〈Original Papers〉 Modulation of diurnal precipitation occurrences observed in the Tibetan Plateau during monsoon season of 1998

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Modulation of diurnal precipitation occurrences observed in the Tibetan Plateau during monsoon season of 1998

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Abstract

Relations between the diurnal change of the radar echo areas and surface condition were examined at the central Tibetan Plateau during the monsoon season in 1998. During the late June, under the synoptic conditions of prevailing surface heat low with Tibetan anticyclone, a weekly time scale modulation was clearly observed in the diurnal changes of the convective activity, such as the delay of the daytime precipitation clouds toward evening, especially over the southern mountainous areas. The feature was confirmed by the diurnal weather changes indicated by multiple surface meteorological elements. Surface energy flux and hydro-meteorological measurements showed that the modulation was associated with weekly scale reducing of morning sensible heating and suppression of the planetary boundary layer development during midday. The increase of soil-surface moisture in the morning was also confirmed by the surface albedo measurements. Therefore, we hypothesize the cause of the delay of daytime precipitation by land-surface moistening due to precipitation in the previous days.

Key words: diurnal variation, land-atmosphere interaction, Tibetan plateau, soil moisture, monsoon

1. Introduction

Over the Tibetan Plateau (TP), evident diurnal variations in convective activities are observed by the satellite images (e.g., Murakami and Matsumoto, 1994; Ueno *et al*., 1995), which had been attracted many scientists revealing the effects to monsoon activities through the latent heat release (Yanai and Li, 1994; Yanai and Tomita, 1998). Associated precipitation is an important factor causing atmosphere and land-surface interactions via an increase in soil moisture and changes of vegetation evapotranspiration. Precipitation amounts directly contribute to the accumulation of glaciers that supply the water to the surrounding areas in the dry season. To reveal the water cycle processes in the TP, intensive hydro-meteorological observations were made from April to September of 1998 through the GAME (GEWEX Asian Monsoon Experiment) Tibet project (Koike *et al*., 1999). Continuous Doppler Radar observation with intensive gauge-based precipitation measurements, conducted in collaboration with the National Space Development Agency of Japan (NASDA), was a highlight of the GAME-Tibet project. The project revealed unique precipitation processes, such as the qualitative differences between convective and stratiform clouds with precipitation amount depending on the time and region (Shimizu *et al*., 2001; Ueno *et al*., 2001; Uyeda *et al*., 2001), and mountain ranges on and periphery of the plateau cause different structure in the cloud system with strong diurnal cycles (Kurosaki and Kimura, 2002; Fujinami and Yasunari, 2004). Seasonal progress of surface turbulence, surface energy partitioning, and soil heat/moisture balance had quantitatively been monitored by multiple hydro-meteorological automated stations (Tanaka *et al*., 2001; Hirose *et al*., 2002; Hong *et al*., 2004). The GAME-Tibet observation data were comprehensively merged by Tamagawa *et al*. (2000), and widely opened to the international communities via internet or compact disc. Recently, comprehensive observation network are extended around the plateau to monitor atmosphere-land interaction including soil moisture condition, and decadal-scale climate changes have been revealed by the linkage of multiple hydro meteorological parameter trends (Su *et al*., 2011; Yang *et al*., 2014; Ma *et al*., 2017).

Functions of land-atmosphere interactions in the precipitation system had been further examined based on the synthesized results of the GAME-Tibet project. For instance, Yang *et al*. (2004) simulated the propagation of convective cells from the mountainous area into the basin during the end of pre-monsoon season due to interactive processes between mountain-valley circulations and rain evaporation cooling. Yamada and Uyeda (2006) analyzed the transition of rainfall characteristics related to the moistening of land-surface during the 1998 monsoon season, and found that the clear increase in amount of gauge-measured precipitation in cases of synoptic condition with a surface heat low and a Tibetan upper high. They attributed cause of increase as the moistening of sub-cloud layers due to the growing of vegetation as

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maturing of monsoon, which reduced the evaporation of precipitation within the sub-cloud layers. Yamada (2007) confirmed the change of lifting condensation levels with cloud structure due to changes of surface wetness in the idealized condition by using cloud resolving storm simulator. Based on the in-situ observation during 2004 monsoon season, Kurita and Yoshimura (2006) pointed out the possibility of large contribution of plant transpiration by comparing the direct sampled isotope value at the vegetated ground and estimated value by Craig-Gordon model. Those studies demonstrated that the interaction between the Planetary Boundary Layer (PBL) and land-surface conditions strongly relates to the structure of precipitation cells, especially during the transitional period from the pre-monsoon (dry) to core-monsoon (wet) seasons, in the central TP.

According to the careful re-examination of the GAME-Tibet radar data, we found weekly scale changes in the diurnal variability of precipitation echo areas in the beginning of monsoon season. In this paper, we clarified linkages between the radar measurements and the multiple surface meteorological elements caused by diurnal convective activities, and possible functions of soil moisture in changing the diurnal variability of precipitation activity were discussed in relation to the results of previous studies.

2. Data

The NASDA and GAME-Tibet scientists conducted continuous Doppler Radar observations from the end of April to the beginning of September 1998 over the Naqu basin (around 91.5-92.5ºE; 31.0-32.5ºN, Fig. 1a). Intensity of the radar reflectivity was observed by a conical scan at a 0.7 elevation angle in 10-minuets interval. The observation covered a 128-km radius area with its center at 91.9ºE; 31.4ºN (Fig. 1b, a dash circle). The coverage area is classified into two parts, one is the central and northwestern flat areas of the basin below 5000 m a.s.l. covered with sparse short grasses or bare soil on the seasonal permafrost comprising the central wet plain of the TP, and the other is the mountainous areas in the south-east above 5000 m a.s.l. The intensity mode data have a tendency to miss the low and weak precipitation echoes as going far from the center, and also missed the data at the mountain shadows in the far south. Data on the polar coordinates were converted to distribute in Longitude-Latitude coordinates with 1 km interval, with correction of attenuation by the precipitation. We used the surface meteorological data and surface energy fluxes measured at the NAQU-FX site (91°53.97'E; 31°22.17'N, 4580 m a.s.l.) located about 10 km west of the radar site by Choi *et al.* (2004) and Hong *et al.* (2004). The station was located in a 10-km scale flat field, consisting of dry bare soil and patchy grasses with canopy height less than 0.1 m. Sensible and latent heat flux were evaluated by variance measurements at 2.9 m above surface, and soil heat flux was evaluated by the soil heat transducer with correction of storage term by soil temperature probe measurements. Radiosonde data from the AMDO station (Endo *et al.*, 1999) were also utilized in our analysis.

