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• **Original Paper** •

The Characteristics and Controlling Factors of Water and Heat Exchanges over the Alpine Wetland in the East of the Qinghai–Tibet Plateau

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ABSTRACT

Alpine wetland is one of the typical underlying surfaces on the Qinghai–Tibet Plateau. It plays a crucial role in runoff regulation. Investigations on the mechanisms of water and heat exchanges are necessary to understand the land surface processes over the alpine wetland. This study explores the characteristics of hydro-meteorological factors with in situ observations and uses the Community Land Model 5 to identify the main factors controlling water and heat exchanges. Latent heat flux and thermal roughness length were found to be greater in the warm season (June–August) than in the cold season (December–February), with a frozen depth of 20–40 cm over the alpine wetland. The transfers of heat fluxes were mainly controlled by longwave radiation and air temperature and affected by root distribution. Air pressure and stomatal conductance were also important to latent heat flux, and soil solid water content was important to sensible heat flux. Soil temperature was dominated by longwave radiation and air temperature, with crucial surface parameters of initial soil liquid water content and total water content. The atmospheric control factors transitioned to precipitation and air temperature for soil moisture, especially at the shallow layer (5 cm). Meanwhile, the more influential surface parameters were root distribution and stomatal conductance in the warm season and initial soil liquid water content and total water content in the cold season. This work contributes to the research on the land surface processes over the alpine wetland and is helpful to wetland protection.

Key words: alpine wetland, Qinghai–Tibet Plateau, land surface processes, atmospheric factor, surface parameter

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Article Highlights:

- The frozen depth of Zoige alpine wetland is between 20 cm and 40 cm.
- Longwave radiation and air temperature are dominant atmospheric factors controlling land surface processes over the alpine wetland.
- Root distribution and liquid water content have greater influence on heat fluxes and water and heat transfers within the soil, respectively.

1. Introduction

The Qinghai–Tibet Plateau (QTP) is characterized by complex and diverse topographic features, and there are significant differences in water, heat, and momentum flux exchange under different underlying surfaces (Luo et al., 2018; Sun et al., 2020). To obtain a good understanding of the land surface processes on the QTP, a series of atmospheric science experiments have been carried out since the 1970s,

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such as the Qinghai–Tibet Plateau meteorological science experiment and the third Tibetan Plateau atmosphere scientific experiment (Zhao et al., 2018). The water and heat exchanges between the land and atmosphere are generally impactful on the QTP due to strong solar radiation and are further considerably regulated by the complex terrain (Lu et al., 2020). In the pre-monsoon period, sensible heat flux is the major energy source delivering heat to the atmosphere, whereas latent heat flux is greater than sensible heat flux during the monsoon season (Li et al., 2015). Additionally, the transfers of water and heat in the soil reinforce the complexity of land–atmosphere interactions (Ma et al., 2022). Soil water content changes surface albedo, heat capacity, and vegetation growth conditions, and soil temperature affects soil water movement and transformation processes, further affecting the energy and water cycles (Chen et al., 2018).

As an important component of the QTP, alpine wetland is one of the most climate-sensitive and ecologically vulnerable areas (Chen et al., 2020). Its responses to climate changes have varied spatially and temporally due to different geographic environments, variety of wetland formation, and human disturbances (Wang et al., 2020). The water and heat transfers over the alpine wetland have important ecological functions, such as water supply (Elias et al., 2001) and climate regulation (Wong et al., 2017). The wetland area decreased overall at a rate of 0.23% yr^{-1} on the QTP during 1970–2006 (Zhao et al., 2015), and the areas of freshwater marsh, salt marsh, and wet meadow declined by 46.6%, 53.9%, and 15.6%, respectively, from 1970–2010s (Xue et al., 2018). The evapotranspiration of wetland is mainly supported by the soil water from lateral flow from the melting of upstream glaciers and snow (Wang et al., 2022), although the surface still becomes dry and the runoff has been decreasing with continued climate warming (Zhang et al., 2016). Furthermore, there are many studies on the classification, information extraction, biodiversity, greenhouse gases, landscape diversity, and degradation over the alpine wetland (Jiang et al., 2017; Maucieri et al., 2017; Kaplan and Avdan, 2019; Orimoloye et al., 2020). However, the mechanisms of water and heat exchanges among soil, alpine wetland surface, and atmosphere, as well as the influences of atmospheric forcing factors and surface parameters have rarely been discussed up to now due to the lack of the observations.

This study aims to investigate the characteristics of hydro-meteorological factors over the alpine wetlands in the warm season (June–August) and cold season (December–February) with in situ observations from the Zoige Plateau Wetland Ecosystem Research Station of the Chinese Academy of Sciences. Combined with the latest version of the Community Land Model (CLM) 5, the contributions of atmospheric factors and new surface parameters in the CLM5 to the water and heat transfers among soil, alpine wetland surface, and atmosphere are also evaluated. This research will help advance our understanding of the land surface processes over the alpine wetland on the QTP and holds great significance for the optimization of parameterization schemes in the model.

2. Study area and data

The Zoige Alpine wetland (7080 km^2) is the largest plateau marsh wetland in the world, located on the eastern margin of the QTP, with an average elevation of approximately 3500 m (Chen et al., 2018). It belongs to the subhumid continental monsoon climate zone, and the mean annual temperature and precipitation were 0.7°C and 645 mm, respectively, during 1975–2011 (Li et al., 2014). The dominant plants are swamp and meadow vegetation, including *Trollius farreri*, *Caltha palustris*, *Carex mulienses*, and *Gentiana formosa*.

