Summertime Thermally-Induced Circulations over the Lake Nam Co Region of the Tibetan Plateau

YANG Xianyu[1] (杨显玉), LÜ Yaqiong[2,3] (吕雅琼), MA Yaoming[3] (马耀明), and WEN Jun[1*] (文 军)

1 *Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou* 730000, *China*

2 *School of Engineering, University of California, Merced, CA* 95344, *USA*

3 *Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing* 100085, *China*

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ABSTRACT

Performance of the fifth-generation Pennsylvania State University/National Center for Atmospheric Research Mesoscale Model (MM5) over the Lake Nam Co region of the Tibetan Plateau was evaluated based on the data from five surface observation sites in 2006. The interaction between two thermally-induced circulations (lake breezes and mountain-valley winds) was also investigated. The results show that MM5 could be used to simulate 2-m air temperature; however, MM5 needs improvement in wind field simulation. Two numerical simulations were conducted to study the effect of the lake on the local weather and wind system. The original land cover of the model was used in the control experiment, and the lake was replaced with grassland resembling the area surrounding the lake in the sensitive experiment. The results of the simulations indicate that the lake enhanced the north slope mountain-valley wind and the mountain changed the offshore flow direction at the north shore. During the day, a clear convergent zone and a strong upflow were observed over the north slope of the Nyainqêntanglha Range, which may cause frequent precipitation over the north slope. During the night, the entire area was controlled by a south flow.

Key words: Lake Nam Co, MM5, lake breeze, mountain-valley wind

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1. Introduction

Thermally-induced circulations, such as lake breezes (LBs) driven by the uneven heating of land and lake, are important in changing local weather and boundary layer meteorology. For instance, LBs can generate snow storms (Peace and Sykes, 1966; Braham and Dungey, 1995; Steenburgh et al., 2000), develop LB fronts (Daggupaty, 2001), affect the movement of trace particles (Harris and Kotamarthi, 2005), transport photochemical pollutants (Kitada et al., 1986; McKendry et al., 1998), and influence ozone concentrations (Hanna and Chang, 1995). Unlike the LB characteristics and effects in the Great Lakes and Lake Michigan (Lyons, 1972; Keen and Lyons, 1978), those in other regions, such as Lake Nam Co over the Tibetan Plateau (TP), have not been thoroughly investigated.

The TP is located in central Asia and is the highest and most extensive plateau in the world. Previous studies have indicated that the TP has profound thermal and dynamical impacts on atmospheric circulation in the Northern Hemisphere as well as on the global climate (Manabe and Broccoli, 1990; Yanai et al., 1992; Kutzbach et al., 1993; Zou et al., 2014). In addition, the TP is among the areas most sensitive to global climate change (Liu and Chen, 2000). Lake Nam Co is the largest lake in the central TP and is

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*Corresponding author: jwen@lzb.ac.cn.

located on the northern foot of the Nyainqêntanglha Range. The Lake Nam Co region includes a heterogeneous land cover typical in the TP (e.g., lake, meadow, marsh, glacier, permafrost, or crops). Uneven heating over these land cover patches can cause multiple thermally-induced circulations, particularly LBs and mountain-valley winds, over the Lake Nam Co region. The interactions between these circulations can considerably alter the local wind systems, resulting in various meteorological consequences (McGowan and Sturman, 1996; Bischoff-Gauβ et al., 2006). Understanding the interactions between the LBs and mountain-valley winds over Lake Nam Co is fundamentally important in the evaluation of the impact of the local wind system on weather and climate. Furthermore, analyzing the characteristics of local wind systems can provide valuable information about the relationship between Lake Nam Co and these local wind systems, which can be used to estimate the effect of evaporative water vapor from Lake Nam Co on the local atmospheric water vapor (Xu et al., 2011), boundary layer convection (Zhou et al., 2011), aerosol deposition (Cong et al., 2010; Wang et al., 2014), and pollen and trace gas transport (Cong et al., 2010; Lu et al., 2010; Xia et al., 2011).

This study aims to (1) evaluate the performance of the fifth-generation Pennsylvania State University/National Center for Atmospheric Research (PSU/NCAR) Mesoscale Model (MM5) in simulating 2-m air temperature and wind fields, and (2) investigate the interactions between two thermally-induced circulations, i.e., LBs and mountain-valley winds, at Lake Nam Co using the MM5. Section 2 presents the data collected from the field observation sites and the numerical experiment design. An evaluation of the performance of MM5, the simulation results, and related discussion are described in Section 3. The conclusion is given in Section 4.