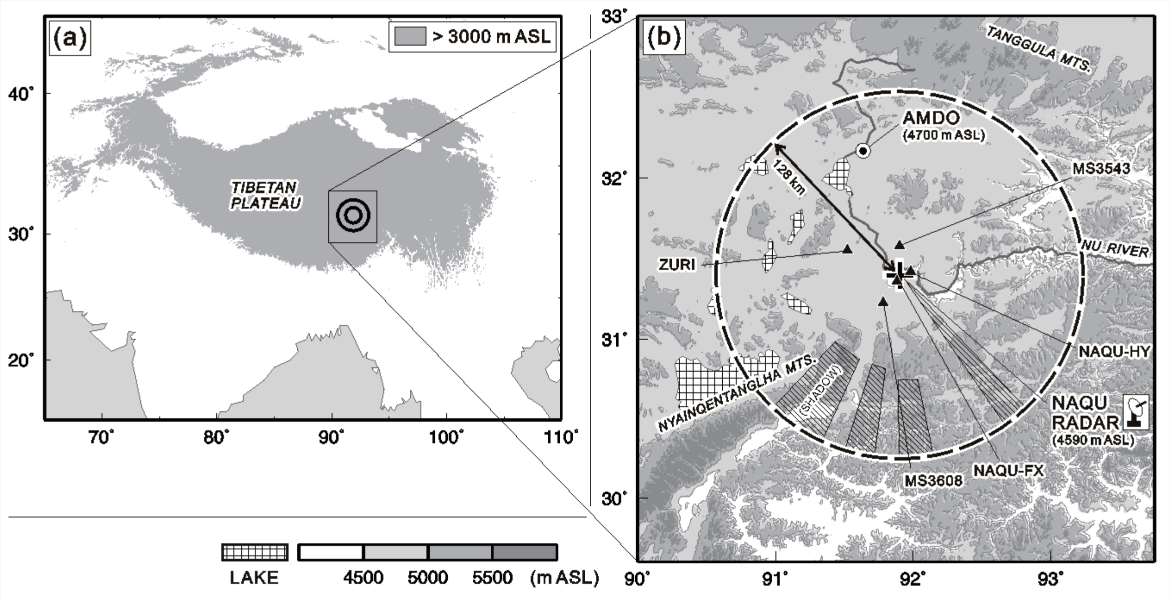

Fig. 1 Tibetan Plateau and Location of the Naqu basin (a), and coverage of the NASDA radar intensity mode data (dashed circle) with location of meteorological observation sites (b). Missing areas of radar data due to mountain shadows were hatched on the Fig. 1b.

3. Results

3.1. Modulation of diurnal variation in convective activity

Monsoon onset at Naqu basin in 1998 was around June 15 by means of rapid increase in 250 hPa geopotential height followed by a continuous precipitation period and starting the northward cloud cover extension from the south of the plateau area (Ueno *et al*., 2001). Radar echo frequencies with moderate (10-20 dBZ) and strong (more than 20 dBZ) intensity are counted every hour within a 128-km radius observation area (15448 km^2), and converted as area percentages. Normally, hourly data are the average of 6 scan data with 10-minuits interval. In cases of observation frequency less than 3 scans per an hour, the hourly data was treated as missing. Seasonal progress (June 1 to Sept. 16) of the diurnal changes in the area percentage of moderate and strong echo intensity is shown in Fig. 2. It is clear that the percentage increased in the daytime, and diminished at night. This tendency was more evident for a strong intensity case (Fig. 2b). Multiple precipitation gauges observed major intermittent precipitations at night (Ueno *et al*., 2001) when the echo top was mostly low (Uyeda *et al*., 2001), and the intensity mode observation with conical scans was difficult to observe targets locating far away from the radar site with lower echo top. We interpreted that nighttime precipitations were difficult to examine by the intensity mode data, and this study focused only on the daytime convective activities.

In Fig. 2, we paid attention on the Period A, June 11-30 as indicated by a box with dot-line. It is quite evident

