NOTES AND CORRESPONDENCE

Role of Patchy Snow Cover on the Planetary Boundary Layer Structure during Late Winter Observed in the Central Tibetan Plateau

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Abstract

The one-dimensional structure of a daytime planetary boundary layer (PBL) with shallow cloud development was captured by intensive sonde observation during the late winter season at the central Tibetan Plateau (TP), and its relationship to patchy snow cover conditions was revealed. The diurnal change of potential temperature was evident in the atmosphere up to 1 km above ground, indicating PBL development, and frequent cloud formation in the afternoon and night over the PBL was confirmed by the increase of relative humidity in the sonde data profile and abrupt decrease of brightness temperature in the satellite images. Day-to-day changes of PBL and nighttime stable layer developments were dependent on the speed of the sub-tropical jet stream prevailing 5 km

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above the surface and the changing of snow cover conditions after snowfall events. Numerical simulations confirmed that the increase of land-surface albedo, imitating the continuous snow covers, could suppress the PBL and cloud development. The positive feedback of land-atmosphere interactions through the PBL development on patchy snow cover and re-distribution process of shallow and dry snow cover were discussed.

1. Introduction

The Tibetan Plateau (TP) has been explained as a heat sink in the sub-continental scale circulation during the winter (Yeh and Gao 1979). According to operational analysis data, westerlies tend to flow around the plateau, and the planetary boundary layer (PBL) develops 1.5 km above the plateau with weakening of near-surface winds on the TP (Murakami 1981a). Vertical circulation mainly prevails over Assam and southeastern edge of TP by diurnal orographic heating (Murakami 1981b). On the other hand, thermal effects of spring TP to the successive Asian monsoon activities have been indicated by several studies. For instance, Yasunari et al. (1991) demonstrated in the global circulation model (GCM) that the albedo effect dominates, especially over the TP, among the regions in the Eurasian continent because of lower latitudes with sufficient insolation. Sato and Kimura (2007) proposed a unique hypothesis that the thermal effects of spring TP cause the mid-tropospheric subsidence over north India, which disturbs the northward propagation of the Indian monsoon. According to the reanalysis data, February to April corresponds to a transitional period when the surface sensible heating and the column-integrated total heating over the TP change from negative (heat sink) to positive (heat source) (Wu et al. 2007). From the point of view of cloud convections, Fujinami and Yasunari (2001) found an active convective season over the plateau from March to April by satellite images, and Oku and Ishikawa (2004) also indicated a robust decrease of the cloud free ratio in the same season. According to an intensive sonde observation in April by Taniguchi and Koike (2007), mid-tropospheric warming was associated with cumulus convections, and a numerical simulation demonstrated the necessity of condensation processes to initiate the convection. Those studies indicated that the heating process of the plateau surface has already started in early spring, when the retreat of snow covers and development of top-soil melting layer are activated under the rich sub-tropical solar radiation. However, there are still a few observations of lower troposphere synchron-

ized with observing the land-surface condition during the transition period between the winter and pre-monsoon season.

According to the snow cover observation by Sato (2001), days with snow cover in winter increase with the latitude, but long-lasting snow covers are not typical. The results of the study showed a negative correlation between the air temperature anomaly and the days of snow cover and attributed it to the localized albedo effects. Ueno et al. (2007) characterized the snow cover in central TP as patchy distribution that is favorable for sensible heating from the bare land surface even in late winter, when the albedo was strongly determined by the local snow cover portion. The major factor of developing patchy snow cover is the redistribution process of dry snow on the micro-scale topography under the condition of a small amount of precipitation. The amount of winter precipitation is small in the TP, for example, several 10 mm for a single precipitation event mainly induced by the western disturbances (Ueno 2005), which matches the condition. According to the snow-profile observation in February 2004, a drifted snow cover consisted of several layers, indicating that redistribution occurred after each precipitation event. There must be, then, a threshold of precipitation that would cover the entire land surface and cause a sudden increase of the local albedo. Another key factor for the redistribution is a strong surface wind that is linked to the PBL structure. A strong Sub-tropical Jet stream (STJ) prevails over the southern plateau in winter, but the linkage between the STJ and PBL development has not been investigated. A numerical simulation is a powerful tool to diagnose the structure of the lower troposphere, but few studies have shown the performance of a mesoscale simulation to investigate the PBL development over the plateau in late winter.