2. Study area and numerical experiment design

2.1 Study area

Lake Nam Co is the largest lake (1920 km^2) in the central TP (Guan et al., 1984). It is located 4718 m above sea level and approximately 120 km northwest of Lhasa, Tibet (Fig. 1). The terrain of this area is complex. The Nyainqêntanglha Range lies southeast of the lake. With its peak at 7111 m and average height between 5300 and 6300 m, this mountain range physically obstructs northwesterlies or southeasterlies. The vegetation types surrounding Lake Nam Co include grass, wooden tundra, mixed shrubs and grass, bare sparse vegetation, and crop grass mosaic, as defined by the USGS (United States Geological Survey) 25 vegetation categories. Three synoptic systems control this area: the South Asian anticyclone, which controls the 100-hPa upper layer; the subtropical high-pressure system, which is usually divided into eastern and western parts by the TP after mid July; and the southeast warm and wet airflow, which appears during the monsoon season (Qiao and Zhang, 1994). With the monsoon precipitation, the Lake Nam Co region experiences a moist and cool climate during summer. The average annual precipitation in the Lake Nam Co region is 281.8 mm, and the average annual temperature is 0℃ (You et al., 2007). During our study period, the average sunrise time in the Lake Nam Co region was 0700 Beijing Time (BT), and the average sunset time was 2100 BT.

In 2005, five observation sites were established in the study area (Fig. 1) by the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. The Nam Co (NMC) site is a comprehensive site equipped with a variety of observation facilities, including an eddy covariance flux and boundary layer tower, atmosphere chemistry sensors, and hydrological stations. The meteorological data for 2-m air temperature and 10-m wind from the boundary layer tower were used in this study. The other four sites, Baoji (BJ), North Slope (NP), South Slope (SP), and Yakou (YK)) were installed with auto weather stations (BJ and NP used a CR1000 data logger, SP and YK used a CR10X data logger, from the Campbell Scientific), and the meteorological data collected from these sites are 2-m air temperature and 2.4-m wind observations.

2.2 Model and numerical experiment design

Numerical models play an important role in weather simulation and forecasting (Wang and Yu,

