainous regions to the central part of the valley.

4) The thermally induced cross-valley circulation prevailed until the early afternoon. However, the up-valley wind along the valley developed in the late afternoon and continued to flow until midnight. The intensity of the up-valley wind increased with increasing the thermal contrast between the coastal and inland regions in central Japan. The cold, moist air advection by the up-valley wind contributed to the cooling and humidifying of the PBL during the evening hours.

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