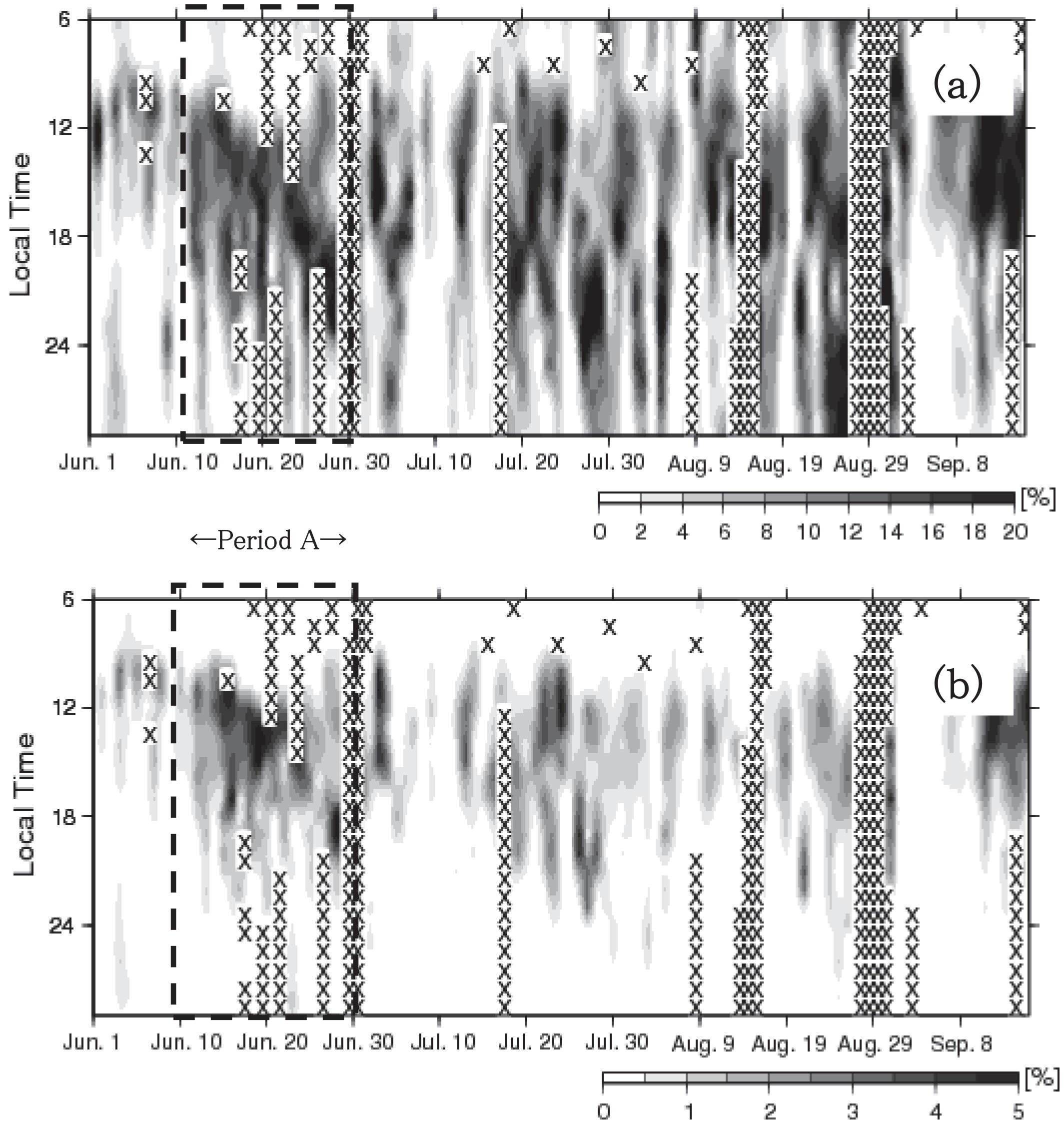

Fig. 2 Intra-seasonal variation of diurnal changes in radar echo coverage observed by NASDA Doppler Radar intensity mode, in cases of (a) 10-20 dBZ and (b) more than 20 dBZ. Cross areas indicate missing of observation.

that the daytime maximum of the echo area appeared at noon at the beginning, and shifted to the evening toward the end the period (Fig. 3). The feature is evident both for the areas with moderate and strong echo intensity. In the details, there seems to be two steps of modulation such a delay of occurrence of precipitation from 03 UTD to 05 UTC during June 14-26 and a delay of occurrence of minimum black body temperature (Tbb) delayed from 11 UTC to 16 UTC after June 24. Average distribution of daytime radar reflectivity showed large increase of dBZ above the southern mountain areas. Many of the past studies pointed out that convections tend to initiate over the mountains in the TP (e.g. Fujinami *et al*., 2005; Yang *et al*., 2004). Therefore, it is plausible that convective precipitation started at around noon over the southern mountainous areas in the Naqu basin at the beginning of monsoon onset, and the start time gradually delayed during successive two weeks. Unfortunately, morning radar echo data are missing on June 21 and 24 giving some uncertainty on the Fig. 2. GMS hourly infra-red (IR) data could also showed similar but ambiguous features, especially after June 13, on the same type of the figure (Fig. 4). The reason may be that the IR data in the tropics sometimes overestimates the convective activity by the anvil of cumulonimbus, especially in the edge of the image, which prevents to observe actual precipitation activities.

Next, diurnal changes of weather during the Period A were examined by surface meteorological elements to compare with the modulation signal observed on the radar echo data. AWS data at NAQU-FX station were utilized where intensive multiple surface meteorological and hydrological elements were measured and the sites were close to the southern mountainous areas in the Basin (Fig.1b). Figure 5 shows the day-time cross section of downward shortwave radiation, wind speed, and water vapor pressure. Diurnal changes of these three parameters were closely related each other as follows. In the morning, strong solar radiation and weak wind prevailed, indicating the fair and calm weather. In the afternoon, the radiation and humidity decreased with increase of wind speed. The decrease of solar radiation indicates development of clouds, and the increase of wind speed may indicate increase of turbulence at the ground surface associated with the cloud development. The afternoon decrease of humidity corresponded to the results of Kuwagata *et al*. (2001), which revealed the daytime reduction of water vapor pressure in the lower PBL in the valley area due to the thermally-induced circulation during early-monsoon or pre-monsoon periods. Thus, the series of diurnal change in surface measurements clearly indicates the daytime development of thermal convective clouds over the southern basin. Important thing is that