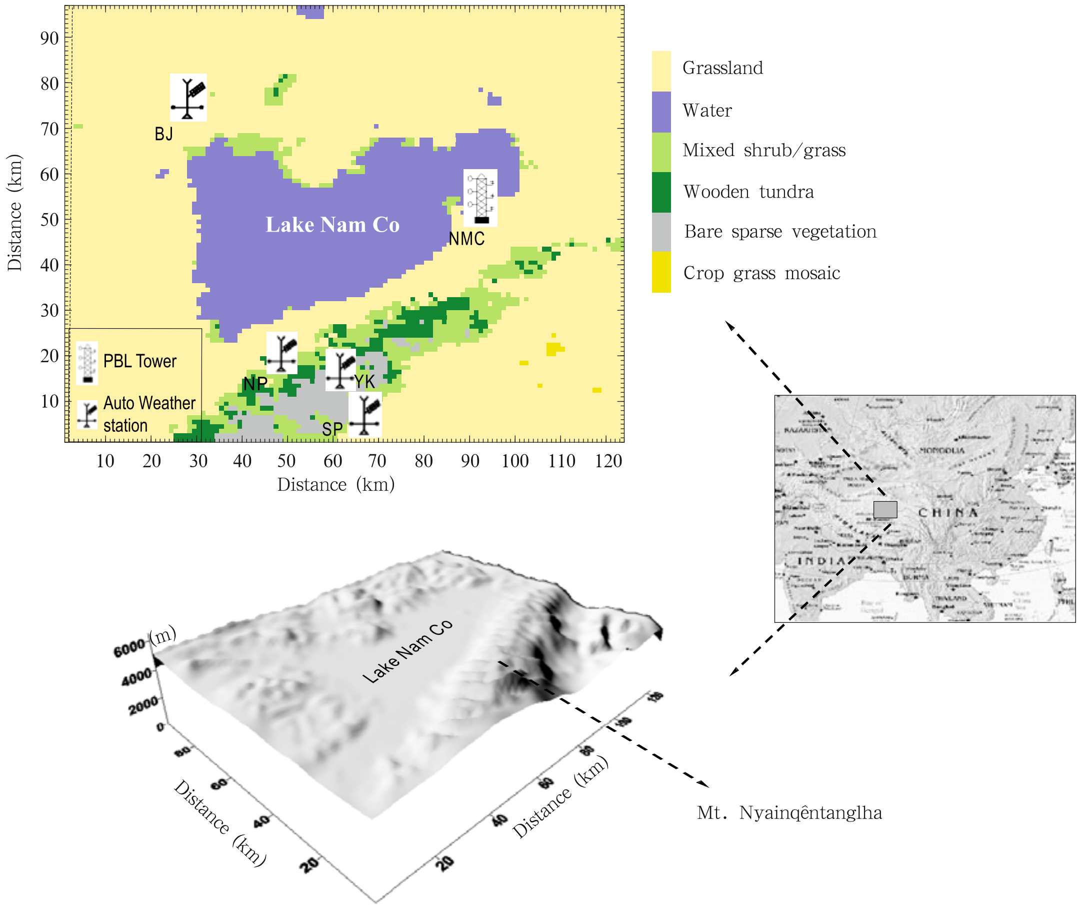

Fig. 1. Geographic map of the Lake Nam Co region showing land use, topography, and the locations of the five observation sites.

2013; Wu et al., 2014; Zhou et al., 2014). The MM5 is a regional mesoscale model developed and maintained by PSU and NCAR. The application of high-resolution mesoscale models is useful in operational weather forecast, particularly in areas where topography, land surface properties, and heterogeneity modulate synoptic weather to cause localized weather phenomena. In this study, MM5 was used to explore the influence of Lake Nam Co on the local wind system. In addition, the performance of the MM5 was evaluated in an area with complex terrain and vegetation types to provide a basis for improving the model. The MM5 is a nested-grid primitive-equation model that uses a terrain-following sigma vertical coordinate (Dudhia, 1993). Three nested domains (one-way nest) were defined for the purposes of this study. Their resolutions are 9, 3, and 1 km for the outer to inner domains, respectively, and the grid cells for these resolutions are 60×80, 73×91, and 97×124, respectively.

We used the 1°×1° NCEP/FNL analysis data as the boundary and initial conditions. Two 48-h simulations were carried out between 0800 BT 4 and 0800 BT 6 July 2006, under a fair synoptic background favorable for local thermally-induced circulations. The two simulations were the control experiment (LAKE), in which the original land surface was used, and the sensitive experiment (LAND), in which all the lake grid cells were replaced by grassland similar to the terrain that surrounds the lake. The comparison between the two experiments aimed to emphasize the lake effects on the local wind system. In the vertical, 23 unevenly spaced sigma levels were employed. The model includes various physical parameterizations for radiative transfer, cloud microphysics, cumulus convection, boundary layer turbulence, and land surface exchange processes. The physics schemes employed for this experiment were Grell cumulus parameterization (Grell et al., 1991), a medium-range forecast planetary boundary layer scheme (Hong and Pan, 1996), a simple ice microphysics scheme, a cloud radiation scheme (Dudhia, 1989), and a simple multilayer soil model. The parameterization scheme for the sensible heat flux (SH) used in the MM5 is the vertical diffusion scheme, which is integrated with the MRF (Medium Range Forecast) planetary boundary layer scheme. The model outputs, which are generated every hour, are obtained for the following analysis.

3. Results

3.1 Model evaluation

Figure 2 shows that the MM5 simulated the 2-m air temperature (T2) better than the wind speed at the five sites. The root-mean-square error (RMSE) of T2 at the five sites was between 1.25 and 2.2℃. The YK site showed the smallest T2 RMSE, whereas the BJ site showed the largest T2 RMSE. Although the model captured the diurnal cycle of T2, it underesti-

