Variations of the Surface Wettability Index over the Tibetan Plateau During 1971–2005*

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ABSTRACT

Based on 1971–2005 monthly mean maximum/minimum temperature, wind speed, relative humidity, sunshine duration, and precipitation data at 25 stations over the Tibetan Plateau, a study of the largest potential evapotranspiration (LPE) is performed by using the Penman-Monteith model. The surface wettability index (SWI) is calculated and examined, together with its space distribution, interannual and seasonal variations, as well as associated causes. The results suggest that the annual area rainfall exhibits a pronounced increasing trend at 15.0 mm per decade; the annual LPE shows a different-degree decrease at –4.6— –71.6 mm/10 yr. In the southwestern Ngari prefecture and Nyalam county, the annual SWI displays insignificant decline trends compared to increasing trends in other areas of Tibet (0.02–0.09 per decade). For Tibet, on average, the SWI experiences a noticeable rise at 0.04/10 yr, particularly in 1981–2005. On a seasonal basis, the SWI shows increasing trends, especially in summer. In the 1970s–1980s, the interannual variation is characterized mainly by lower temperature and lower humidity. From the 1990s, air temperature keeps on rising, leading to an appreciable increase in SWI, displayed as a type of warm and humid climate. The salient increases (decrease) of precipitation and relative humidity (mean temperature daily range) are the principal causes of the greatly enhanced SWI in the region. The pronounced decrease in mean wind and sunshine duration also plays an active role.

Key words: largest potential evapotranspiration, surface wettability index, affecting factors, trend, Tibetan Plateau

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1. Introduction

The global climate warming has been undisputable. As presented in the Fourth Assessment Report of IPCC, global temperature has risen by 0.74°C, on average, for the last century (1906–2005) and 11 of the 12 years suffering the warmest temperature occurred in 1995–2006 since 1850. IPCC (2007) claimed that the temperature rise rate in the past 50 years is almost two times as much as that of the last 100 years. Therefore, study of temperature change becomes the leading topic. On the other hand, more and more scientists are devoted to studying changes in the water regime, that is, the regional humidity pattern (Ci et al., 2002; Shi, 2003; Li et al., 2003). Study of wettability distribution aims to determine the regional largest possible evapotranspiration and the wettability index (Chen and Zhang, 1996; Zhang and Li, 1999). In recent years, many Chinese researchers have made investigations on aridity and wetness in China (Ma and Fu, 2001; Jin et al., 2004; Ma, 2005; Sun and Yuan, 2006; Liu et al., 2006). They discovered that from the 1960s to 1970s there took place an abrupt shift from a wetter to a drier climate, but with different intensities from one region to another in the country. The fluctuation of the climate and the conversion between dry and moist climate types display a marked interdecadal feature (see Yang et al., 2003). During 1961–2000, over east of 100°E in northern China, the borderline between semi-moist and semi-arid climates

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experienced constant fluctuations while marching eastward. The division line made a farther eastward and southward shift in the 1990s compared to that of the 1960s, resulting in the expanded (diminished) semi-arid (semi-wet) area. This implies that the climate is going towards aridity. Over west of 100°E, the area of extreme dryness has been being diminishing and the humidity index is on the increase (Wang et al., 2004). Looking at the Tibetan climate in the past 30 years, we found that temperature and precipitation are on the increase as opposed to the decrease of the largest potential evapotranspiration (LPE) over the plateau, of which most regions show the trend from a dry to a wet climate (Wu et al., 2005). Over the middle valley of the Yarlung Zangbo River, rainfall (LPE) from the mid-late 1980s to 1990s increased (significantly decreased), thus resulting in moistened surface condition (Du et al., 2006).

Analysis of the 1971–2005 trends of change in surface humidity and associated causes over the plateau allows us to differentiate ecological environmental properties between the past and the present and to investigate the causes of changes in the Tibetan ecology, thereby providing scientific basis for studies on future climate change and for the protection and restoration of the ecology there.

2. Data and the SWI definition

A limited number of meteorological stations with not too long observation history are distributed over the vast stretch of Tibet. For objective analysis of the surface wettability, we used the 1971–2005 monthly maximum/minimum temperature, relative humidity, precipitation, wind velocity and sunshine hours from 25 stations (see Fig. 1).