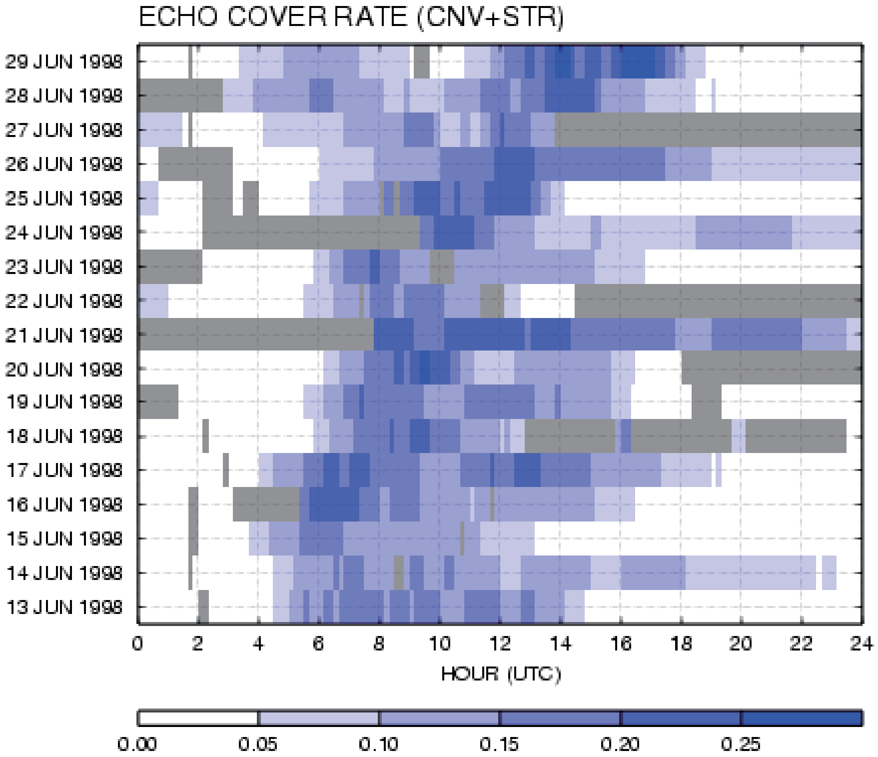

Fig. 3 The same for diurnal changes in radar echo coverage by blue color as Fig.2a except for the period A. Time line from bottom to top in the left axis.

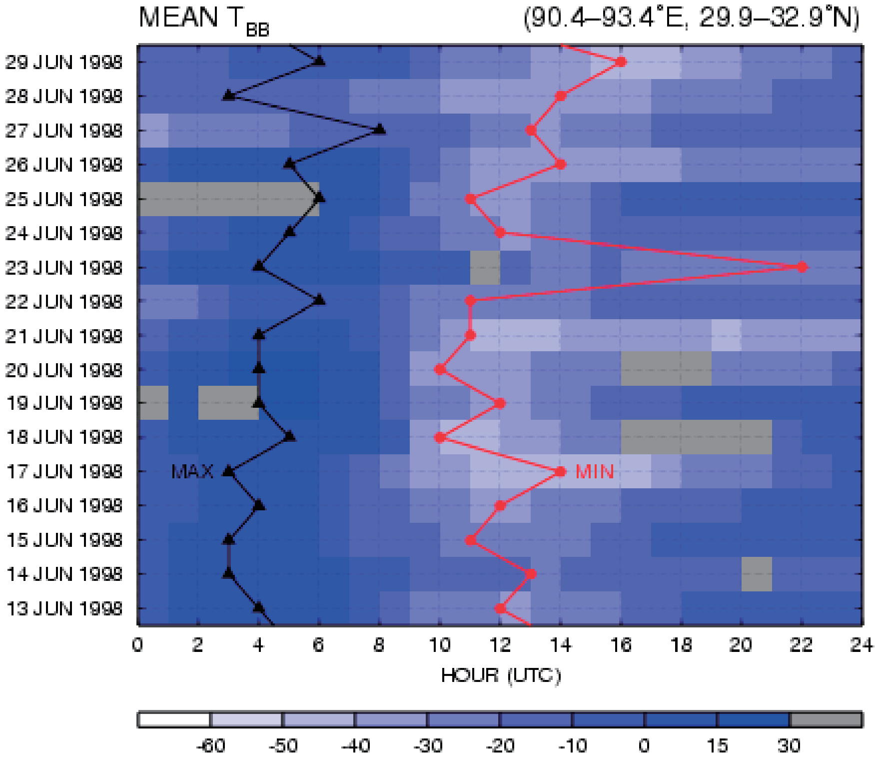

Fig. 4 The same as Fig. 3 except for averaged GMS-Tbb data over the radar observation area.

the modulation of a series of diurnal changes as observed in the radar echo data was also found in Fig. 5 (marked as dashed lines). At the monsoon onset, such as on June 15, cloudy weather prevailed after around 12:00PM, but it delayed to around 16:00AM on June 27. During 9:00AM to 14:00PM LTM on June 21 and 24, missing periods of the radar observation, radiation and precipitation data confirmed fair weather with no rain fall in the morning in the southern Naqu basin. We drew the same figure by using the surface observation data at AMDO site, located in the northern basin (Fig. 1b), but the shift of weather change was not obvious. Namely, the delay of daytime convective activities associated with cloudy weather with precipitations over the southern Naqu basin was confirmed by the independent measurements, such as radar observation and surface meteorological observation.

Next, PBL structure changes during the Period A were examined by the Radiosonde data at AMDO station. The station located 70 km north of the radar site, corresponded to the lee-side of southerly monsoon flow and plausible to capture the PBL condition over the basin ahead (Fig. 1b). Day-to-day changes in potential temperature and specific humidity profiles at 12:00 LTM are shown in the Fig. 6. At the beginning of the period A, neutral stratification of the potential temperature with a constant mixed moisture profile developed below the 7500 m a.s.l., which indicated the daytime development PBL as mentioned by Kuwagata *et al*. (2001). However, the thickness of the PBL decreased as time passed and its height dropped below 6500 m a.s.l. by the end of the Period A. This result also supported the delay of convective activities shown by the radar observation. Even though the location of AMDO is about 100 km far from the southern mountainous area, the result suggested that the delay or weakening of morning PBL development through the period was also dominated over the basin.

