Modeling the Effects of Lakes in the Tibetan Plateau on Diurnal Variations of Regional Climate and Their Seasonality

LINGJING ZHU,a,b JIMING JIN,a,b,c AND YIMIN LID,e,f

a Key Laboratory of Agricultural Soil and Water Engineering in Arid and Semiarid Areas, Ministry of Education, Northwest A&F University, Yangling, China; b College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, China; c Department of Watershed Sciences, Utah State University, Logan, Utah; d State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; e University of Chinese Academy of Sciences, Beijing, China; f CAS Center for Excellence in Tibetan Plateau Earth Sciences, Beijing, China

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ABSTRACT: In this study, we investigated the effects of lakes in the Tibetan Plateau (TP) on diurnal variations of local climate and their seasonal changes by using the Weather Research and Forecasting (WRF) Model coupled with a one-dimensional physically based lake model. We conducted WRF simulations for the TP over 2000–10, and the model showed excellent performance in simulating near-surface air temperature, precipitation, lake surface temperature, and lake-region precipitation when compared to observations. We carried out additional WRF simulations where all the TP lakes were replaced with the nearest land-use types. The differences between these two sets of simulations were analyzed to quantify the effects of the TP lakes on the local climate. Our results indicate that the strongest lake-induced cooling occurred during the spring daytime, while the most significant warming occurred during the fall nighttime. The cooling and warming effects of the lakes further inhibited precipitation during summer afternoons and evenings and motivated it during fall early mornings, respectively. This study lays a solid foundation for further exploration of the role of TP lakes in climate systems at different time scales.

KEYWORDS: Complex terrain; Inland seas/lakes; Lake effects; Model evaluation/performance; Regional models

1. Introduction

Lakes play a vital role in affecting local and regional climate due to their larger heat capacity, lower albedo, and smaller roughness when compared to land (Bonan 1995). Lakes modulate surface energy and water balance (Dutra et al. 2010; Rouse et al. 2008; Samuelsson et al. 2010), inducing lake–land temperature contrasts at both diurnal and seasonal scales (Long et al. 2007; Rouse et al. 2005; Stepanenko et al. 2010; Subin et al. 2012a). It is commonly known that a lake surface is cooler during the daytime and warmer during the nighttime relative to the nearby land surface (Thiery et al. 2015). Likewise, when compared to land, lakes store more heat during the late spring and summer and release it more strongly during the fall and early winter, inducing a cooler surface and warmer surface, respectively (Lofgren 1997; Samuelsson et al. 2010). The temperature differences between a lake and the nearby land surface produce an air pressure gradient, developing local atmospheric circulations and lake–land breezes and changing regional energy and moisture transfers (Crosman and Horel 2010; Keen and Lyons 1978; Moroz 1967). Through these processes, lakes significantly redistribute local and regional heat and water, thereby altering the climate, especially in regions with abundant lakes (Rouse et al. 2008, 2005; Samuelsson et al. 2010; Subin et al. 2012a).

As the largest lake cluster in China (more than 1000 lakes larger than 1 km² with a total area of about 43 000 km²) (Zhang et al. 2014), the lakes in the Tibetan Plateau play an important role in land–atmosphere systems (Li et al. 2009; Rüthrich et al. 2015; Singh and Nakamura 2009). The strong surface heterogeneity of the TP, due partly to different sizes of lakes, affects large-scale circulations and further downstream climate (Bao et al. 2010; Chow et al. 2008; Duan et al. 2012; Liu et al. 2012; Wu et al. 2012; Ye and Wu 1998). With the significant warming over the TP in recent years (0.36°C decade⁻¹ for the period of 1957–2007) (Wang et al. 2008), most TP lakes have also undergone pronounced changes in terms of surface areas, water level/storage, and ice processes (Huang et al. 2017; Phan et al. 2012; Song et al. 2013; Zhang et al. 2011). For example, the average annual temperature for Serling Co (the second largest lake in the TP) increased at a rate of 0.49°C decade⁻¹ for the period of 1979–2017, and local precipitation enhanced at a rate of 46.5 mm decade⁻¹ (Zhu et al. 2019). Therefore, the effects of TP lakes and their changes on local and regional climate are worth characterizing and quantifying.