The Japan International Cooperation Agency (JICA) conducted a project for the Japan-China Meteorological Disaster Cooperative Research Center (hereafter, the JICA project) during 2005–2009, and intensive land-surface and sonde observations were done from the end of February to middle March 2008 in the Naqu Basin, central TP,

to investigate the land-atmosphere processes and their effects on atmospheric circulations over the plateau in the following pre-monsoon seasons. In this study, we analyzed the time sequence of sonde data together with surface meteorological elements and revealed the structure of PBL with cloud convections and their function of forming snow-cover heterogeneity during the late winter season of 2008. Then, a numerical simulation was performed to examine the sensitivity of PBL development by changing the surface albedo.

2. Observation and data

Under the JICA project, intensive sonde observations were conducted at 6 sites in and around the TP. This study focused on the sonde data at the Naqu site, where an automated surface meteorological observation and a manual land-surface observation were simultaneously conducted. The Naqu site in a basin of central TP (see the Fig. 1 of Zhang et al. 2011 in this JMSJ-JICA special issue) in which the southern border of the basin is a part of the northern Nyainqentanglha Mountain range.

Fig. 1. Time-latitude cross section of zonal wind speed at 250 hPa along 90°E by JRA25 data. Intensive observation period at the Naqu site is marked by an arrow.

Aerological data from February 25 to March 19, 2008 was obtained at the Naqu meteorological bureau in a Naqu City (92°04'E, 31°29'N, 4,508 m a.s.l.). Sondes were launched at the hours of 1, 7, 13, and 19 Beijing Time (BJT), which is 8 hours in advance of the Universal Time Coordinate (UTC) and 2 hours before the sun-synchronized local time (LT). Meteorological data, such as temperature, humidity, shortwave downward radiation, and wind speed and direction, were measured at a 1-m level from the ground surface by an Automated Weather Station (AWS) at the BJ observation site (91.78°E, 31.36°N, 4,610 m a.s.l., Hong et al. 2004) about 15 km southwest of Naqu City. Land-surface observation with snow cover measurements was also conducted every morning for March 10–16 to the south of Naqu City (92°02'E, 31°27'N, 4,490 m, Tsutsui et al. 2009). Japanese 25-year Re-analysis project data (JRA25; Onogi et al. 2007) are used to capture the intra-seasonal variations of synoptic scale atmospheric circulations. METEOSAT Infra-red (IR) satellite data (provided by the European Organization for the Exploitation of Meteorological Satellites) and MODIS Snow Products (provided by the National Snow and Ice Data Center, Hall et al. 2007) are used to assess the plateau-scale cloud convection activity and snow cover distribution.

3. Synoptic and land-surface conditions

According to the Outgoing Longwave Radiation (OLR) distribution published by the U.S. Department of Commerce National Oceanic and Atmospheric Administration (NOAA), Climate Diagnostic Bulletin (NOAA/NWS/NCEP), March 2008 was characterized as relatively warm and dry climate in the southern and western plateau. The intra-seasonal variation of upper troposphere zonal winds along 90°E is shown in Fig. 1. A strong STJ core located around 25–33°N, and it temporally shifted northward in early January and early February. The jet stream stayed to the south of 30°N during March, and it diminished in May without a northward transition. During a JICA observation period (indicated by an arrow in Fig. 1), the STJ core located around 28°N over the southern Naqu Basin, and it shifted southward with a weakening wind speed over the Naqu area around March 4 and 15. Those periods corresponded to passing or traveling mid-latitude troughs that provided weak precipitations in Naqu basin (as explained later).