3.2. Surface conditions

Two factors can be considered on the causes of the modulation of daytime convections. One is the change of synoptic conditions during the periods which modified the potential convective instability in the lower troposphere day by day. Yamada and Uyeda (2006) classified the precipitation events around the Naqu basin into three types based on the synoptic conditions, such as Upper-high (UH) type, Trough (TR) type, and No-low (NL) type, evaluated by the variation of geopotential height at 500 and 200 hPa and horizontal advection of the relative vortices at 250 hPa. According to their results, UH type prevailed during the Period A accompanied with so called “Tibetan anticyclone” centered at the southern rim of the plateau with surface heat low appeared on the plateau. This synoptic condition suitably explains the evident diurnal convective activity for the Period A, but can not

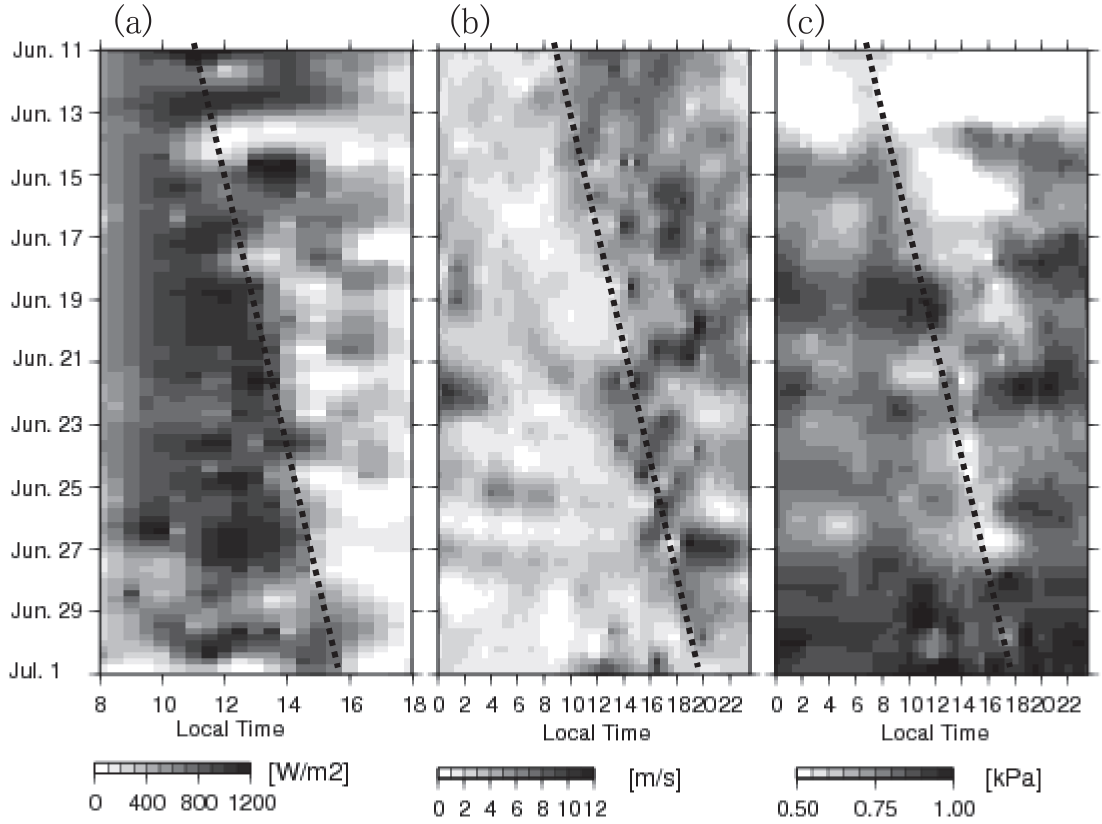

Fig.5 Changes of diurnal variations in (a) insolation at 1.5 m (Wm^{-2}), (b) wind speed at 3.5 m (ms^{-1}) and (c) water vapor pressure at 3.5 m (kPa), observed at NAQU-FX site by GAME/Tibet project, 11-29 June 1998. A few missing data were interpolated by measurements at MS3608. Modulation of the diurnal variation was marked by dashed lines.

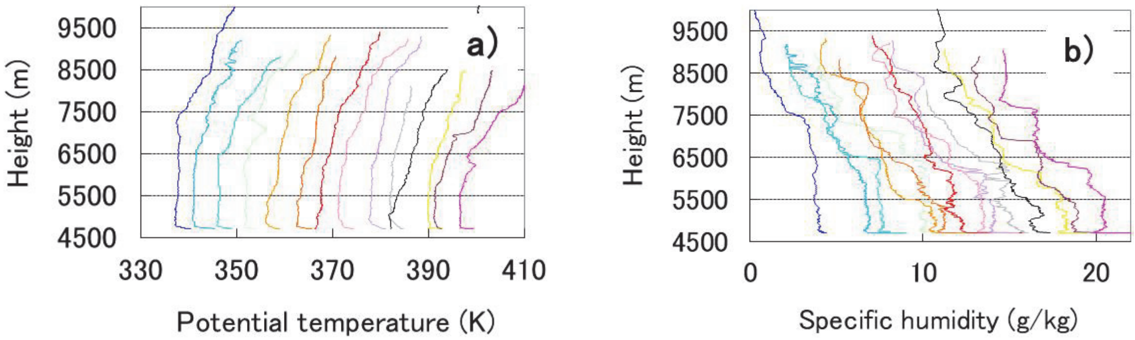

Fig. 6 a) Potential temperature, and b) specific humidity profiles during period A, observed at Amdo site. 14 profiles at 12 LTM from June 15 to June 28 are depicted from left to right. Unit is Kelvin for a) and g•kg^{-1} for b) at the leftmost profile, and another profiles were shifted with +5 K (+1 g•kg^{-1}) right side per a day.

explain the weekly scale change of the modulation. One possibility is the effect of spatial variability of the heat low location within the plateau area. According to Zhang *et al*. (1998), low-pressure vortex with variety of vertical structure was frequently analyzed. The vortex tends to appear along the 34°N with longitudinal distribution depending on the location of upper high maximum (see Fig. 8.1 and 8.19 of Zhang *et al*., 1998). But, the life time of the vortices is several days, and it is still difficult to explain the weekly scale modulation of convective activity.