The Zoige Plateau Wetland Ecosystem Research Station (Fig. 1) of the Chinese Academy of Sciences (102°48'E, 33°54'N) is a freshwater site in the Flower-lake Natural Reserve, with a T-200B precipitation rain gauge, a set of eddy-covariance systems (HMP155A, CSAT3 ultrasonic anemometer, and PTB210), and an ECH20 EC-TM produced

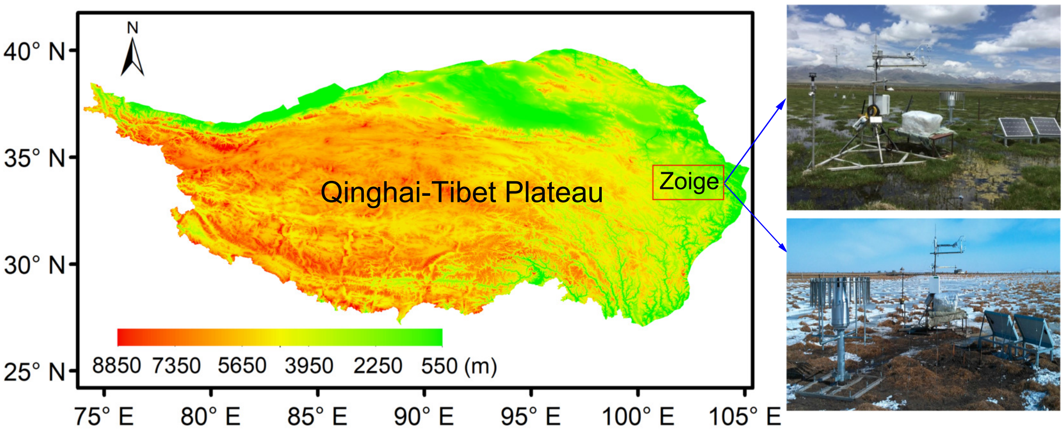

Fig. 1. The geographic location and observational instruments of the Zoige Plateau Wetland Ecosystem Research Station of the Chinese Academy of Sciences (upper right and lower right panels are in the thawing period and frozen period, respectively).

by Campbell Scientific in Utah, USA (Chen et al., 2018). A CR5000 data acquisition unit was used to collect the observations of air temperature, relative humidity, wind speed, air pressure, precipitation, downward and upward shortwave radiation, downward and upward longwave radiation, friction velocity, sensible heat, latent heat, and soil moisture and temperature at five depths (5 cm, 10 cm, 20 cm, 40 cm, and 80 cm) at a frequency of 30 min. Datasets from 2017–18 were divided into warm season (June–August) and cold season (December–February) parts after quality control (Chen et al., 2020), with an energy closure of 0.81.

3. Methodology

3.1. *The calculation of roughness lengths*

The Monin–Obukhov similarity theory was used to describe flux–gradient relationships in a surface layer. Land surfaces have diverse responses to airflow, which can be indicated by the aerodynamic roughness length $Z_{0\mathrm{m}}$ (m), which refers to the height above the ground where the wind speed is zero. The thermal roughness length $Z_{0\mathrm{h}}$ (m) is the height at which the temperature profile is epitaxial to the surface temperature. $Z_{0\mathrm{m}}$ and $Z_{0\mathrm{h}}$ can be calculated with the logarithmic wind profile method (Yang et al., 2008)

$$\ln Z_{0m} = \ln(Z) - \psi_m(\zeta) - ku/u_* \,, \tag{1}$$

$$\ln Z_{0\mathrm{h}} = \ln(Z) - \psi_h(\zeta) - k(T_a - T_0)/P_r T_* \,, \tag{2}$$

$$\zeta = Z/L = ZkgT_*/T_a u_*^2 \,, \tag{3}$$

where Z (=2.5 m) is the observation height, k (=0.4) is the von Kármán constant, u is the wind speed (m), ζ is the atmospheric stability, L is the Obukhov length (m), g (=9.81 m s^{-2}) is the gravitational constant, T_a is the air temperature (K), T_0 is the surface skin temperature (K), P_r (=1, if $\zeta >= 0$ and 0.95, if $\zeta < 0$) is the Prandtl number, u_* is the frictional velocity (m s^{-1}), T_* is the frictional temperature (K), and ψ_m and ψ_h are the integrated stability correction terms for wind and temperature profiles, respectively. According to the universal functions shown in Högström (1996),

$$\psi_\mathrm{m}(\zeta) = \begin{cases} \ln[(1+x^2)(1+x)^2/8] - 2\tan^{-1}x + \pi/2 & (\zeta < 0) \\ -6\zeta & (\zeta \geqslant 0) \end{cases} , \tag{4}$$

$$\psi_\mathrm{h}(\zeta) = \begin{cases} 2\ln((1+y)/2) & (\zeta < 0) \\ -7.8\zeta & (\zeta \geqslant 0) \end{cases} , \tag{5}$$

$$x = (1 - 19.3\zeta)^{1/4},\ y = 0.95(1 - 11.6\zeta)^{1/2}. \tag{6}$$

Following the Monin–Obukhov similarity theory, T_* can be obtained from the sensible heat flux calculation scheme as follows:

$$T_* = -H/(\rho c_\mathrm{p} u_*) \,, \tag{7}$$

where H is the sensible heat flux (W m^{-2}), ρ is the air density (kg m^{-3}), and c_p (=1004 J (kg K)$^{-1}$) is the specific heat of air at constant pressure. T_0 is converted from the observed upward longwave radiation ($L\uparrow$) and downward longwave radiation ($L\downarrow$):

$$\varepsilon\sigma T_0^4 = L\uparrow - (1-\varepsilon)L\downarrow \,, \tag{8}$$

where ε (=0.975) is the spectral radiance and σ [=5.67× 10^{-8} W (K^4 m^2)$^{-1}$] is the Stefan–Boltzmann constant.