Due to their wide distribution and ability to modulate energy and water transfer, TP lakes are likely to affect TP precipitation at diurnal and seasonal scales. TP precipitation is generated mainly by small (<100 km²) and medium (100–10 000 km²) convective systems (Hirose and Nakamura 2005) and characterized by a significant diurnal cycle with maxima from late afternoon to midnight and minima from early morning to noon (Fujinami et al. 2005; Li et al. 2014; Xu and Zipser 2011). This diurnal cycle of TP precipitation changes with the season; it is strong from May through September...
when the TP is affected the most by the monsoon, but weak during other months (Fu et al. 2006; Singh and Nakamura 2009; Yu et al. 2007; Zhou et al. 2008). The extensively distributed TP lakes enhance the surface heterogeneity and affect microscale to mesoscale convective systems, further affecting the diurnal variations of TP precipitation with the season.

So far, the effects of TP lakes on the diurnal variation of TP precipitation with the season and the related physics have not been comprehensively and systematically investigated. Numerous studies have explored the climatic effects of TP lakes at different spatiotemporal scales by using in situ measurements or satellite data (Rüthrich et al. 2015; Singh and Nakamura 2009; Wang et al. 2017; B. Wang et al. 2015; Zhu et al. 2019). However, in situ measurements are limited to a small number of TP lakes over short periods, while satellite data have only a few connected variables and do not provide an in-depth understanding of the physical processes linking the atmosphere and lakes in the TP (Pepin et al. 2015). High-resolution lake–atmosphere coupled models are important tools and have been applied to investigating the effects of TP lakes on the climate. However, previous studies focus mainly on the single lake (Li et al. 2009; Gerken et al. 2013; Li et al. 2015; Dai et al. 2018) or specific periods such as the summer (Wu et al. 2019). The effects of TP lakes on the diurnal cycle of regional climate and its seasonality are needed to explore with the high-resolution lake–atmosphere coupled models.

In this study, we applied the Weather Research and Forecasting (WRF) Model (Skamarock et al. 2008), a fully coupled regional climate–lake model (Gu et al. 2013), to quantify the impact of TP lakes on the diurnal cycle of precipitation with the season. A set of simulations for an 11-yr period (2000–10) with the WRF Model was first conducted to evaluate the performance of WRF in simulating near-surface climate, lake surface temperature (LST), and precipitation over lake regions in the TP. Another set of simulations was conducted without the TP lakes to identify the role of TP lakes in climate systems. In the following, section 2 introduces the data and model used in this study, section 3 evaluates and analyzes the modeling results, and conclusions and a discussion are presented in section 4.

<table>
<thead>
<tr>
<th>Lake depth (m)</th>
<th>Default</th>
<th>Calibrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>≥25</td>
<td>10</td>
<td>10³</td>
</tr>
<tr>
<td>&lt;25</td>
<td>1</td>
<td>10²</td>
</tr>
</tbody>
</table>

Table 1. The default and calibrated $m_d$ when the LST is above the freezing point.

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Fig. 1. (a) TP lake distribution and lake depths (m) in the WRF simulations: The area in the black curve covers the TP, and the evaluation area is included in the red curve. The bottom figures are regions selected to be averaged for the (b) Nam Co, (c) Lake Qinghai, and (d) Selin Co areas and their altitudes (m).
2. Data and model

a. Data

The China Meteorological Forcing Dataset (CMFD) was used to evaluate our model simulations in this study, which was made through fusion of remote sensing products, reanalysis dataset, and in situ observation data at weather stations (He et al. 2020; Yang et al. 2010). This dataset, including temperature and precipitation, covered the period of 1979–2018 with a spatial resolution of 0.1° × 0.1° at a 3-hourly time step, which was verified with in situ observations (Chen et al. 2011; Guo and Wang 2013; Liu and Xie 2013). Version 7 of the Tropical Rainfall Measuring Mission (TRMM) precipitation product (Huffman et al. 2007) was also used to assess our simulated precipitation over the TP and lake regions. The TRMM data were at a 0.25° spatial resolution with a time step of 3 h for the period of December 1997–February 2019, covering the region between 60°N and 60°S. From these three datasets, we selected data only from 2000 through 2010 for model evaluation, which was our study period. We evaluated modeled LST for the TP with the monthly Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature products at a resolution of 0.05° × 0.05° for 2003–10, a time span that overlapped with our study period. The Interim European Centre for Medium-Range Weather Forecasts reanalysis data (Dee et al. 2011) were used to provide initial and lateral boundary conditions for our regional climate model. The data were at a 0.5° horizontal resolution and a 6-h time interval.