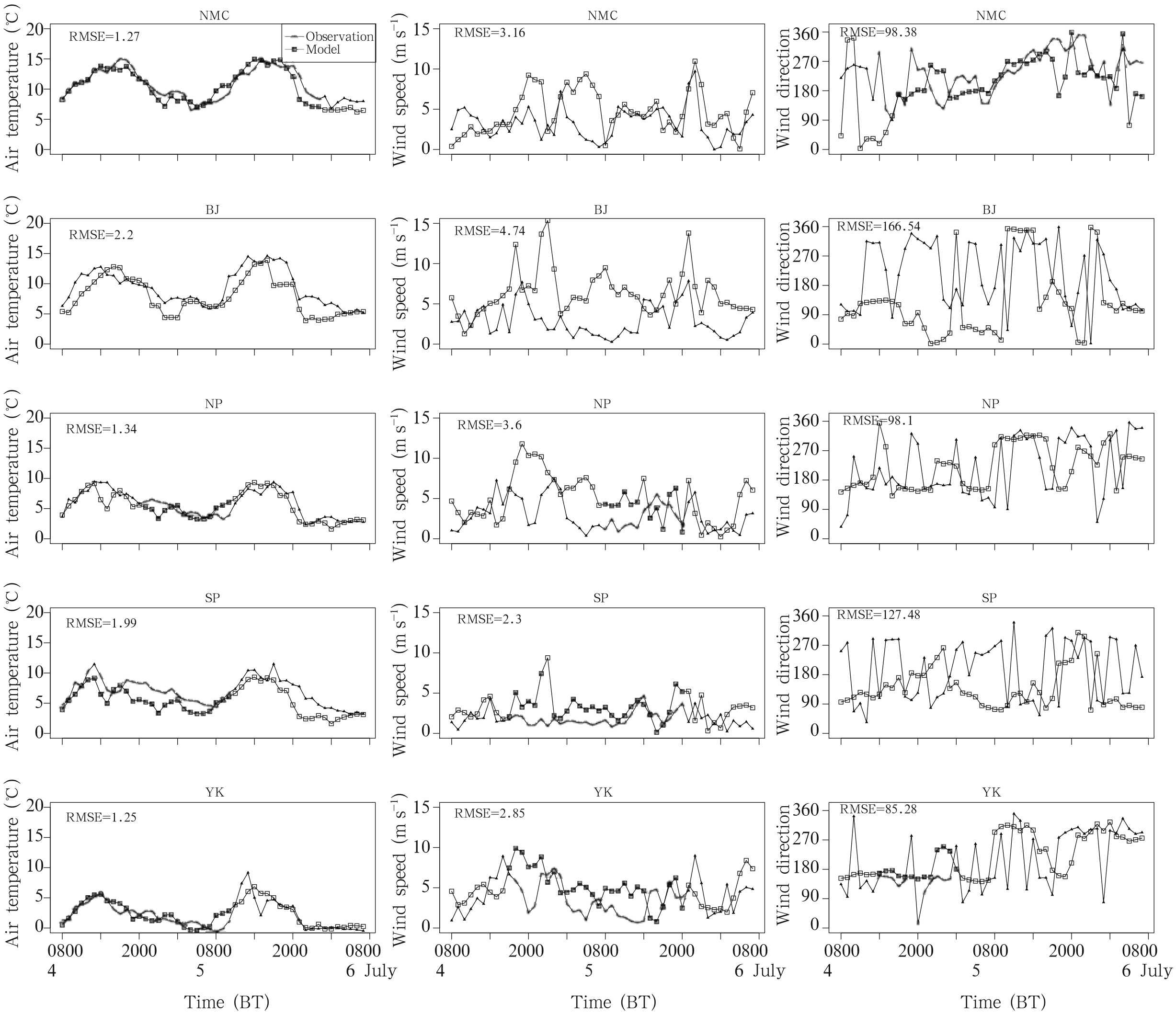

Fig. 2. Modeled and observed 2-m air temperature, wind speed, and wind direction for the five observation sites from 0800 BT 4 to 0800 BT 6 July 2006. All simulated winds are the instantaneous 10-m wind speed and direction. The observed wind at the NMC site is the instantaneous 10-m wind speed and direction, whereas at the BJ, NP, SP, and YK sites, the observed wind is the instantaneous 2.4-m wind speed and direction.

mated the nighttime T2 in all the five sites; this underestimation could affect the wind field simulation. The MM5 overestimated the overall wind speeds of all the five sites, with the RMSE ranging from 2.3 to 4.7 m s^{-1}. The simulation was more accurate on the second day (5 July) than on the first day (4 July). The RMSE of the wind speed was reduced by 28% on the second day.

Regarding the wind direction, the observations showed a significant hourly variation that was difficult for the model to capture. At the SP site, the observed wind direction regularly shifted between easterly (90°) and westerly (270°) from 0800 to 2000 BT 4 July, whereas the model showed a gradual change from 90° to 270° over the same time period. At the YK site, the observed wind direction shifted regularly between southeasterly (90°–180°) and northwesterly (270°–360°) from 0800 to 2000 BT 5 July, whereas the simulated wind direction gradually changed from northwesterly to southeasterly. As with the wind speed, the wind direction simulation was better on the second day (5 July) than on the first day (4 July). The model captured the wind direction well from 0900 to 1300 BT 5 July at the NMC, BJ, and NP sites. At the NMC site on 5 July, the simulated diurnal wind direction was reasonably accurate, but the nocturnal simulation for southeasterly (90°–180°, from land to lake) was 4 h earlier than that in the observations, which is likely because the simulated SH over the land decreased too rapidly near sunset.