According to the MODIS Snow Products, seasonal snow did not cover entire areas of the plateau in February and March, but it was limitedly distributed in the Himalayas and the western or eastern mountainous areas over the plateau. The areal snow cover portion was smaller in the central and southern plateau, and weekly scale wide-range snow covers appeared along the Tanggula mountain range stretching from west to east in the central TP after passing synoptic scale disturbances. To the south of Naqu City, where land-surface observations were conducted, snow covers with a thickness of approximately 4 cm covered less than 15% of the ground through the observation period, except for snowfall days. Volumetric soil moisture in the upper soil layer was mostly dry, around 5–10%. In the snow-free areas, a soil layer above 5 cm depth was not frozen (the so-called active layer), and where the daytime skin surface temperature sometimes exceeded 10°C, even the air temperature was below 0°C. Namely, large surface temperature contrasts existed around the patchy snow covers in the late winter, causing much larger sensible heating than the continuous snow cover condition with micro-scale thermal heterogeneity, and evaporation or sublimation prevailed from the snow covers and their peripheries. During the observation period, we experienced a snow fall in the morning of March 15, when almost all ground surfaces were covered by snow, but it recovered to a patchy distribution in the next day with a strong surface wind condition.

4. PBL structure and cloud convections

A picture in Fig. 2 was taken facing east at noon of March 6, 2008, at Damsyung (4,600 m) located in the middle between Lhasa and Naqu City. The day corresponds to the weakening period of the

STJ in the upper troposphere and two days after the snowfall at the BJ site. In the picture, a snow-covered mountain is a part of the Niyangchentang-gula Mountain range, and the snow-covered portion on the near side plain was around 50% with a depth of 10–20 cm. The air temperature was -5°C , and clouds covered almost 30%. A noteworthy scene is the development of cloud convection to the center right in the picture. Such Stratocumulus cloud development was frequently observed in the daytime during the intensive observation period in the Naqu Basin. Namely, diurnal cloud development on the snow-covered areas is not rare in the central plateau area in late winter season.

To reveal the one-dimensional structure of the lower troposphere with cloud convection, time-height cross section of wind, potential temperature (θ), and relative and absolute humidity are shown in Fig. 3 based on the sonde observation at the Naqu meteorological observatory. In Fig. 3a, strong winds (more than 50 m/s) with weekly scale variability existed at 10–15 km above sea level (a.s.l.), 5–10 km above the plateau surface that corresponds to the STJ core. The appearance of strong wind speed days agreed with the feature in re-analysis data, as shown in Fig. 1. Below 6–8 km a.s.l., θ profiles showed a large diurnal variation. Profiles of θ were averaged at four observation times through the observation period (Feb. 25–March 19) and shown in Fig. 4a. In the night and early morning, most lower atmospheres with almost 1 km depth (below 6,500 m a.s.l.) were stable, and they changed to a neutral stratification in the noon and evening. From a climatological viewpoint, the maximum height of PBL is around 6,500 m a.s.l. Fujinami and Yasunari (2001) also indicated that the daytime profile of the low-level θ (between 400 hPa and 500 hPa) in the re-analysis data

Fig. 2. Cloud development with patchy snow cover fields observed near Damsyung City (4,600 m a.s.l.) facing east. The picture was taken on March 6, 12:01 AM LT, 2008.

Fig. 3. Time-height cross section of a) potential temperature with (u, v) component winds, b) relative humidity, and c) specific humidity by sonde observation in Naqu City. Labeled data corresponds to 1:00AM BJT (−1:00AM LT). Black boxes in a) correspond to the periods in Cases B and C.

Fig. 4. Diurnal variation of potential temperature (left) and relative humidity (right) profiles averaged through the observation period in Fig. 3.