b. Model and methodology

The WRF Model version 3.6 (Skamarock et al. 2008) was employed in this study to explore the effects of TP lakes on regional climate. WRF is a nonhydrostatic mesoscale modeling system that is often adopted for regional weather and climate simulations and forecasts. The lake model in WRF was originally developed by Hostetler et al. (1993) and was taken from the Community Land Model version 4.0 (CLM 4.0; Oleson et al. 2010). It is a one-dimensional (1D) model and includes up to 5 snow layers on the lake ice, 10 water layers, and 10 sediment soil layers below the lake bottom. We selected observed precipitation and temperature data for the TP over June 2006 to conduct a series of sensitivity WRF simulations and chose the following combination of physical schemes, which produced the best simulations: Dudhia shortwave radiation (Dudhia 1989), Rapid Radiative Transfer Model longwave radiation (Mlawer et al. 1997), Community Atmosphere Model 5.1 microphysics (Neale et al. 2010), Kain–Fritsch cumulus (Kain 2004), University of Washington planetary boundary layer (Bretherton and Park 2009), and CLM 4.0.

With this combination, we further calibrated the WRF Model with LST observations for the TP lakes. The eddy diffusivity scheme from the CLM 5.0 was introduced to WRF to better simulate the LSTs for the TP lakes. In this scheme, the

<table>
<thead>
<tr>
<th>Table 2. Comparison between simulated and observed (OBS) air temperatures at 2-m height for both spatial and temporal patterns.</th>
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<tbody>
<tr>
<td>Air temperature at 2-m height</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Spatial</td>
</tr>
<tr>
<td>Temporal</td>
</tr>
</tbody>
</table>
total eddy diffusivity $K_w$ (m$^2$ s$^{-1}$) for liquid water in the lake body is given as (Subin et al. 2012b)

$$K_w = m_d (k_e + K_{ed} + k_m),$$

where $k_e$ is due to wind-driven eddies, $K_{ed}$ is a modest enhanced diffusivity intended to represent unresolved mixing processes, $k_m$ is the molecular diffusivity of water, and $m_d$ is a factor which increases the overall diffusivity for large lakes, intended to represent 3D mixing processes such as caused by horizontal temperature gradients. The factor $m_d$ is 1 when the lake depth is smaller than 25 m and equals 10 when the lake depth is larger than and equal to 25 m (Table 1). When the LST is below the freezing point (0°C), the $k_e$ is turned off in the model. We performed sensitivity tests with the changed $m_d$ and then chose the values as shown in Table 1. Meanwhile, the momentum/heat/vapor roughness lengths at the water surface were reduced from the default $1 \times 10^{-3}$ m for the unfrozen lake and $5 \times 10^{-3}$ m for the frozen lake without snow to $2 \times 10^{-4}$ m based on Subin et al. (2012b) and B. Wang et al. (2015, 2019). In these model calibrations, we used observed lake depths for Nam Co, Lake Qinghai, and Serling Co (Lei et al. 2013; Wang et al. 2014; J. Wang et al. 2015), and the lake depth data from Kourzeneva (2010) were applied to the rest of the TP lakes. The above calibrated WRF Model generated very accurate production

<table>
<thead>
<tr>
<th>Precipitation</th>
<th>OBS</th>
<th>$R$</th>
<th>RMSE (mm month$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial</td>
<td>TRMM</td>
<td>0.70</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>CMFD</td>
<td>0.77</td>
<td>22</td>
</tr>
<tr>
<td>Temporal</td>
<td>TRMM</td>
<td>0.90</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>CMFD</td>
<td>0.91</td>
<td>18</td>
</tr>
</tbody>
</table>

**TABLE 3.** Comparison between simulated and observed (OBS) precipitation for both spatial and temporal patterns.

**FIG. 3.** Spatial distribution of annual mean precipitation (mm month$^{-1}$) for the TP: (a) TRMM data, (b) CMFD data, and (c) WRF_LAKE simulation. (d) Time series of monthly mean precipitation (mm month$^{-1}$) averaged over the TP for 2000–10.