There are two possible reasons for the poor wind field simulation. First, the wind field extracted from the model is the instantaneous 10-m wind (the model does not output the 2-m wind field), whereas the observed wind is the instantaneous 2.4-m wind for the BJ, NP, SP, and YK sites and is only the instantaneous 10-m wind for the NMC site. This mismatch could account for some of the overestimated wind speeds, because the 10-m wind speed is typically higher than the 2-m wind speed due to the lower surface drag. Second, the site-level observation and the 1-km resolution grid cells may not align perfectly, which would make the comparison inappropriate. We extracted the simulation from the grid cell that was nearest to each observation site. The large variation in the observed wind direction may be because of the widely varying local topography, which means that the topography of the grid cell is significantly different from that of the site. With a 1-km resolution, the model may neglect a certain topography that could affect wind direction, particularly at the three more mountainous sites.

Although the wind direction simulations show large biases, the simulations still reflect the wind direction changes of the lake/land breezes. In Fig. 3, the LB is represented by blue arrows and the land breeze by red for the NMC and BJ sites from 0800 BT 5 to 0800 BT 6 July. At the NMC site, the onset of the LB in both the simulation and the observation was around 1200–1300 BT, although the simulated wind direction changed back to land breeze earlier than did the observation. At the BJ site, the onset of the LB in the simulation (1500 BT) was earlier than that in the observation (1700 BT). The observed wind direction from 1700 to 2100 BT varied between the lake and the land breeze, whereas the model showed a consistent LB. Between 2200 and 0000 BT, the land breeze prevailed in both the simulation and the observation. Moreover, the wind direction changed again to LB in both the simulation and observation from 0200 to 0700 BT, which was likely because the coupling of two southerlies (hill to valley wind at the north slope and land to lake wind at the south shore) overwhelmed the nighttime land breeze at the BJ site. However, given

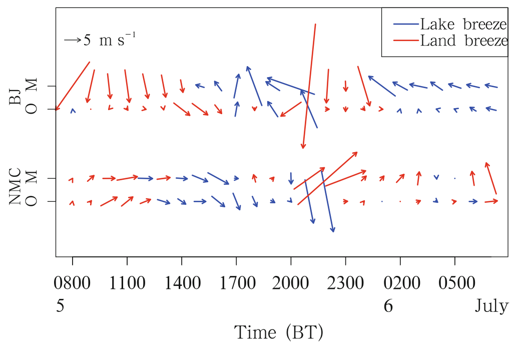

Fig. 3. Modeled and observed wind vectors at the NMC and BJ sites from 0800 BT 5 to 0800 BT 6 July 2006. The letter O indicates observed values and M indicates simulation values. The LB is indicated in blue and the land breeze is in red.

that the model simulated a poor wind direction at night, this conclusion must be verified with additional observations at the north shore.

3.2 Interaction between LBs and mountain-valley winds

Figure 4 shows the 10-m surface wind vector at 1400 and 2000 BT for the innermost domain. At 1400 BT, a clear divergence wind pattern in the central part of the lake suggested that an obvious LB was well established (Fig. 4a) in the LAKE simulation, whereas the LAND simulation was dominated by a southwesterly (Fig. 4b). At 1400 BT, the wind velocity over the lake area in the LAKE simulation (Fig. 4a) should have been greater than that in the LAND simulation (Fig. 4b) because of the small momentum roughness length of the lake surface, but the thermally-induced LB was dominant and overwhelmed such a wind velocity enhancement from the small lake momentum roughness length. The mountain-valley winds were observed in both the LAKE and LAND simulations. However, the north slope wind in the LAKE simulation was stronger (0.3 m s^{-1} higher on average) than that in the LAND simulation, most likely because the LB penetrated inland and enhanced the on-slope wind on the north slope. Thus, the lake influenced not only the LB but also the vicinity of the up-slope winds.

Over the mountainous regions, a clear convergence zone was observed (near the solid line in Fig. 4a) because of the opposite wind directions on the north and south slopes. The area controlled by the wind shear zone could potentially generate strong convective clouds and precipitation. The MODIS image obtained on 4 July (Fig. 5) showed strong convection