approached to neutral stratification in the early spring season. However, the actual PBL height changed day-by-day depending of the upper wind speed and land-surface condition, as explained later. In the PBL, near-surface relative humidity increased in the night and reduced in the daytime with temperature changes (Fig. 4b). Over 6,500 m a.s.l., the diurnal change of θ profile was small, and the lapse rate of θ became more stable (around 1.1 K/100 m) over 9,500 m a.s.l., corresponding to the free atmosphere, where the STJ prevailed. There was a transition layer at 6,500–9,500 m a.s.l., where the θ lapse rate is smaller (around 0.3 K/100 m), and the relative humidity increased again in the evening and night. In this layer, θ profiles were modulated in a weekly scale (Fig. 3a), suggesting the enhancement of land-surface and atmosphere interactions changes depending of the synoptic conditions. For instance, a nocturnal stable layer was deeper after the snowfall days, such as on March 5–7 and 16–17, suggesting the effects of radiative cooling over snow cover with weakening of STJ. It is also noteworthy that the active convection in the southern Naqu Basin shown in Fig. 2 was coincidentally observed in the period of March 5–7. On the other hand, deeper neutral stratification in the afternoon was sometimes found with stronger STJ, such as on Feb. 29, March 3, 9–11, and 19, when the surface wind speed was also strengthened in the afternoon (as shown later), suggesting the development of a stronger thermal mixing layer. Over 7,500 m a.s.l., relative humidity frequently increased more than 50% with diurnal variations (Figs. 3b, 4b), indicating the occurrences of stratocumulus over the PBL, such as shown in Fig. 2. However, the STJ prevailed above 10 km a.s.l. through the period, and strong wind shear prevented the developments of tall cumulus clouds like those observed in the warm season (see Fig. 13 in Ueno et al. 2001). On the other hand, absolute humidity increased only below 2 km above the ground with day-to-day variability (Fig. 3c). Especially, around March 4 and 15, a rich relative humidity layer reached the ground (Fig. 3b) with an increase of near-surface absolute humidity (Fig. 3c), indicating the occurrence of snowfall. Thus, Fig. 3 clearly captured diurnal variations of a one-dimensional structure of PBL with cloud generation between the STJ and patchy snow cover areas. Patchy snow cover plays an important role to initiate daytime convections and caused apparent diurnal signals in the surface observation data, as ex-

plained in the next section. The cloud development shown in Fig. 2 was earlier than the feature shown in Fig. 4b, and we presume that convections in the mountainous area start earlier than those in the plain areas, such as around Naqu City.

5. Surface observation

Time sequences of meteorological elements observed at the BJ AWS site are shown in Fig. 5. The precipitation amount was not available because the gauge system cannot accurately evaluate the amount of solid precipitation. Diurnal air temperature changes ranged between 7°C and –20°C during the period, and, correspondingly, the relative humidity varied (Figs. 5d, f). Most days, the daytime temperature exceed 0°C with a significant decrease of relative humidity, except on March 4, 5, and 15. One example of the unique weather was the evident diurnal variation of wind speed (Fig. 5a). Strong westerly winds with more than 5 m s^{–1} were observed every afternoon at the 1 m level, and they sometimes exceeded 10 m s^{–1}. Examples of periods with strong surface wind accompanied with strong upper STJ are February 25–26 and March 10–13. It is plausible that a larger downward momentum flux due to the development of a daytime convective layer could strengthen the surface winds in the strong STJ days, as shown in Fig. 3a. This mechanism is confirmed by a numerical simulation in the next section. On the contrary, nocturnal weather was calm, with wind speed less than 2 m s^{–1}. Most of the nocturnal flow contained southerly components (Fig. 5c), and we speculate that this is a drainage wind from mountain ranges in the south of Naqu Basin. The ground surface temperature estimated from upward long-wave radiation was compared with the surface brightness temperature (T_{bb}) observed by the METEOSAT-IR sensor over the AWS site, shown in Fig. 5e. They agreed well in the morning with rapid increases, but the T_{bb} became lower than the surface temperature in the afternoon, reaching below 240 K. AWS kept measuring a ground surface temperature, while the T_{bb} indicated the cloud top temperature that caused temperature discrepancies. Many previous studies warn against the usage of T_{bb} data on TP during the cold season as an index of cloud convections because freezing or snow-covered ground temperature information was contaminated in the T_{bb} value. However, the present observation demonstrated that daytime cloud development over PBL can be captured from the diur-

Fig. 5. Time sequences of meteorological components by AWS at the BJ site, such as a) 1 m level wind speed, b) upward shortwave radiation, c) 10 m level wind direction, d) 1 m level air temperature, e) ground surface temperature (solid line) with METEOSAT Tbb (open circle), and f) 1 m level relative humidity. Tbb estimated from METEOSAT-IR channel is indicated by circles in e).

nal changes of Tbb by careful examination of local weather with local thresholds determined from surface skin temperature.