**FIG. 4.** Time series of observed (black line) and simulated (red line) monthly mean LSTs (°C) averaged over (a) Nam Co, (b) Lake Qinghai, (c) Serling Co, and (d) WRF-resolved TP lakes for 2003–10. The $R$ values, RMSEs (°C), and biases (°C) are also given in the figure.
simulations when compared with observations (discussed again in section 3c). In this study, two sets of production simulations at a 10-km horizontal resolution were carried out with the calibrated WRF Model for the period of 2000–10. The first set was conducted by including 86 model resolved lakes accounting for 80% of the total lake area in the TP (WRF_LAKE; Fig. 1), while the second set was done by replacing all those resolved lakes with the nearest land-use types (WRF_NOLAKE), mostly grassland or mixed shrubland in this case. For these simulations, the model domain, encompassing the entire TP area, consisted of 425 grids along the east–west direction and 230 grids along the north–south direction. In the vertical direction, the WRF Model was configured with 30 layers, and the top layer was set to 50 hPa. To avoid potential climate drift, the WRF Model ran for each year individually from 1 September of the previous year through 31 December of the current year; the first 4-month simulations were discarded for model spinup, and the remaining 12-month simulations were analyzed.

<table>
<thead>
<tr>
<th>Lake-area precipitation</th>
<th>OBS</th>
<th>R</th>
<th>RMSE (mm month⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nam Co</td>
<td>TRMM</td>
<td>0.87</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td>CMFD</td>
<td>0.88</td>
<td>22</td>
</tr>
<tr>
<td>Lake Qinghai</td>
<td>TRMM</td>
<td>0.92</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>CMFD</td>
<td>0.95</td>
<td>21</td>
</tr>
<tr>
<td>Selin Co</td>
<td>TRMM</td>
<td>0.72</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td>CMFD</td>
<td>0.87</td>
<td>19</td>
</tr>
</tbody>
</table>
3. Model evaluation

a. Air temperature at the height of 2 m

The simulated air temperature at a height of 2 m with WRF_LAKE for the TP was evaluated with the CMFD data. This temperature was accurately simulated by WRF_LAKE as shown in Fig. 2. The spatial coefficient correlation ($R$) and root-mean-square error (RMSE) are 0.84 and 2.22°C, respectively (Table 2). The observed seasonal cycles were also well reproduced by WRF_LAKE, with an $R$ of 0.99 and RMSE of 0.75°C (Table 2). Hence, WRF_LAKE was able to realistically capture the spatiotemporal distributions of observed air temperature at 2-m height.

b. Precipitation

Simulated precipitation with calibrated WRF_LAKE for the TP was assessed with the TRMM and CMFD data (Fig. 3). We can see that the WRF Model well captured the spatial distribution of observed TP precipitation. The $R$ values between the simulations and the TRMM and CMFD data are 0.70 and 0.77, and their RMSEs are 23 and 22 mm month$^{-1}$, respectively (Table 3). The time series of simulated precipitation averaged over the TP agreed very well with observations in both amplitude and phase (Fig. 3d). The value of $R$ is 0.90 with TRMM and 0.91 with CMFD, while the RMSE is 18 mm month$^{-1}$ with both TRMM and CMFD (Table 3). Therefore, the WRF Model was able to accurately reproduce observed precipitation over the TP.