3.2. *Numerical simulations*

The CLM5 has been updated with notable improvements in soil and plant hydrology, snow density, carbon and nitrogen cycling and coupling, river modeling, and crop modeling (Lawrence et al., 2019). It has been used in many previous studies for the simulations of heat and water transfer processes. The forcing datasets for the CLM5 include air temperature, relative humidity, wind speed, air pressure, precipitation, and downward shortwave radiation and longwave radiation at a frequency of 30 min. To check the main atmospheric factors controlling the heat flux transfer between the atmosphere and alpine wetland surface and the changes in soil moisture and soil temperature, a set of point sensitivity tests (shown in Table 1) were carried out for air temperature, relative humidity, air pressure, precipitation, and downward shortwave radiation and longwave radiation with two perturbations (25% increase (IN) and 25% decrease (DE) of default values). In addition, the influences of two new surface parameters [Medlynslop (Med) and Rootprof_beta (Root)] and the initial soil water states [Initial soil solid water content (Solid), Initial soil liquid water content (Liq), and Initial soil water content (SW)] were also evaluated with IN and DE tests, and the results are summarized in Table 1. Medlynslop and Rootprof_beta represent the influences of stomatal conductance and root distribution, respectively. The CLM5 has 15 soil layers, ranging from 0.0071 m to 35.1776 m. Due to different frozen characteristics of soil moisture and soil temperature over the alpine wetland (section 4.1), the 5-cm

Table 1. Sensitivity tests for atmospheric variables and surface parameters.

Factors	+25%	−25%
Relative humidity	IN_RH	DE_RH
Longwave radiation	IN_LR	DE_LR
Air pressure	IN_AP	DE_AP
Precipitation	IN_P	DE_P
Air temperature	IN_AT	DE_AT
Shortwave radiation	IN_SR	DE_SR
Medlynslop	IN_Med	DE_Med
Rootprof_beta	IN_Root	DE_Root
Initial soil solid water content	IN_Solid	DE_Solid
Initial soil liquid water content	IN_Liq	DE_Liq
Initial soil water content	IN_SW	DE_SW

depth (thickness is 4.55 cm) and 40-cm depth (thickness is 20.38 cm) were extracted to represent the shallow layer and deep layer, respectively. Land use type was set as 100% wetland, and spin-up (30 yr) was performed before the model reached a steady state.

4. Results

4.1. *Characteristics of hydro-meteorological factors*

Figure 2 shows the variations in heat fluxes in the warm season and cold season and the changes in soil moisture and soil temperature. The diurnal sensible heat flux and latent heat flux were unimodal in both the warm season and cold season, with peak values at approximately 1400 LST (Local Standard Time; LST = UTC +8 h). The fluctuation of sensible heat flux was greater before 1600 LST in the cold season and during 1600–2300 LST in the warm season, respectively, while the latent heat flux was always greater in the warm season than in the cold season. As shown in Fig. 2c, soil moisture was greater than 0.6 $m^3 m^{-3}$ in the alpine wetland during the thawing period. It is noteworthy that the freeze mainly occurred in the shallow layers (5 cm–20 cm), and soil moisture was always within 0.6 $m^3 m^{-3}$–0.8 $m^3 m^{-3}$ in the deep layers (40 cm and 80 cm) during the cold season. This is supported by the observation shown in Fig. 2d, in which the soil temperature was above 0°C in the deep layers. Therefore, 5 cm–20 cm and 40 cm–80 cm were regarded as shallow layers and deep layers, respectively. Soil temperature decreased from August until February in the shallow layers. It was hysteretic in the deep layers.

On account of great differences in water and heat transfers in the warm season and cold season, the characteristics of atmospheric factors and land surface parameters might also vary with season. Figure 3 shows important atmospheric and land surface factors. The friction velocity was positively correlated with wind speed, and it had a greater increasing rate in the cold season than in the warm season. Air temperature and surface temperature were below 0°C at 1800–0800 LST, and during this time they were mostly in agreement in the warm season and cold season. The surface temperature was higher than the air temperature in the daytime. The crest value of the surface temperature occurred at 1400 LST, and the maximum air temperature was delayed to approximately 1600 LST. Notably, the surface temperature was higher in the cold season than in the warm season in the afternoon (specifically from 1100–1800 LST). This might be due to the great evaporation in the warm season. Figures 3c–d show the frequency distributions and sliding averages of the aerodynamic roughness length (Z_{0m}) and thermal roughness length (Z_{0h}). They were each assigned the results of their crest values. Z_{0m} was greater in the cold season than in the warm season, with values of 0.039 m and 0.064 m, respectively. However, Z_{0h} was greater in the warm season, and Z_{0h} was an order of magnitude smaller than Z_{0m} in the cold season.

4.2. *Atmospheric control factors*

Water and heat interactions between land and atmosphere are mainly controlled by radiation transfer and water vapor transfer, corresponding to incident shortwave and longwave radiation and relative humidity and precipitation, respectively. In addition, air temperature and air pressure also impact water and heat transfer as driving factors in the land surface models. To check the influences of atmospheric fac-