The wind direction at AWS changed to an anti-clockwise direction from northwest to south on March 4–8 and 15–17 (Fig. 5c), when the low level absolute humidity increased (Fig. 3c), indicating a changing low-level air mass. An abrupt increase of upward short-wave radiation was found on March 4 at the AWS site (Fig. 5b), indicating the occurrence of snow cover. In the two periods, synoptic charts showed a cyclonic disturbance traveling from the west along the southern periphery of TP, and the feature resembled a terrain-locked low-pressure system that causes winter precipitation over the Himalayas, as analyzed by Lang and Barros (2004). The two observed precipitation events with low-level southerly winds were then

also attributed to the synoptic-scale disturbances moving eastward along the southern TP. It is speculated that the reduction of daytime downward shortwave radiation (figure omitted) by the synoptic-scale disturbance decreased the sensible heating from the patchy bare-soil surface and suppressed the development of PBL with the weakening of daytime surface winds. This feedback can provide favorable conditions for long-lasting continuous snow cover and enhance the albedo effects.

6. Sensitivity study by numerical simulation

According to Ueno et al. (2007), the local albedo decreased with a decrease of the patchy snow cover portion, and, at the same time, the sensible heat increased with an increase of the net radiation in the spring. Those are plausible conditions for the development of the BPL with an increase of the

downward momentum flux that could increase surface winds and accelerate the re-distribution processes of dry snow cover. To assess the albedo effect for daytime PBL development, a numerical simulation was performed. The Weather Research and Forecast (WRF) model version 3.0.1.1 (Skamarock et al. 2008) was used following the instructions in Ueno et al. (2011). Four cases of three successive days were chosen, including a spin-up day without snow fall events, such as Case A: March 1–3, Case B: 5–7, Case C: 10–12, and Case D: 17–19. The upper jet stream is weak for Cases A and B and strong for Cases C and D. Three sectors were set on the Lambert projection with horizontal grid spacing of 60 km, 20 km, and 4 km. The third sector was set to cover 85°E–95°E, 30°N–35°N, including the Naqu area but excluding the southern complex mountain ranges over the TP. The Mellor-Yamada-Janic scheme (after Mellor and Yamada 1982) was adopted for the calculation of the plateau boundary layer, and land surface components were calculated by the Noah land surface scheme (Chen et al. 1996; Chen and Dudhia 2001; Ek et al. 2003). JRA25 reanalysis data were used for the atmosphere boundary condition in the first sector, and the land surface condition was interpolated to 1.25 grid spacing from the JRA25 data using the Noah land surface scheme. The Noah scheme decreases the albedo below a certain threshold of snow depth to represent the patch snow cover condition (Ek et al. 2003) that matches the situation examined in this study. As we have no detailed observation data to verify the plateau-scale circulation patterns produced by the model, only the boundary condition of snow cover and one-dimensional structure of the troposphere were examined over Naqu City.

As a control run, the initial albedo distribution was simulated below 0.3, indicating a snow-free condition, except in the mountain ranges (Fig. 6a) and the northwestern portion over the TP that agrees with the feature observed by the MODIS images (figure was omitted). According to the simulation, the snow depth was below 10 cm, and the albedo ranged around 0.25–0.3 at the south of Naqu City, which agreed with the observed surface conditions. The vertical structure of horizontal wind vectors with θ in Cases B and C is shown in Fig. 5b. The diurnal developments of the neutral θ layer (PBL) below 7 km were quite similar to the observations, as shown with the black boxes in Fig. 3a. In the simulation, clouds also occurred at 1,000–

