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Effect of a cold, dry air incursion on atmospheric boundary layer processes over a high-altitude lake in the Tibetan Plateau

Zhaoguo Li [a,*], Shihua Lyu [b,c], Lijuan Wen [a], Lin Zhao [a], Yinhuan Ao [a], Shaoying Wang [a]

[a] Key Laboratory of Land Surface Process and Climate Change in Cold and Arid Regions, Northwest Institute of Eco-Environment and Resources, Chinese Academy of Sciences, Lanzhou 730000, China
[b] Plateau Atmosphere and Environment Key Laboratory of Sichuan Province, School of Atmospheric Sciences, Chengdu University of Information Technology, Chengdu 610225, China
[c] Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters, Nanjing University of Information Science & Technology, Nanjing 210044, China

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A B S T R A C T

High-altitude lakes are frequently exposed to extreme meteorological conditions, but the surface and atmospheric boundary layer (ABL) processes have received little attention under specific weather conditions. This study used the multi-source field data, re-analysis and remote sensing data to investigate the varying patterns and driving forces of the convective boundary layer (CBL) height over Ngoring Lake in the Tibetan Plateau (TP) before and after the cold air incursion. Daily cumulative surface heat flux and buoyancy flux over the land were markedly larger than those over the lake on a clear summer day, but an opposite pattern was observed accompanied by the cold air incursion. CBLs determined by the potential temperature thinned (depth < 100 m) over the lake in the daytime and thickened (400–600 m) at night on a clear day. Along with the arrival of the cold air, CBL rapidly thickened to 2280 m over the lake, exceeded than the maximum value at adjacent Madoi station. Cold air dramatically cooled the middle-upper atmosphere but the temperature of the lower atmosphere cooled down slowly, partly due to a sharp increase of sensible heat flux over the lake, both of which linked up to weaken the potential temperature gradient. Moreover, increasing wind speed and vertical wind shear further facilitated the buoyancy flux to exert higher heat convection efficiency. All of these factors acted together to cause the rapid growth of CBL over the lake. This investigation provided a more in-depth knowledge of boundary layer dynamics in the lake-rich region of the TP.

1. Introduction

In recent years, numerous efforts, ranging from the field observation (Barlow et al., 2011; Han et al., 2010; Laiti et al., 2013) to the numerical modeling (Brunsell et al., 2011; Gerken et al., 2013; Lü et al., 2004; Reen et al., 2014), have been made to explore the atmospheric boundary layer (ABL) processes over heterogeneous surfaces (e.g. lake, oasis and urban). A radiosonde study suggested that the convective boundary layer (CBL) can grow up to 1750 m in the Nam Co Lake basin (Lü et al., 2008). However, it is difficult to inspect in detail the ABL characteristics near the water surface, because radiosondes were not launched over the lake surface. Observations at Erhai Lake showed that the lake's influence on the local atmosphere was the most significant below 500 m (Xu et al., 2010). The ABL integrates the information of surface fluxes and conditions at spatio-temporal (diurnal) scales. Numerous studies have demonstrated that the boundary layer structure is influenced by the land surface processes (Dolman et al., 1997; Peters-Lidard and Davis, 2000; Santanello et al., 2007; Steeneveld et al., 2005; Stull, 1988). Thereinto, the sensible heat flux (H) is the principal thermodynamic factor affecting the development of the boundary layer (Santanello et al., 2007; Trier et al., 2004; Zhang et al., 2011). In return, the variation of ABL can also be transmitted to the surface fluxes. Different distribution patterns of temperature and humidity in the ABL can lead to different convection developments, which alter the surface energy balance and the basin's water cycle (Gerken et al., 2013).