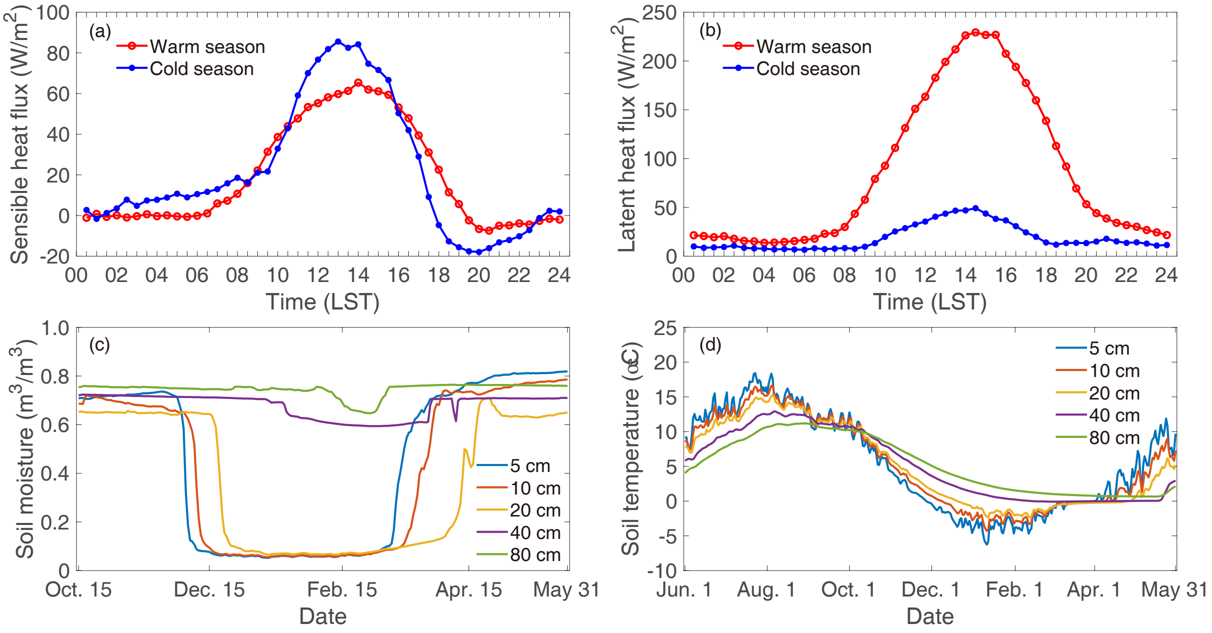

Fig. 2. The characteristics of water and heat budgets over the alpine wetland [(a) and (b) are diurnal variations of heat fluxes in the warm season and cold season; (c) and (d) are soil moisture and soil temperature at five soil depths].

tors on the transfers of sensible heat and latent heat flux in the warm season and cold season, sensitivity tests were performed and are shown in Fig. 4. The 5-cm depth and 40-cm depth were selected to represent the shallow layer and deep layer, respectively, for their significant fluctuations in time series. The energy was not conserved in IN_AT. Compared to other factors, the changes in incident longwave radiation had a greater influence on sensible heat flux at night in the warm season with an average deviation of 37.0 W m^{-2}, while the most controlling factor during the day was air temperature, followed by incident longwave radiation, air pressure, and incident shortwave radiation. Similar results are found for sensible heat in the cold season, but the influences of longwave radiation and air temperature wane. Their average deviations, compared with the control test, dropped to 23.9 W m^{-1} and 27.7 W m^{-2}, respectively. Latent heat flux

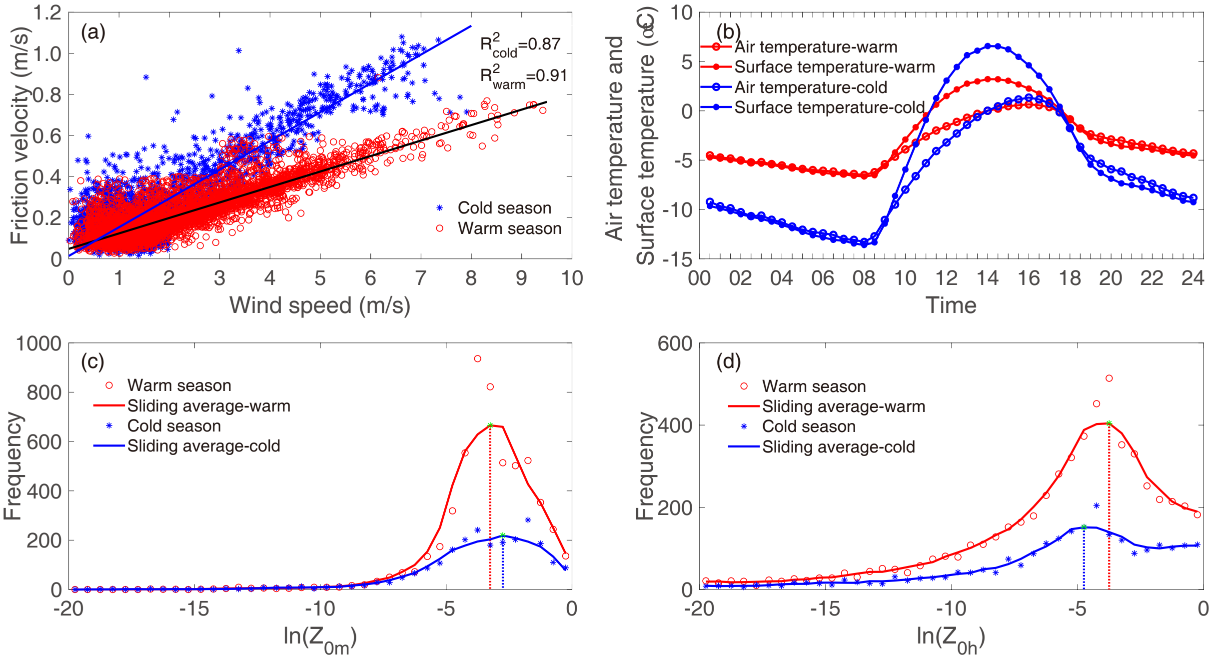

Fig. 3. The characteristics of atmospheric factors and land surface parameters over the alpine wetland [(a), (c), and (d) are frequency distributions of friction velocity, wind speed, aerodynamic roughness, and thermal roughness; (b) is diurnal variations of air temperature and surface temperature].