2,000 m above ground level, where the cloud top level was slightly overestimated from the humid layer observed in a sonde profile. The simulations for Cases A and D also represented the PBL development with cloud generations as the observations. Next, as a sensitivity run, the albedo was kept to 0.7 in the third sector during the simulation periods without changing the surface hydrology. The daytime PBL was apparently suppressed for all the cases with a reduction of the surface wind speed (Fig. 6c). The daytime cloud development was also suppressed except in Case C. Namely, a numerical experiment confirmed that patchy snow cover conditions with lower albedo could induce daytime PBL development with daytime cloud occurrence and strengthening of surface wind speed. For the period of Case C (March 11–12), the sonde was used to observe an increase of relative humidity in the upper-level (Fig. 3b), and METEOSAT image showed cloud cover extension from south to northeast over the TP. The cloud development in Case C was then attributed not only to the land-surface heating but originally to the effects of the large-scale ascending motion by a synoptic scale disturbance. Simulated surface winds in the control run is stronger in the Cases of C and D than in those of A and B, and the reduction of the surface wind speed in the sensitivity runs is more evident for Cases A and B. To assume the occurrence of the plateau scale snow cover, third sector was extended to the areas above 4,000 m a.s.l. that covered almost all plains and mountains on the TP (see Fig. 6a), and the sensitivity run was conducted again for Case C (stronger STJ condition with synoptic cloud formation). Then, the potential temperature below 1,000 m above ground level clearly decreased with intensification of a stable layer, and the surface wind speed in the late afternoon was weaker. On the other side, the upper general flow was not affected, and cloud generations were also recognized, although their developments were more moderate (stratified type). Those experiments suggested that the size of the continuous snow cover on the plateau is another important factor affecting the near-surface stability and daytime development of PBL.

7. Summary

The vertical structure of the planetary boundary layer was examined on the basis of intensive sonde observations from late February to early March in 2008 at the central Tibetan Plateau area. Diurnal

Fig. 6. Numerical simulation for Cases B and C for a) the albedo distribution, b) potential temperature with horizontal wind vectors for control runs, and c) for sensitivity runs. A contour line in a) corresponds to 4,000 m a.s.l.

development of convective layer with cloud development was clearly observed under upper STJ that changed its location and intensity on an intra-seasonal time scale. Infrared images over the plateau in the cold season have sometimes been interpreted to be frozen land instead of clouds. How-

ever, many of the images could capture daytime shallow cloud development over the PBL, which leads to an underestimation of the actual ground-surface temperature. The cloud top height was limited under the jet stream due to strong wind shear, and strong daytime surface winds prevailed with

the development of PBL. Snowfall events were detected two times by passing synoptic scale disturbances when the STJ was weakened and southerly winds prevailed in the Naqu area. The precipitation amount was supposed to be small, and successive heavy snow-covered areas were not identified around Naqu City. Numerical simulations confirmed the daytime PBL and cloud development in the case of a low albedo (snow free or patchy snow cover) in the late winter.

Ice-albedo feedback has been used to explain the suppression of surface temperature and convection over high-elevation areas, such as in TP. However, the actual snow cover distribution was patchy due to re-distribution processes of snow cover with conditions of strong winds and less precipitation. Open bare-soil areas could produce large sensible heating under strong subtropical insolation in the spring, such as that estimated by Ueno et al. (2007), and strengthen the surface wind speed with the development of PBL under STJ. It is plausible that the strong winds accelerate the re-distribution processes of shallow snow cover. Then, patchy snow covers are maintained as a positive feedback mechanism. One possible mechanism to cut this feedback is the occurrence of heavy and continuous snow cover with a certain amount of precipitation. The origins of water vapor for diurnal development of low-level clouds, as observed in this study, is expected to be sublimation or melting of snow cover over the TP. However, to provide enough precipitation to make continuous snow cover, intrusion of rich water vapor is required from the outside of the TP. Slower speed or stagnant synoptic scale disturbances may satisfy this condition. STJ starts to weaken from March to April with prevailing of the synoptic scale trough in the south of the TP, and further analysis is expected to reveal the function of stagnant cyclones and heavy snow covers that could modulate land-atmosphere interactions over patchy snow cover areas.

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