c. LST

The LSTs simulated by WRF_LAKE were verified with MODIS data for the TP lakes. Figure 4 shows the time series of simulated and observed LSTs averaged over the WRF-resolved TP lakes and Nam Co, Lake Qinghai, and Serling Co; the latter are the three largest lakes in the TP. For the WRF-resolved TP lakes, the simulated LSTs agreed well with observations although the model underestimated the LSTs over winter, spring, and summer with a bias of $-2.33^\circ$C. The $R$ and RMSE are 0.99 and $2.63^\circ$C, respectively. In addition, WRF_LAKE reasonably reproduced the phase and magnitude of observed LSTs for Nam Co, Lake Qinghai, and Serling Co, with $R$ values of 0.94, 0.97, and 0.95, RMSEs of 1.90, 1.92, and 2.24°C, and biases of $-0.07^\circ$, $-0.21^\circ$, and $0.15^\circ$C, respectively. Therefore, WRF_LAKE performed well in simulating the temporal variations of LSTs for the TP, setting the stage for exploring the effects of TP lakes on the regional climate.

d. Diurnal cycles of precipitation with the season over the three largest TP lakes

We assessed the WRF_LAKE simulations for the diurnal cycles of precipitation and their seasonal changes over the regions of Nam Co, Lake Qinghai, and Selin Co, the three largest lakes in the TP. Figure 5 shows seasonal variations in the diurnal cycles of observed and simulated precipitation over these three lakes. For observations, we can see that most precipitation fell during the monsoon season (May–September). At a diurnal scale, minimum precipitation occurred during the late morning and maximum precipitation happened during the late afternoon through evening. In general, WRF_LAKE reasonably reproduced observed diurnal precipitation variations with the season. For Nam Co, the observed diurnal variations in precipitation were realistically reproduced by WRF_LAKE with $R$ values of 0.87 against TRMM and 0.88 against CMFD, respectively (Table 4). However, the simulated precipitation peak occurred in July while the observed peak is seen in August. The RMSEs between WRF_LAKE simulations and the TRMM and CMFD data over the Nam Co region are 27 and 22 mm month$^{-1}$ (Table 4). The simulated diurnal variations with the season in precipitation over Lake Qinghai were relatively well consistent with observations in the pattern, which get $R$ values larger than 0.9 with both the TRMM and CMFD data. Nevertheless, the magnitudes were largely overestimated by the WRF_LAKE simulations, obtaining RMSEs of 30 mm month$^{-1}$ against TRMM and 21 mm month$^{-1}$ against CMFD (Table 4). Over Selin Co, WRF_LAKE largely captured the temporal precipitation patterns, but it generated an earlier peak ($-9$h) than observations at the diurnal scale. The $R$ values are 0.72 and 0.87, and RMSEs are 28 and 19 mm month$^{-1}$ with the TRMM and CMFD data over the Selin Co region (Table 4). Despite the simulation biases, WRF_LAKE could still reproduce the diurnal precipitation variations with the season over these three largest lakes in the TP, providing confidence for further exploration of the effects of TP lakes on precipitation.

4. Effects of TP lakes on local climate

a. Surface temperature variations

For this study, we examined how TP lakes affected the diurnal variation of surface temperature with the season by comparing the simulations produced with WRF_LAKE and WRF_NOLAKE. TP lakes here were defined as the entire lake...
grids over the TP in WRF_LAKE (Fig. 1), which account for 80% of the total lake area in the TP. As shown in Fig. 6, the TP lakes favored a cooling effect during the daytime and a warming effect during the nighttime when compared to the land in WRF_NOLAKE. The cooling effect was due largely to the reduction in solar radiation absorbed by the lake surface (Fig. 7a). The transparency of the lake water allowed a large portion of incoming solar radiation to pass through the lake surface and penetrate the deeper layers, while incoming solar radiation was mostly absorbed by the land surface. Thus, solar radiation absorption at the lake surface was much weaker than that at the land surface, leading to a cooler lake surface. The cooled lake surface decreased longwave radiation and thus increased net longwave radiation during the daytime (Fig. 7b). The sensible heat flux at the lake surface was also reduced by the cooling (Fig. 7c), while the latent heat was minorly affected due to the much moisture over the lake except during the summer (Fig. 7d). The strongest cooling of 17.6°C occurred at noon in May, but the maximum reduction in solar radiation absorption at the lake surface happened in April. In April, the upper and lower lake layers had large temperature differences (figures not shown), triggering significant heat transfer (Fig. 7e). In May, such temperature differences decreased due to the temperature increase in the top part of the lake, reducing the heat transfer from the lower part of the lake to the surface and slowing the lake surface temperature increases. However, the land surface temperature kept the same pace to increase in April and May, which resulted in the larger temperature difference between the lake and the nearby land in May than in April. In addition, the strong suppressed sensible heat release (Fig. 7c) weakened the cooling effect in April. As a result, the maximum temperature decrease occurred in May. The warming effect during the nighttime was induced by the greater heat transfer from the deeper part of the lakes to the lake surface than that from the deeper soil to the land surface (Fig. 7e). In the fall,
the lake surface water cooled and sank to deep depths due to the density gradient, inducing the water mixing and a large amount of lake-stored heat transferring upward to heat the surface (Fig. 7e). The lake surface was thus warmer than the nearby land surface with minor heat supported by the soil, favoring increased sensible and latent heat flux on the lake surface (Figs. 7c,d). The strong warming in October was partly offset by the significant evaporation cooling, and thus the largest warming of 16.5°C occurred early in the morning in November (Fig. 7d). Clearly, the TP lakes significantly changed the diurnal energy transfer with the season, thereby modulating the surface temperature of the lakes.