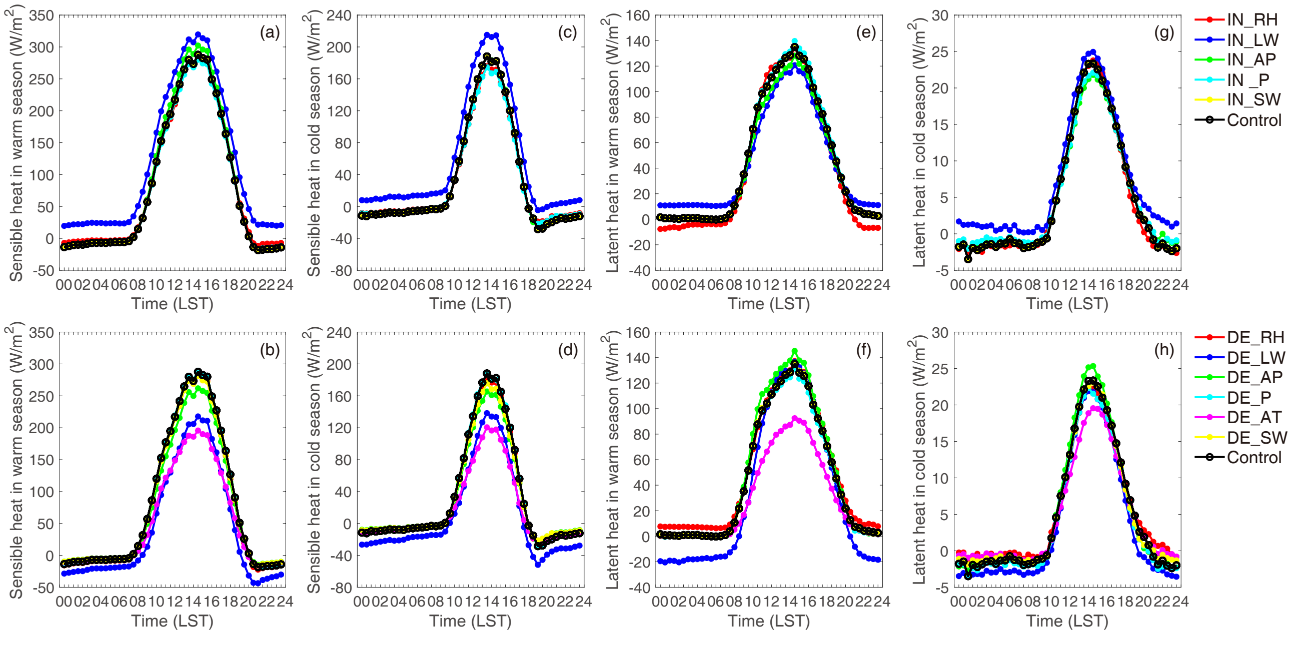

Fig. 4. The sensitivity tests of atmospheric factors affecting heat fluxes in the warm and cold seasons (the first line and second line are 25% increase and decrease of the control test, respectively).

was primarily controlled by incident longwave radiation and relative humidity at night in the warm season. The main influencing factors in the daytime were air temperature and air pressure, and the latent heat flux mainly decreased in DE_AT with an average deviation of 15.5 W m^{-2}. Latent heat flux also changed with incident longwave radiation, relative humidity, and air temperature in the cold season, but the influences of atmospheric factors were negligible compared with sensible heat flux.

Atmospheric factors also impact water and heat transfer within the soil. Figures 5 and 6 show the changes in soil temperature and soil moisture under sensitivity tests in the warm season and cold season. The fluctuation was very significant in the shallow layer. Soil temperature was dependent on incident longwave radiation in both the shallow layer and deep layer in the warm season and cold season. The air temperature was also influential on soil temperature in the shallow layer with an average deviation of 2.5°C. On all accounts, incident longwave radiation and air temperature were control factors whose influences on soil temperature

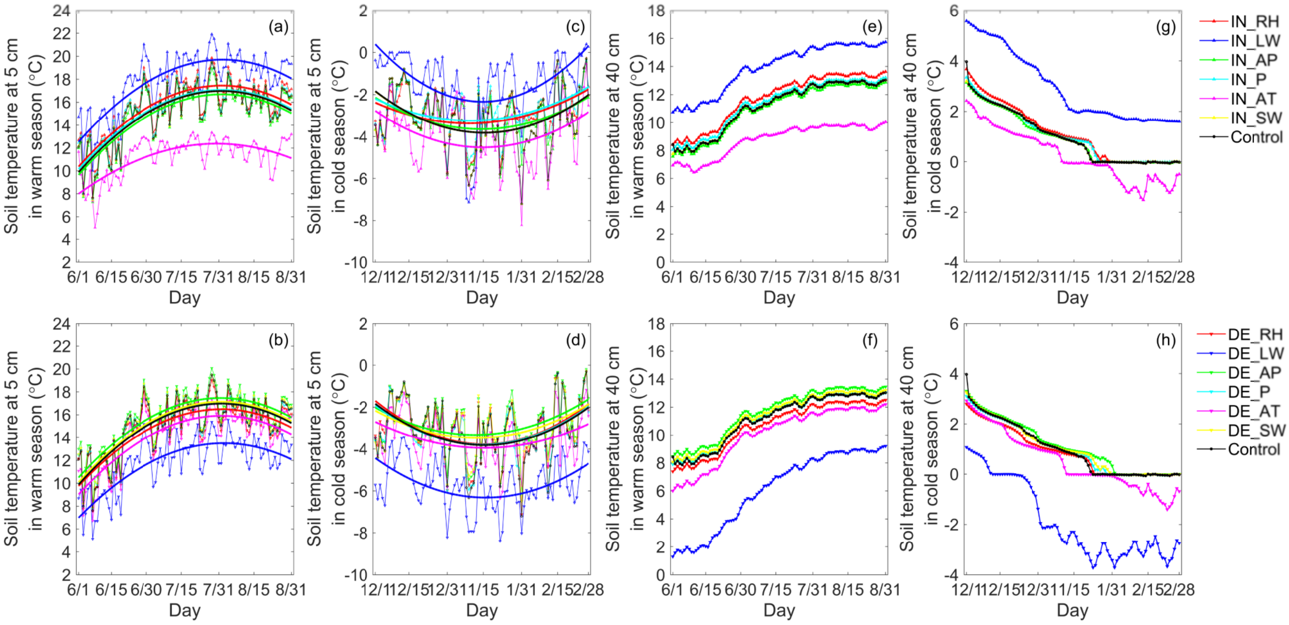

Fig. 5. The sensitivity tests of atmospheric factors affecting soil temperature in the warm and cold seasons [the first line and second line are 25% increase and decrease of the control test, respectively; smooth lines in (a–d) are corresponding nonlinear fittings with correlation coefficients greater than 0.8].