Another factor is the change of landscape to modify the initiate or development condition for convective clouds. Pielke (2001) reviewed the studies about the influence of vegetation and soils on the cumulus convective rain fall, where increase of soil moisture or vegetation coverage is explained to cause two different functions with nonlinear interactions. One is the function of moistening PBL to cause higher CAPE which is favorable for cumulous

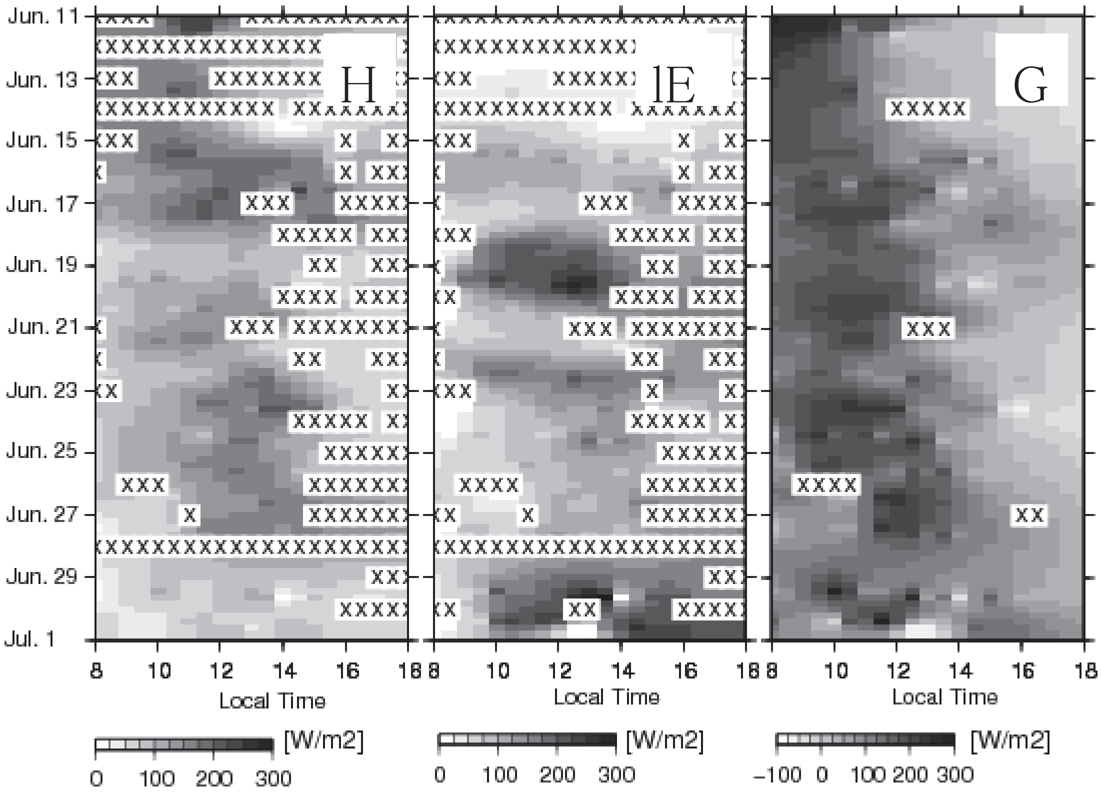

Fig. 7 Same as Fig. 3, except for daytime sensible (H), latent (lE), and soil (G) heat fluxes (Wm^{-2}) observed at NAQU-FX site. Cross mark indicates missing of the data.

clouds development. The other is the reducing of sensible heating which suppresses to initiate the cumulus clouds. For instance, Rabin *et al*. (1990) found by the satellite images that cumulus clouds forms earliest over the regions characterized by high sensible heat flux, and are suppressed over regions characterized by high latent heat flux, during relatively dry atmospheric condition with weak forcing from the atmosphere. Clark and Arritt (1995) found by the numerical simulations that large value of initial soil moisture delay the onset of precipitation but increase the precipitation amount.

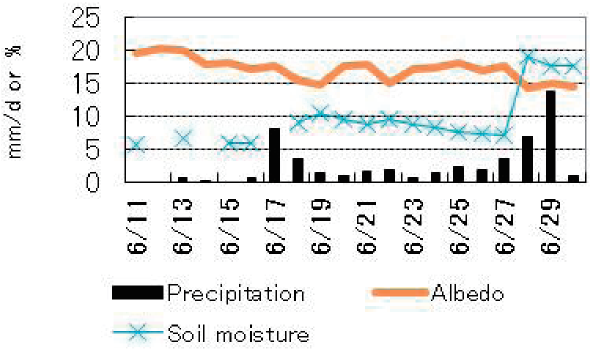

Fig. 8 Morning (10-12 LTM) average albedo (%), soil moisture at 0.05 m (%), and daily precipitation (mm/d) at NAQU-FX station.