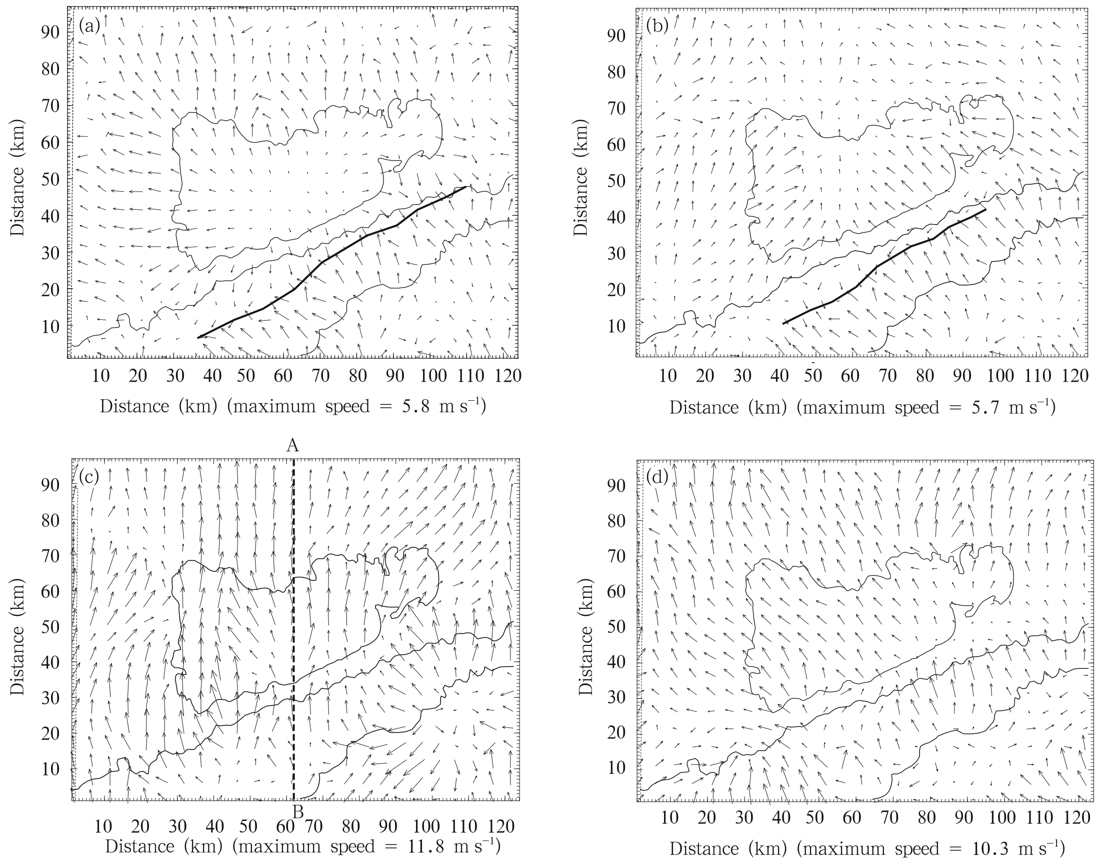

Fig. 4. 10-m wind vectors for the 1-km domain at (a, b) 1400 BT and (c, d) 2000 BT 4 July 2006 from the LAKE and LAND simulations, respectively. The thick line in (a) and (b) is the wind shear line. The solid lines show the boundary of Lake Nam Co and Mt. Nyainqêntanglha. The dotted line AB in (c) shows the cross-section along which the simulated wind vectors displayed in Fig. 8 are obtained.

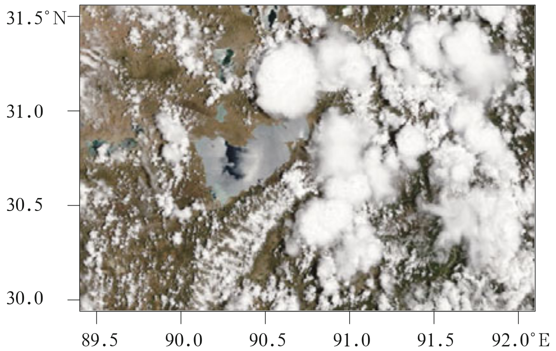

Fig. 5. The MODIS image for the Lake Nam Co region at 1250 BT 4 July 2006.

over the eastern mountain ridge during this time, which also confirmed that no convection occurred over Lake Nam Co as simulated by the MM5. When the lake was replaced (Fig. 4b), most areas were dominated by southerlies, and the up-slope northerlies were very weak. At 2000 BT, a strong southerly wind prevailed in most of the areas under the LAKE simulation (Fig. 4c), whereas only a weak down-slope southerly was observed in the LAND simulation (Fig. 4d). The stronger southerly in the LAKE simulation than in the LAND simulation at 2000 BT could have been because of the southerly land breeze combined with the down-slope southerly (Li et al., 2009). For the LAKE simulation, the wind velocity was greater at 2000 BT (Fig. 4c) than at 1400 BT (Fig. 4a), which was likely because of the dominant strong background wind velocity overwhelming the weak thermally-induced effect at night. In general, the surface wind is weak in the morning and strong in the late afternoon or evening over the TP. At 2000 BT, the wind enhancement in the LAKE simulation (Fig. 4c) was because of the dominant strong background wind velocity, while the thermally-induced circulation was weak for a small temperature difference between the lake and the land (mountain).