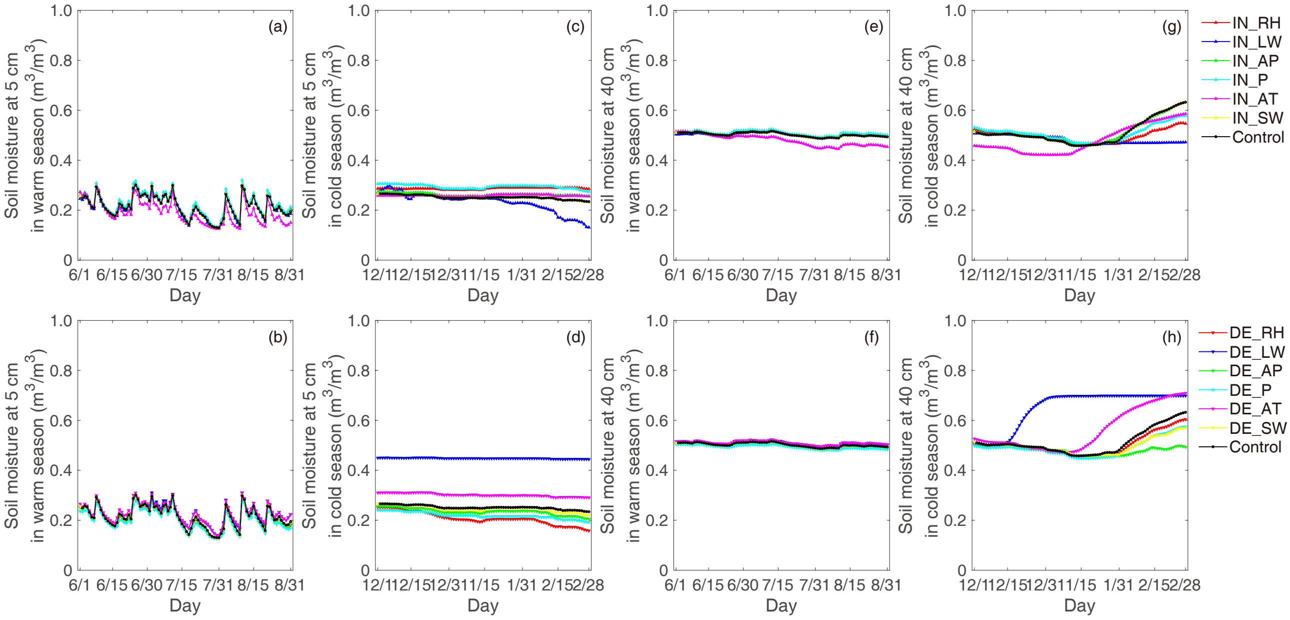

Fig. 6. The sensitivity tests of atmospheric factors affecting soil temperature in the shallow layer (a–d) and deep layer (e–h) in the warm and cold seasons (the first line and second line are 25% increase and decrease of the control test, respectively).

reached the 40-cm depth. Soil temperature decreased with increasing air pressure and incident shortwave radiation and decreasing incident longwave radiation and relative humidity, especially in the warm season. Soil moisture fluctuated at a depth of 5 cm in the warm season. It decreased with increasing incident longwave radiation and air temperature and decreasing precipitation, relative humidity, air pressure, and incident shortwave radiation. The control factors were precipitation and air temperature in the warm season, with a more significant influence on the shallow layer (0.02 m^3 m^{-3} and 0.01 m^3 m^{-3}, respectively). However, the influences of atmospheric factors were greater in the cold season, in which incident longwave radiation and air temperature were more important to soil moisture. In addition, the influences of precipitation and relative humidity were also noteworthy at the 5-cm depth, and air pressure was important to soil moisture at the 40-cm depth.

4.3. *Surface influential variables*

Medlynslop and rootprof_beta are two new parameters in photosynthesis and the plant hydraulic scheme, respectively. A high Medlynslop indicates high stomatal conductance, and rootprof_beta nonlinearly affects vertical root distribution in plant hydraulics (Lawrence et al., 2019). In addition, the initial water states of the soil, including the initial soil solid water content, initial soil liquid water content, and initial soil water content, are also important to water and heat transfer within the soil and between the land surface and atmosphere. Figure 7 shows the influences of those surface parameters on the heat fluxes in the warm season and cold season. Sensible heat flux and latent heat flux were overestimated and underestimated by the CLM5, respectively. Compared to simulations in the warm season, the differences with observations were reduced in the cold season. Sensible heat flux decreased with increasing rootprof_beta and initial soil liquid water content during the day in the warm season, and the most influential parameters were Medlynslop (2.8 W m^{-2}) and rootprof_beta (4.5 W m^{-2}). However, the influences of surface parameters on sensible heat flux diminished in the cold season. Latent heat flux was also mainly influenced by Medlynslop and rootprof_beta, and it decreased with increasing rootprof_beta and decreasing Medlynslop in the warm season, while the influence of surface parameters was negligible in the cold season.

Figures 8 and 9 show the influences of Medlynslop, rootprof_beta, and initial soil water content on water and heat transfer in the shallow soil layer and deep soil layer. Compared to other surface parameters, the initial soil liquid water content and total water content were dominant influences on soil temperature at the 5-cm depth in the warm season. Soil temperature decreased with the initial soil solid water content in the shallow soil layer, but it was the opposite in the deep soil layer. The most influential parameter to soil temperature at the 40-cm depth in the warm season was the initial soil liquid water content with an average deviation of 0.38°C, while the initial soil solid water content was as important as the initial soil liquid water content with the opposite effect in the cold season. Soil moisture increased with decreasing initial soil liquid water content and increasing initial soil solid water content and total water content. It was mainly affected by rootprof_beta and Medlynslop in both the shallow layer (0.004 m^3 m^{-3} and 0.006 m^3 m^{-3}, respectively) and deep layer (0.003 m^3 m^{-3} and 0.004 m^3 m^{-3}, respectively) in the warm season, while the surface control factors were initial soil liquid water content (0.08 m^3 m^{-3}) and total water content (0.07 m^3 m^{-3}) in the shallow layer in the cold season. The influence of the initial soil solid water content was improved to soil moisture in the deep layer.