b. Precipitation variations

Diurnal precipitation changes with season induced by the TP lakes were explored by comparing the simulations produced by WRF_LAKE with those by WRF_NOLAKE. Figure 8 shows that the effects of the TP lakes on precipitation demonstrated strong diurnal variations that change with the season. Precipitation significantly decreased from the afternoon through evening during the summer, and the largest decrease occurred in the afternoon in July with a value of 72 mm month⁻¹, a 57% reduction from that without the lakes. Precipitation increased from the evening through the morning during the fall, and the largest increase was 36 mm month⁻¹ at midnight in September, a 65% enhancement when compared to that over the land. During the summer daytime, the cooling effect induced by the TP lakes stabilized the atmosphere, triggered downward motion over the lakes (Figs. 9a–d), and thus suppressed precipitation. Although stronger downward motion occurred during the daytime in spring than in summer, precipitation changed much less than that in summer, owing to the lower atmospheric water vapor over the TP in spring. Figure 10 also shows that the sinking motion over the TP lakes in spring was induced mainly by the stronger dry convective stability, while such motion in the summer was developed due to the greater moist convective stability. During the fall nighttime, the warming effect of the TP strengthened evaporation and thus moistened the low-level air (figures not shown). The warmer and moister air parcels above the lakes destabilized the low-level atmosphere (Fig. 10b) and motivated upward motion (Figs. 9e–h), further strengthening precipitation in the fall nighttime. As mentioned above, the cooling and warming effects of the TP lakes altered the stability of the low-level atmosphere, further leading to diurnal precipitation changes with the season.

c. Impact of the TP lakes on the surface temperature and precipitation in different climate zones

The impact of the TP lakes on the surface temperature and precipitation in different climate zones is discussed here. The monthly LST generated by WRF_LAKE during April–June and October–December averaged over 2000–10 were given in Fig. 11. The lakes on the north TP have a later freezing (LST < 0°C) time and an earlier melting (LST > 0°C) time than those on the south TP, which is also found in the MODIS data (figures not shown). In this study, the TP lakes were divided into the north lakes (in the blue dashed circle) and the south lakes (in the red dashed circle) as shown in Fig. 11 to discuss the surface temperature and precipitation over the lakes in different climate zones. For this study, we selected 36 north lakes and 34 south lakes in WRF_LAKE following the above temporal pattern for analysis.

The simulated lake-induced changes in the surface temperature and precipitation by the north and south TP lakes over 2000–10 were shown in Figs. 12 and 13. Both the north and south TP lakes favored a daytime cooling and nighttime warming, which is consistent with the discussions in section 4a. However, the north lakes generated a one-month delay with the strongest cooling effect, and the strongest warming effect occurred one month earlier when compared to the south lakes. Meanwhile, the strength of the cooling and warming effects of the north lakes was weaker than those of the south lakes. The differences in the phase and strength resulted from the colder climate on the north TP than that on the south TP, leading to a longer freezing period for the north lakes. The different climate conditions over the north and south TP also contribute differences in lake-induced precipitation. Both north and south TP lakes significantly inhibited overlap precipitation in the afternoon from late spring through early fall. The south lakes motivated fall precipitation during nighttime through the morning, but the north lakes did not.