The large temperature gradient between the lake and the land was the driving force of the LB in the LAKE simulation. For the LAKE simulation, the 2-m air temperature over the lake was 12℃, which was nearly 5℃ lower than that over the surrounding land (Fig. 6a). By comparison, the original lake area in the LAND simulation (Fig. 6b) showed a higher temperature (20℃), thereby generating a southerly. The existence of the lake reduced not only the air temperature but also the SH over the lake. In the LAKE experiment (Fig. 7a), the SH over the lake was 100 W m^{-2}, which is roughly 1/3 of that over the land (300 W m^{-2}). Over the mountainous region, the SH reached a maximum value of over 600 W m^{-2}. Such a remarkable difference is important in the formation of thermal circulation (Segal and Arritt, 1992). In the LAND simulation (Fig. 7b), without the lake, the average SH of the entire area was larger than that in the LAKE simulation by 100 W m^{-2}.

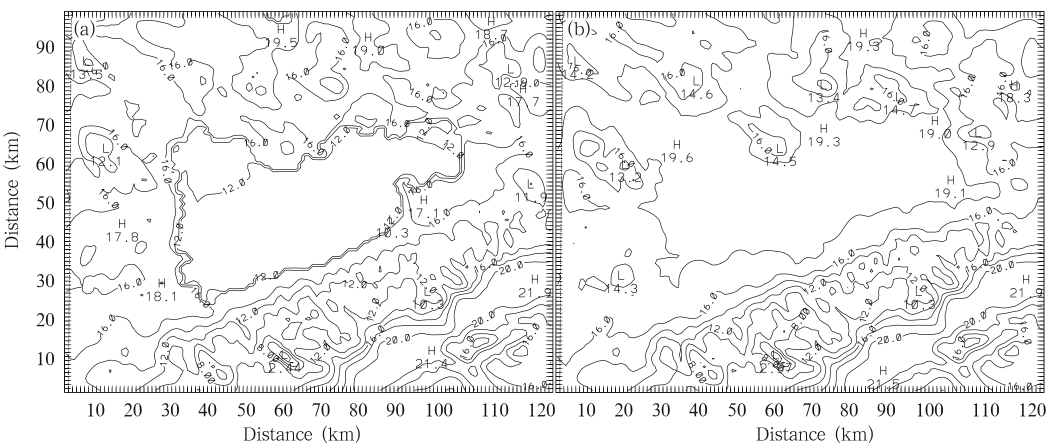

Fig. 6. Distributions of 2-m air temperature at 1400 BT 4 July 2006 for the (a) LAKE and (b) LAND simulations. The contour interval is 4℃, and the L and H markers on the plots indicate low and high values that do not fit into the contour level.

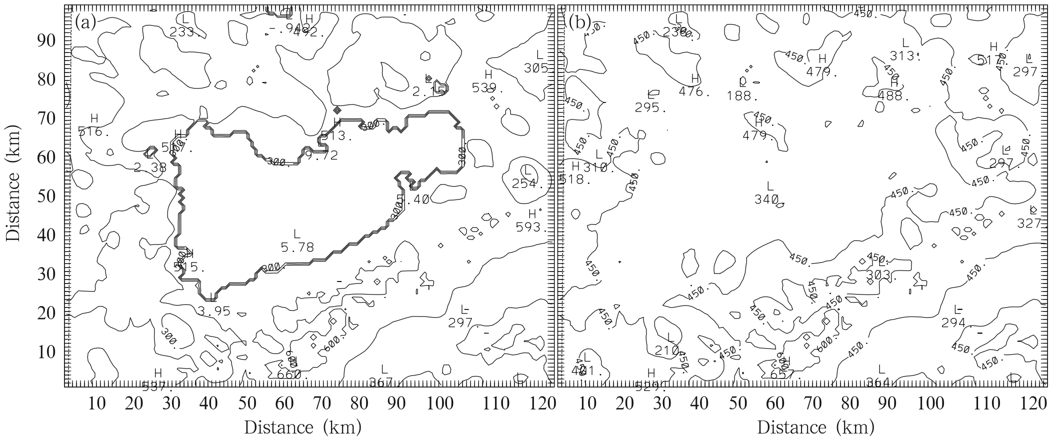

Fig. 7. As in Fig. 6, but for SH contour. The contour interval is 150 W m^{-2}.

Figure 8 shows cross-sections of the wind vector and potential temperature at 1400 BT along line AB in Fig. 4c for the LAKE (Fig. 8a) and LAND (Fig. 8b) simulations. The downward flow controlled the layers lower than 7500 m above the lake at 1400 BT, when the LB was well established, and the LAND experiment showed an upward vertical flow because of the well-mixed turbulence. Over the convergence zone of the mountain, the air reached up to approximately 8500 m because of the coupling of LB and winds, whereas such a flow was reduced to nearly 1000 m in the LAND simulation when the flow was caused by the mountain-valley winds alone. In the LAKE simulation, the potential temperature was 2°C lower in the boundary layer than that in the LAND simulation, but the two values exhibited no difference in the upper layer.