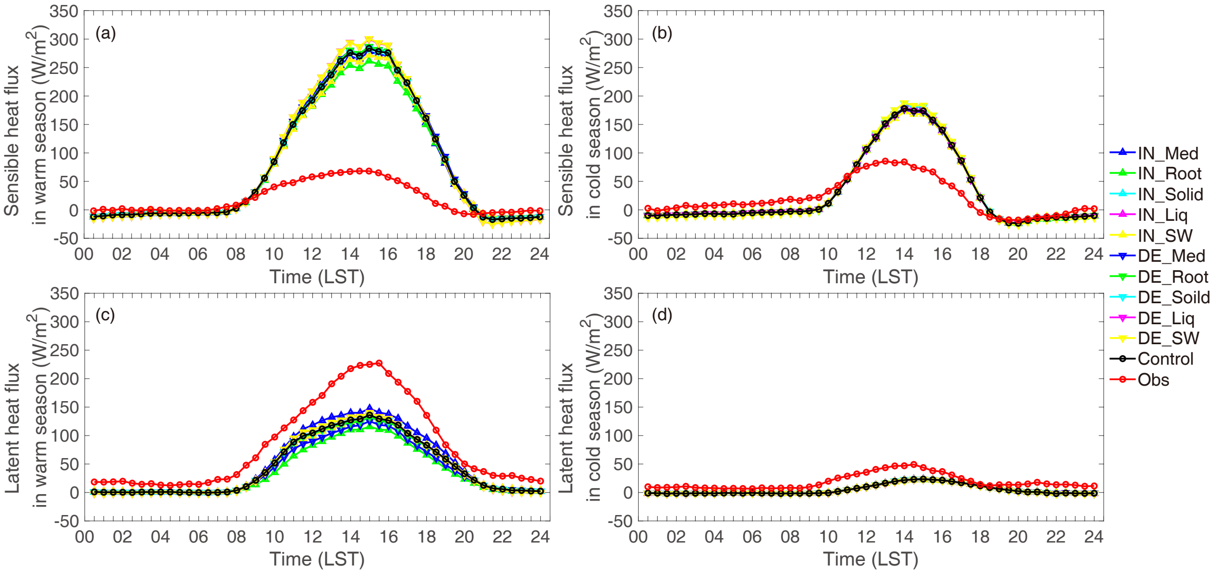

Fig. 7. The sensitivity tests of surface variables affecting sensible heat flux (a–b) and latent heat flux (c–d) in the warm and cold seasons.

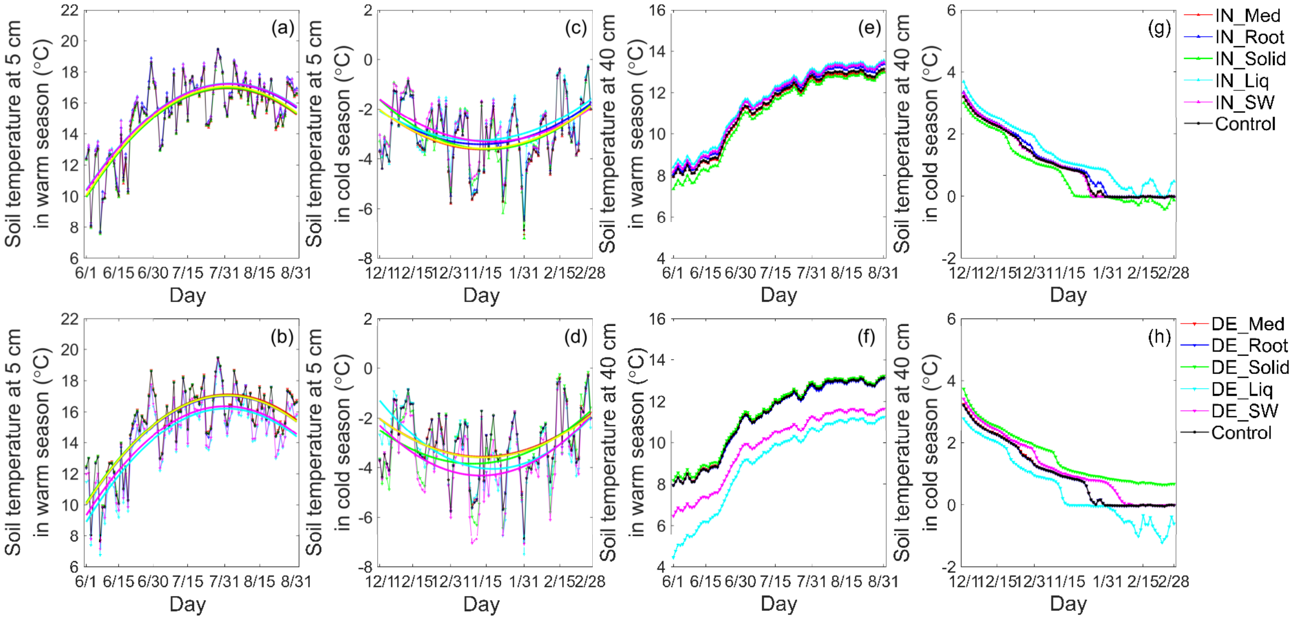

Fig. 8. The sensitivity tests of surface variables affecting soil temperature in the warm and cold seasons [the first line and second line are 25% increase and decrease of the control test, respectively; smooth lines in (a–d) are corresponding nonlinear fittings with correlation coefficients greater than 0.8].