A recent study of Pietersen et al. (2015) showed that both mesoscale and synoptic scales circulations can exert their influence on the boundary layer dynamics. Mesoscale circulation such as the sea or lake breeze usually leads to an internal boundary layer on the edge area of the sea or lake and aggravate the complexity of the ABL processes (Sills et al., 2011; Talbot et al., 2007). Specific weather conditions, such as the dry, cold air intrusion with strong wind, can significantly promote the sensible and latent heat fluxes via enhanced thermal and mechanical turbulent mixing (Liu et al., 2009). The increased vertical fluxes would lead to stronger atmospheric convection and lake-effect precipitation (Dreher et al., 2004). In addition to the thermodynamics factors, the dynamic factors such as strong wind shear, can weaken the inversion strength at the top of the CBL by increasing the diffusion efficiency and entrainment, and then enhance the convection efficiency of the buoyancy

* Corresponding author.
E-mail address: zgli@lzb.ac.cn (Z. Li).

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flux (Conzemius and Fedorovich, 2006). The dynamics of the ABL development have been widely explored (Pietersen et al., 2015), and the influence of dry, cold air on the lake surface energy exchange (Liu et al., 2009; Zhang and Liu, 2013), or atmospheric convection and precipitation in the late autumn and early winter (Agee and Gilbert, 1989) were also extensively studied. Zurn-Birkhimer et al. (2005) investigated the convective structures in a cold air outbreak over Lake Michigan during Lake-ICE, and found that the surface heat flux and wind shear show the relationship of interplay for establishing convection patterns using the large-eddy simulation. Throughout this process, the maximum mixed-layer depth did not occur under conditions of the strongest surface heating. However, the response of ABL processes to specific weather events and the cause were still rarely addressed over the high-altitude lake, due to the difficulty of observing.

In general, high-altitude lakes are frequently exposed to extreme meteorological conditions and more sensitive to variations in meteorological forcing (Rueda et al., 2007). The Tibetan Plateau (TP), with an average elevation of 4000 m above sea level, contains numerous lakes, encompassing a total area of approximately 45, 000 km^2 (Xu et al., 2009). The environmental specificity poses unpredictable challenges in the boundary layer study in the TP (Lee et al., 2015), where the air density is just 50–60% of that at sea level, which can create a higher atmospheric convection efficiency under the same surface thermal conditions (Zhang, 2007). Moreover, the solar radiation is intense but the air temperature is low on the plateau. This unique geography and climate environment causes a persistent unstable boundary layer over the lakes and enhances the surface heat flux (sensible and latent heat flux) (Li et al., 2015; Rueda et al., 2007), which favor the formation of a deep CBL. Therefore, the effects caused by the cold air event in the TP may be different from that in other regions.

In this study, the field observation data collected from the Ngoring Lake basin in summer 2012, re-analysis data and remote sensing data, were used to investigate the varying patterns of the CBL and its influencing factors in a high-altitude lake before and after the cold, dry air incursion. The scientific objective of this study is to investigate the cause of rapid growth of CBL over a high-altitude lake after the cold air arrival. The hypothesis is that the deep CBL mainly derived from an increased lake surface heat flux and a decreased atmospheric temperature gradient rather than the residual layer over the surrounding land. The paper is structured as follows. Section 2 describes the study area, field experiments and data collection. Section 3 details the synoptic background, radiosonde trajectories, CBL variations in height and influencing factors. The effect of local circulation on observed boundary layer structure was discussed in Section 4. Finally, Section 5, presents the conclusions. The study of boundary layer process in the lake-rich region is a challenging task as this region can be affected by different scale circulations. Further in-depth investigation in this study will bring to light the characteristics and driving forces of boundary layer evolution over high-altitude lakes under specific weather conditions.

2. Data sources and methodology

2.1. Study area and field experiments

A field experiment was conducted on the western shore of Ngoring Lake from July 23 to August 1, 2012 (Fig. 1). Ngoring Lake is located in the source area of the Yellow River on the eastern TP. It has a surface area of 610 km^2 and a mean depth of 17 m. The mean altitude of the lake surface is 4274 m above sea level. Gyaring Lake (526 km^2) is situated to the west of Ngoring Lake (Fig. 1). Ngoring Lake and Gyaring Lake, are the highest, large freshwater lakes in China. They are surrounded by low hills with alpine meadows. Located 30 km to the east of Ngoring Lake is a long-term meteorological observatory - Madoi station (MD) (34°55′03″N, 98°12′57″E, 4279 m AMSL). Based on meteorological data acquired from the Madoi station (1953–2012), the air temperature varies from 7.7 °C in July to −16.2 °C in January, averaging −3.7 °C, and the average annual precipitation is 321.4 mm. The Ngoring Lake basin is characterized by a cold and semi-arid continental climate.