5. Conclusions and discussion

The purpose of this study was to investigate and quantify the impact of lakes in the TP on the diurnal variations of local climate and their changes with the season for the period of 2000–10 with the WRF Model at 10-km resolution. The WRF Model was evaluated with TRMM and CMFD data for temperature and precipitation simulations. The simulated LSTs were assessed with MODIS land
FIG. 9. Simulated seasonal variations in diurnal differences of vertical velocity (m s\(^{-1}\)) between WRF_LAKE and WRF_NOLAKE (WRF_LAKE \(\text{LT} 09-12\) - WRF_NOLAKE) averaged over the TP lakes for 2000–10 (positive is upward). The dots indicate differences statistically significant at the 90% level.
surface temperature data. In addition, the diurnal variations of simulated precipitation with the season over the three largest lakes in the TP were also evaluated with TRMM and CMFD. Our model evaluation showed that the model well captured the spatiotemporal patterns of observed precipitation and temperature over the TP. The phase and magnitude of the simulated LSTs in the TP agreed well with observations. Furthermore, the model reasonably reproduced the seasonality of diurnal variations of observed precipitation over the three largest TP lakes.

Two sets of simulations with and without the TP lakes were conducted and compared to explore the local climatic effects of the TP lakes. Our simulations showed that the diurnal local climate changes induced by the TP lakes were significant (at the 99% level) with the season. The surface temperature decreased most significantly during the spring daytime and increased most meaningfully during the fall nighttime when compared to the land surface temperature. We found that the cooling effect was induced by the reduction in solar radiation absorption at the lake surface, while the warming effect was due mainly to the heat transfer from the deeper part of the lakes to the surface. The daytime cooling effects of the TP lakes further increased the low-level air stability and

![Fig. 10](image1.png)

**Fig. 10.** Simulated seasonal variations in diurnal differences of vertical stability [K (100 hPa)^{-1}] between WRF_LAKE and WRF_NOLAKE (WRF_LAKE – WRF_NOLAKE) averaged over altitudes of 0–3 km above the lake surface for 2000–10: (a) dry convective stability and (b) moist convective stability (positive is stable). The dots indicate differences statistically significant at the 90% level.

![Fig. 11](image2.png)

**Fig. 11.** Monthly variations of spatial distribution in lake surface temperature (LST, °C) generated from WRF_LAKE averaged over 2000–10. The blue dashed curve includes the north lakes, and the red dashed curve includes the south lakes.
inhibited precipitation over the lakes. At the same time, the lake warming effects during the nighttime led to instability in the lower part of the atmosphere and motivated upward motion, increasing precipitation over the lakes. The largest reduction in precipitation occurred during the summer afternoon and evening when the moist convective stability was most strongly enhanced. Meanwhile, precipitation increased mostly during the fall early morning when the strongest warming effect occurred. The TP lakes were divided into the north lakes and south lakes based on the freezing and melting time, and we obtained above-mentioned conclusions in the impact of the TP lakes on the surface temperature and precipitation in different TP climate zones.

Limitations exist in this study. We focused mainly on sensitivity modeling tests to explore the lake effects on local climate over the TP, but our modeling results need to be further verified with observational data. The lake effects on regional climate were not discussed in this paper because they were evident at a synoptic scale but were slight in a climatological pattern according to the model results. Meanwhile, the depth and area variations of the TP lakes were not considered in our simulations. Although these variations could be neglected at the diurnal and seasonal scales in our study, it may be important to take them into account in long-term climate studies of the TP. In addition, the 1D lake model coupled with WRF was unable to simulate three-dimensional (3D) lake circulations. The effects of these circulations on lake processes may not change the conclusions we drew in this study due to the small spatial scales of most TP lakes (e.g., 100–1000 km²). However, a 3D lake model is likely to be important in simulations of large lakes such as Lake Qinghai, Serling Co, and Nam Co, and this would be worth exploring in the future. Despite these limitations, we can see that this study still provides important tools to examine how TP lakes affect climate, hydrology, and ecosystems.
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