The existence of the lake strengthened the mountain-valley wind, especially over the north slope. On 4 and 5 July, at the NP site, a higher mean wind speed was seen at the SP site in both the observation (over 1.2 m s^{-1}) and the simulation (over 1.8 m s^{-1}). This finding could be because of the coupling of the northerly LB at the south shore and the uphill wind at the north slope. The vertical wind profile clearly showed that the wind speed and the upward flow were much stronger with the lake (Fig. 8a) than without the lake (Fig. 8b), which is likely

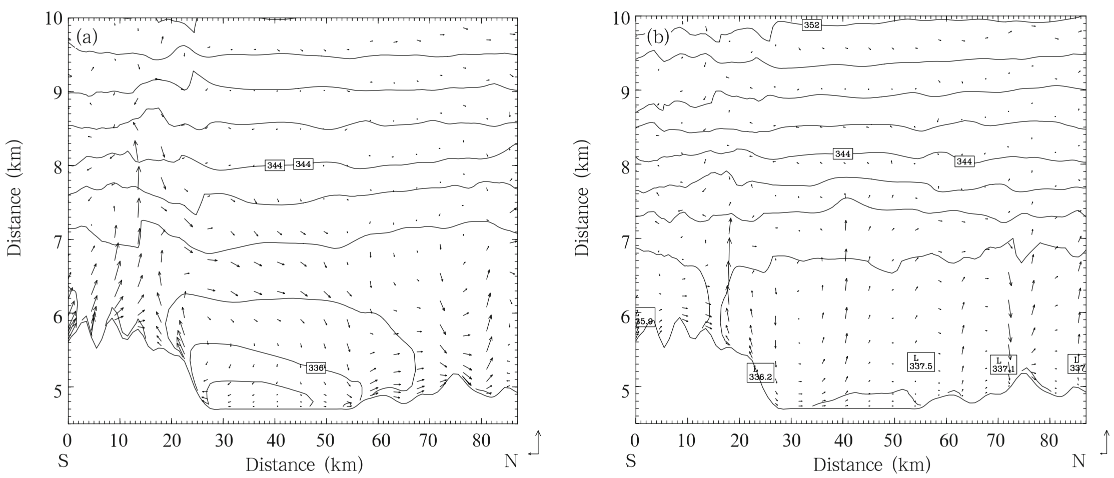

Fig. 8. Vertical cross-sections of potential temperature and wind vector in the north-south direction through line AB (Fig. 4c; A: 31.0°N, 90.5°E and B: 30.1°N, 90.5°E) at 1400 BT 4 July 2006, for the (a) LAKE and (b) LAND simulations. The contour lines denote potential temperature with a 2-K interval. Rectangles with the letter L in (b) indicates the low value of potential temperature that does not fit into the contour level.

because the relatively cool lake surface enhanced the SH gradient between the mountain and the valley.

4. Conclusions

Our study showed that the MM5 can be used to capture the diurnal changes of the 2-m air temperature over the Lake Nam Co region of the Tibetan Platean; however, the MM5 showed a large bias in wind field simulation. Some of the bias may be because of the surface wind field being more sensitive than the air temperature to topographic changes. At a resolution of 1 km, the model failed to capture certain variations that were seen in the observation. Therefore, a high-resolution (e.g., hundreds of meters) numerical study is required for highly heterogeneous regions. In addition, the simulation at the NMC site showed a land breeze occurring 4 h earlier than in the observation, which suggested that simulated sensible heat flux over the land decreased too fast near sunset. Although the model accurately captured the diurnal changes of the 2-m air temperature, it underestimated the nighttime 2-m air temperature at all five observation sites.

The numerical simulations showed that the lake enhanced the north slope's mountain-valley wind, and the mountain changed the offshore flow direction at the north shore. The lake not only generated a lake breeze but also increased the magnitude of the up-slope winds as well as winds over the north slope of Mt. Nyainqêntanglha. The strong southerlies in the LAKE experiment could be attributed to the southerly land breeze combined with the down-slope southerly. In addition, a convergence zone over the north slope of Mt. Nyainqêntanglha and a strong upflow were observed during the daytime, which may have caused convective cloud formation and precipitation on the north slope of the mountain. Further observations on the north slope are needed to evaluate the effect of this convergence zone on the local precipitation.

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