The turbulent fluxes, radiation components and standard atmospheric variables were measured over the lake and grassland. The observation platform of Lake Station (LS) stood in the northwestern Ngoring Lake (97°38′59″E, 35°01′28″N), located 200 m to the northwest lakeshore and 50 m to a small southwest island. Water depth within 200 m around the platform was about 3–5 m. Southeast of the platform faced the center of the lake. Eddy covariance instruments were mounted at a height of 3.0 m, and the sample frequency was 10 Hz. Radiation components were measured 1.5 m above the lake surface. More detailed instrument set-up and footprint analysis for LS were described by Li et al. (2015). Grassland Station (GS) (97°33′16″E, 34°54′51″N), standing on a flat underlying surface, was located 1.5 km west of the lakeshore and 15 km from the LS station. Eddy covariance instruments were mounted at a height of 3.2 m, with a sample frequency of 10 Hz. Radiation components were also measured 1.5 m above the ground using a net radiometer (CNR-1, Kipp and Zonen). A gradient tower station (TS) (97°34′12″E, 34°54′24″N) was located 30 m west of the lakeshore, and the atmospheric variable measurement was taken at five levels (2, 4, 8, 10 and 18 m).

Radiosondes were launched every 3 h at 00, 03, 06, 09, 12, 15, 18 and 21 UTC, during the intensive observing period (July 28–August 1). An intensive observation was primarily committed to investigate the effect of the cold, dry air on the ABL over a high-altitude lake in summer. For ease of comparison with other studies, the local time is partly adopted in this paper, which is deemed to be UTC + 6.5. Note that the radiosonde observations over the lake were interrupted by rain from the evening of July 29 through the next day. Radiosondes were launched over the lake surface at a distance of 200–300 m to the lakeshore from 09:30 to 18:30 (local time). Considering the personnel security, they were launched at the lakeshore (adjacent to the TS) at other times (e.g. at night). Another group of radiosondes was synchronously launched over land at Madoi station, as a controlled trial during July 28–31 (No radiosonde observation after July 31). A portable IMET-3050 403 MHZ GPS upper-air sounding system was deployed, utilizing the IMet-1-AB radiosonde and the Totex-TA600 balloon. The accuracies of temperature and humidity measurements were given by the manufacturer as ±0.3 °C and ±5%. The observation data were processed using IC-PCR1500/2500 software. IMet-1-AB radiosonde has been widely used and validated (Haman et al., 2012; Leblanc et al., 2011). There was a very slight difference in performance between IMet-1 and other radiosonde such as Vaisala RS92 (Trapp et al., 2016).

2.2. Data description

Eddy-covariance data used in this study were processed using the EddyPro 5.0 software package, applying all corrections and post-processing steps for the turbulent flux measurements. The surface temperatures of the lake and grassland were calculated using Eq. (1) according to the Stefan–Boltzmann law.

$$Rl_{up} = (1-\varepsilon)Rl_{dw} + \varepsilon\sigma T_0^4 \quad (1)$$

where σ (=5.67 × 10^{-8} W m^{-2} K^{-4}) is the Stefan–Boltzmann constant, Rl_{dw} and Rl_{up} are the downward and upward long wave radiations, and T_0 is the surface temperature. Based on previous studies (Davies, 1972; Gerken et al., 2012; Yang et al., 2009), a surface emissivity ε of 0.97 was employed in Eq. (1).

In this study, NCEP Final Analysis data with 1° resolution (FNL from GFS, ds083.2) was used to analyze the synoptic background. The Tropical Rainfall Measuring Mission (TRMM) 3B42 precipitation products, the sensible heat flux and surface soil moisture (0–10 cm) values derived from the Global Land Data Assimilation System (GLDAS) were used to validate dry/wet surface status variations in the Ngoring Lake basin during the cold, dry air incursion. TRMM 3B42 removed the