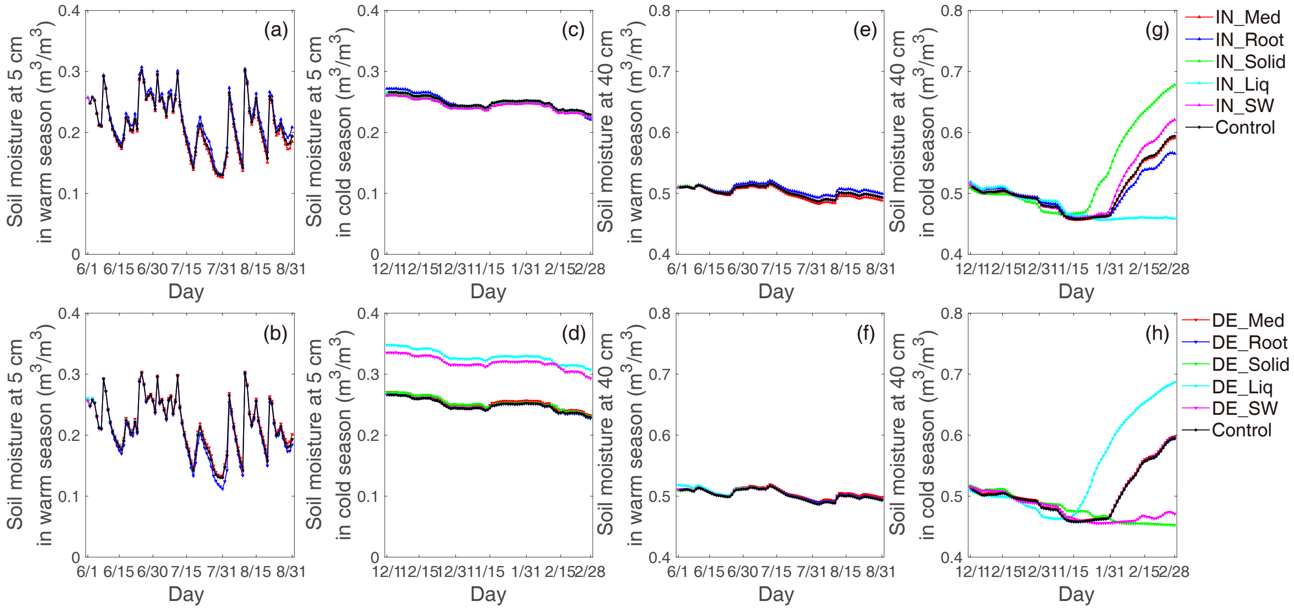

Fig. 9. The sensitivity tests of surface variables affecting soil moisture in the warm and cold seasons (the first line and second line are 25% increase and decrease of the control test, respectively).

5. Discussion

With the advancements of atmospheric boundary layer experiments and in situ observations, there has been great progress on understanding the land surface processes over the alpine wetlands in the QTP. Research has shown that alpine wetland has significant seasonal variations in land–atmosphere energy exchanges (Wang et al., 2022). This study investigated the observations of water and heat exchanges over the Zoige alpine wetland and provided two findings. One is the frozen depth of alpine wetland. The combined results of soil moisture and soil temperature show that the frozen depth of the Zoige alpine wetland is between 20 cm and 40 cm. This information is not only important for scientific understanding but also helpful for wetland conservation and engineering operations. The other finding is that the surface temperature was higher in the cold season than in the warm season in the afternoon (specifically from 1100–1800 LST). This finding is unintuitive because wetland is covered by water and vegetation in the warm season. On one hand, heat from solar radiation can be quickly transferred to deeper layers. On the other hand, evapotranspiration from the underlying surface to the atmosphere is very strong (Cao et al., 2020), which carries a lot of heat. In this study, we also analyzed the controlling atmospheric factors and influential surface parameters to water and heat transfers over alpine wetland and found that longwave radiation, air temperature, and precipitation are the atmospheric factors controlling the land surface processes. Additionally, the importance of surfaces parameters varies between daytime and nighttime and between the warm season and cold season. Some researchers have also investigated the control factors and influencing parameters for water and heat exchanges, and their results have shown that controlling factors vary with underlying surfaces. You et al. (2017) compared surface water and heat exchanges between alpine meadows and bare land and suggested that root turf, canopy, and soil moisture are the main factors affecting energy partition in the hinterland. Soil carbon was found to be the dominant factor controlling the variability of diffusivity in the high latitude permafrost when compared to soil texture, bulk density, and soil moisture (Zhu et al., 2019). It seems that controlling factors vary for underlying surfaces. The robustness of the results is still constrained by the quality of observation data and limitations of the model. Intensive observation, data quality improvement, and parameterization scheme optimization will be helpful in future studies of the important mechanisms to each of the different underlying surfaces on the QTP.

6. Conclusions

The alpine wetland is very sensitive to temperature and precipitation. It plays an important role in runoff regulation. This paper investigated the characteristics of water and heat transfer within the soil and between alpine wetlands and the atmosphere and explored the atmospheric control factors and surface influential variables with in situ observations and the CLM5. The main results are as follows.

(1) Soil frozen depth is between 20 cm and 40 cm over the alpine wetland. The sensible heat flux before 1600 LST was greater in the cold season than in the warm season, while the diurnal latent heat flux was always greater in the warm season. Additionally, the aerodynamic roughness length and thermal roughness length were greater in the cold season and warm season, respectively.

(2) Compared with other atmospheric factors, longwave radiation had a greater influence on heat fluxes at night. Air temperature and longwave radiation were both control factors for sensible heat flux in the daytime. Air temperature and air pressure were control factors for latent heat flux, but atmospheric influences were negligible in the cold season.

(3) Longwave radiation and air temperature were dominant atmospheric factors controlling soil temperature all year round and soil moisture in the cold season. Precipitation and air temperature were more important to soil moisture in the warm season, especially in the shallow layer.

(4) The surface parameters that were most influential on heat fluxes were Medlynslop and rootprof_beta. The initial soil liquid water content was dominant for soil temperature in the warm season, during which soil moisture was slightly affected by rootprof_beta and Medlynslop. Initial soil liquid water content and total water content were the most influential parameters for soil temperature and moisture in the deep layer and shallow layer, respectively, in the cold season.

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