Changes of land-surface condition during the Period A are examined by means of diurnal variations in surface sensible/latent heat fluxes and soil heat flux based on the observed data by Choi *et al*. (2004) at Naqu-FX site (Fig. 7). Day-to-day changes of daily precipitation averaged at four precipitation gauge stations (ZURI, MS3543, NAQU-hy, and MS3608), and morning averaged (10:00-12:00AM) albedo and soil moisture at 0.05 m depth (detecting the moisture around 0-0.15 m depth) observed at Naqu-FX site are also shown in Fig. 8. Some parts of flux data were missing due to weather conditions un-favorable for use of the flux variance technique. From the Fig. 7a, it is found that sensible heating in the morning diminished toward the end of the Period A, and corresponding decrease in land surface temperature was also observed (figure not shown). Distribution of the soil heat flux (Fig. 7c) was clearly modified by the change of radiation due to cloud development. Diurnal variation of the latent heating was difficult to examine due to large number of missing data (Fig. 7b), but the day-to-day variations, such as increasing on June 18 and 21, were more apparent and coincided with water vapor pressure variability (Fig. 5c). After the monsoon onset, sporadic weak precipitation began, mostly in the evening and into the night, and albedo showed gradual decrease from 20% to 15% during the period (Fig. 8). After the relative increase of precipitation on June 17-18, albedo showed relative minimum with relative maximum of soil moisture on June 19 when the increase of latent heat was observed in Fig. 7b. Another relative decrease in albedo on June 22 also corresponds to increase of latent heat, but associated evident increase was not found in the precipitation and surface soil moisture data. Besides, soil moisture was largely increased after June 27 when the precipitation and latent heat apparently increased. Those signal indicate that starting of the precipitation caused increase the surface moisture and reduction (increase) of sensible (latent) heat in the morning. But there were still some discrepancies between the gauge precipitation data or 5 cm depth soil moisture data and surface flux. We supposed the reasons that the precipitation sporadically occurred and provided small amount which could only moisten the skin soil surface. The feature could be detected by lowering of albedo but difficult to detect by the soil moisture sensor embedded at the sub-surface (5 cm) of the soil layer.

4. Summary and discussion

During the period from middle to the end of June in 1998, the transition season from pre-monsoon to mature-monsoon, the Tibetan upper high with a surface heat low prevailed over the TP without severe synoptic trough or disturbances. Under such synoptic condition, characteristics of the diurnal change of convective precipitation area were examined in relation to the land-surface heating conditions. Through the period, a delay of daytime initial convections was clearly observed in the southern radar echo area, and confirmed by surface meteorological measurements located in the southern basin area. Associated decrease of the surface sensible heat and increase of soil moisture at the ground surface in the morning was observed by the flux and albedo measurements at NAQU-FX site and the suppression of developing PBL in the noon was found in the sonde profiles over the northern basin. Land-cover of the NAQU-FX site is classified as dry soil similar to mountain areas, and is quite different from the wetland with full covered vegetations which also frequently distributed in the plain basin areas. Beside, southern mountain slopes with high elevations could catch more precipitation than in the lower basin areas after the monsoon onset. According to the consistency of observational results, we attributed the cause of modulation of the daytime variation of convective activity in the southern mountainous areas by the mesoscale suppression of sensible heating in the morning due to increase of soil moisture at the ground surface associated with precipitation in the previous days. Time scale of the modulation by soil moisture increase was similar to the results of Clark and Arritt (1995). The 1998 pre-monsoon season was drier than in other years, and the Tibetan anticyclone prevailed for a while after the onset of the rainy season. Both those synoptic conditions were favorable for the enhancement of such land-surface reactions. This study focused only on a period in June, but if the appearance of relatively strong radar echo in the Fig. 2 is carefully examined, a similar modulating tendency could be found in the period of July 15 to July 27. Before this period, monsoon-break occurred for a week in which the ground surface can be recovered to drier condition, the same mechanism of June may be adapted. In the late July, westerly troughs prevailed several times, and the modulation signals were not obviously detectable in surface measurements.

Regarding to the relations of land-surface heterogeneity and precipitation, Emori (1998) ideally simulated a very interesting self-interaction mechanism between cumulus convection and soil moisture distribution by conducting two-dimensional numerical experiments. According to his results, the spotty nature of convective precipitation enhanced surface temperature contrasts through a change in evaporation, and could intensify afternoon precipitation. However, his study did not take into account about the effect of evening and nighttime precipitation to next day's surface moisture condition. Especially, the nighttime precipitation tends to have a rather widespread nature of distribution by stratiform clouds (e.g., Shimizu *et al*., 2001) and may cause more impact to moisten the ground surface. This study proposed the modification mechanism of diurnal variation in the precipitation system trough the day-to-day change of soil moisture at the ground surface, especially over the mountains which play important function to initiate morning cloud development.

Up to now, there are few observations in the mountainous areas in the plateau except for the glacier studies even the mountains are supposed to trigger the convections. Especially, the weekly-scale interactions of soil moisture and precipitation systems over the complex topography over the southern TP would be challengeable issues to confirm the hypothesis proposed in this study, because the most evident convections during the monsoon season have occurred there.

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References

Choi, T.J., Hong, J.K., Kim, J., Lee, H.C., Asanuma, J., Ishikawa, H., Zhiqiu, G., Ma, Y., Wang, J., Koike, T., Yasunari, T., Ueno, K. and Tsukamoto, O. (2004): Turbulent exchange of heat, water vapor and momentum over a Tibetan prairie by eddy covariance and flux-variance measurements. *J. Geophys. Res.*, **109**, D21106. doi:10.1029/2004JD004767

Clark, C.A. and Arritt, R.W. (1995): Numerical simulations of the effect of soil moisture and vegetation cover on the development of deep convection. *J. Appl. Meteorol.*, **34**, 2029–2045.

Emori, S. (1998): The interaction of cumulus convection with soil moisture distribution: An idealized simulation. *J. Geophys. Res.*, **103**, 8873–8884.

Endo, N., Kumakura, T., Nakata, A., Fujinami, H., Yasunari, T., Yu, Z., Tao, Z., Hu, Z. and Ma, X. (1999): Characteristics of planetary boundary layer structure in central Tibet during summer season of 1998. *Proc. 1st International Workshop on GAME-Tibet*, Xi-an, China, 77–80.

Fujinami, H. and Yasunari, T. (2004): Submonthly variability of convection and circulation over and around the Tibetan Plateau during the boreal summer. *J. Meteor. Soc. Japan*, **82**, 1545–1564.

Fujinami, H., Nomura, S. and Yasunari, T. (2005): Characteristics of diurnal variations in convection and precipitation over the southern Tibetan Plateau during summer. *SOLA*, **1**, 49–52.

Hirose, N., Koike, T. and Ishidaira, H. (2002): Study on spatially averaged evaporation under soil moisture heterogeneity affected by permafrost micro-topography. *J. Meteor. Soc. Japan*, **80**, 191–203.

Hong, J.K., Choi, T.J., Ishikawa, H. and Kim, J. (2004): Turbulence structures in the near-neutral surface layer on the Tibetan Plateau. *Geophys. Res. Lett.*, **31**, L15016. doi:10.1029/2004GL 019935

Koike, T., Yasunari, T., Wang, J. and Yao, T. (1999): GAME-Tibet IOP summary report. *Proceedings of the 1st International Workshop on GAME-Tibet*, January 1999, Xi'an, China, 1–2.

Kurita, N. and Yoshimura, K. (2006): Direct observation of stable isotope in land-surface evapotranspiration on the Tibetan Plateau. *Proc. Int. Workshop on the Isotope Effects in Evaporation*. Pisa, Italy, National Research Council of Italy's Institute of Geosciences and Georesources, 116–118.

Kurosaki, Y. and Kimura, F. (2002): Relationship between topography and daytime cloud activity around Tibetan Plateau. *J. Meteor. Soc. Japan*, **80**, 1339–1355.

Kuwagata, T., Numaguchi, A. and Endo, N. (2001): Diurnal variation of water vapor over the central Tibetan Plateau during summer. *J. Meteor. Soc. Japan*, **79**, 401–418.

Kun, Y., Wu, H., Qin, J., Lin, C., Tang, W. and Chen, Y. (2014): Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. *Global and Planetary Change*, **112**, 71–91.

Ma, Y., Ma, W., Zhong, L., Hu, Z., Li, J., Zhu, Z., Han, C., Wang, B. and Liu, X. (2017): Monitoring and modeling the Tibetan Plateau's climate system and its impact on East Asia. *Sci. Rep.*, **7**, 44574. doi: 10.1038/srep44574

Murakami, T., and Matsumoto, J. (1994): Summer monsoon over the Asian continent and western North Pacific. *J. Meteor. Soc. Japan*, **72**, 719–745.

Pielke, R.A. (2001): Influence of the spatial distribution of vegetation and soils on the prediction of cumulus convective rainfall. *Rev. Geophysics*, **39**, 151–177.

Rabin, R.M., Stadler, S., Wetzel, P.J., Stensrud, D.J. and Gregory, M. (1990): Observed effects of landscape variability on convective clouds. *Bull. Am. Meteorol. Soc.*, **71**, 272–280.

Shimizu, S., Ueno, K., Fujii, H., Yamada, H., Shirooka, R. and Liu, L. (2001): Mesoscale characteristics and structures of stratiform precipitation on the Tibetan Plateau. *J. Meteor. Soc. Japan*, **79**, 435–461.

Su, Z., Wen, J., Dente, L., van der Velde, R., Wang, L., Ma, Y., Yang, K. and Hu, Z. (2011): The Tibetan Plateau observatory of plateau scale soil moisture and soil temperature (Tibet-Obs) for quantifying uncertainties in coarse resolution satellite and model products. *Hydrol. Earth Syst. Sci.*, **15**, 2303–2316. doi:10.5194/hess-15-2303-2011

Tamagawa, K., Koike, T. and Fujii, H. (2000): An introduction to GAME-Tibet Data Information System (DIS), *Proc. of the 2nd Session of International Workshop on TIPEX-GAME/Tibet, Kunming*, China, pp.172–173.

Tanaka, K., Ishikawa, H., Hayashi, T., Tamagawa, I. and Ma, Y. (2001): Surface energy budget at Amdo on the Tibetan Plateau using GAME/Tibet IOP98 data. *J. Meteor. Soc. Japan*, **79**, 505–517.

Ueno, K., Ohno, T. and Yasunari, T. (1995): Convective activities observed by GMS-IR imagery over the Tibetan Plateau. *Report of Special Research Project on Global Change*. The University of Tsukuba, **3**, 173–181.

Ueno, K., Fujii, H., Yamada, H. and Liu, L. (2001): Weak and frequent monsoon precipitation over the Tibetan Plateau. *J. Meteor. Soc. Japan*, **79**, 419–434.

Uyeda, H., Yamada, H., Horikomi, J., Shirooka, R., Shimizu, S. and Liu, L. (2001): Characteristics of convective clouds observed by a Doppler Radar at Naqu on Tibetan Plateau during the GAME-Tibet IOP. *J. Meteor. Soc. Japan*, **79**, 463–474.

Yamada, H. and Uyeda, H. (2006): Transition of the rainfall characteristics related to the moistening of the land surface over the central Tibetan Plateau during the summer of 1998. *Mont. Wea. Rev*., **134**, 3230–3247.

Yamada, H. (2007): Numerical simulations of the role of land-surface conditions in the evolution and structure of summertime thunderstorms over a flat highland. *Mont. Wea. Rev*., **136**, 173–188.

Yanai, M. and Li, C. (1994): Mechanism of heating and the boundary layer over the Tibetan Plateau. *Mont. Wea. Rev.*, **122**, 305–323.

Yanai, M. and Tomita, T. (1998): Seasonal and interannual variability of atmospheric heat sources and moisture sinks as determined from NCEP-NCAR reanalysis. *J. Climate*, **11**, 463–482.

Yang, K., Koike, T., Fujii, H., Tamura, T., Xu, X. and Bian, L. (2004): The daytime evolution of the atmospheric boundary layer and convection over the Tibetan Plateau: observations and simulations. *J. Meteor. Soc. Japan*, **82**, 1777–1792.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W. and Chen, Y. (2014): Recent climate changes over the Tibetan Plateau and their impacts of energy and water cycle: A review. *Global and Planetary Change*, **112**, 79–91.

Zhang, J., Zhu, B., Zhu, F., Weng, D., Sun, G., Lu, J., Peng Y. and Wang Y. (1998): Advance in the Qinghai-Xizang plateau meteorology, The Qinghai-Xizang Plateau Meteorological Experiment (1979) and Research. Science Press, Beijing, 268pp (in Chinese).

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