The expression for the surface wettability index (SWI) has the form

$$W = P/ET_0, \tag{1}$$

where W is the SWI, P is monthly rainfall (mm), and ET_0 is monthly LPE (mm). For the LPE calculation the FAO (Food and Agriculture Organization)-recommended and corrected Penman-Monteith model (ET_0) was utilized, which is of the form,

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)}, \tag{2}$$

$$R_n = 0.77 \times (0.248 + 0.752\frac{n}{N})R_{so} - \sigma(\frac{T^4_{\max,k} + T^4_{\min,k}}{2})(0.56 - 0.08\sqrt{e_a}) \cdot(0.1 + 0.9n/N), \tag{3}$$

$$G = 0.14(T_i - T_{i-1}), \tag{4}$$

in which $R_{\rm n}$ is net radiation in M J m^{-2}day^{-1} (Zuo et al., 1993), G is soil heat flux (M J m^{-2}day^{-1}), γ is a humidity constant, Δ is the slope of curve of saturation vapor pressure, U_2 is the wind at 2-m level (m s^{-1}), e_a is actual vapor pressure (hPa), e_s is saturation vapor pressure (hPa), σ is the Stefen-Boltzmann

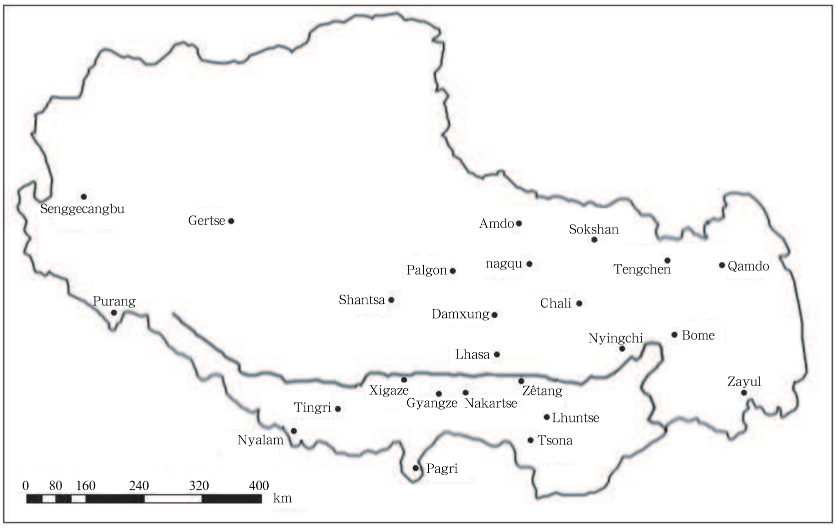

Fig. 1. The distribution of selected stations over the Tibetan region.

constant (4.903×10^{-9}M J $K^{-4}m^{-2}day^{-1}$), $T_{\max,k}$ ($T_{\min,k}$) is the maximum (minimum) temperature at the absolute temperature scale (K), T_i (T_{i-1}) is the mean temperature for the current (previous) month (°C), n (N) is measured sunshine (possible insolation) hours (h), and $R_{\rm so}$ is radiation in clear sky (M J $m^{-2}day^{-1}$).

By arithmetic averaging, the seasonal features of the related meteorological elements are obtained from the series of annual rainfall, mean temperature, LPE and SWI, with December-February denoting winter, March–May spring, June-August summer, and September–November autumn. The climatic characteristics of Tibetan SWI in the study period are examined.

The trend of meteorological variables is estimated by

$$Y = a_0 + a_1 t, \tag{5}$$

where Y stands for a meteorological factor, t for time, a_0 a constant term, and a_1 the linear trend, with $a_1\times10$ denoting the climatic tendency rate per decade.

3. Analysis of results

3.1 Precipitation tendency rate

Table 1 shows that on average, the 1971–2005 (1981–2005) rainfall exhibits a pronounced increasing trend at 15.0 (28.8) mm per decade for the Tibetan region, and the 1971–2005 seasonal precipitation is on the increase, too, with the summer increase reaching 8.8 mm per decade, such being the case for 1981–2005 seasonal rainfall except winter. And the trends seem to further intensify in future, especially in summer which is crucial to plant growth. As shown in Table 1, the summer tendency rate reaches 21.9 mm per decade in this season.

Table 1. Tendency rates of annual and seasonal rainfall, LPE, and SWI over 1971–2005 and 1981–2005

Element	Time interval	Spring	Summer	Autumn	Winter	Annual
Rainfall	1971–2005	3.3△	8.8	1.7	1.1	15.0▲
(mm per decade)	1981–2005	5.3▲	21.9▲	2.3	–0.8	28.8★
LPE	1971–2005	–5.2▲	–2.9★	–5.4★	–7.5★	–24.0★
(mm per decade)	1981–2005	–5.9	–13.3★	–7.9★	–7.1★	–34.3★
SWI	1971–2005	0.02▲	0.07▲	0.03	0.02△	0.04★
(1 per decade)	1981–2005	0.03▲	0.14★	0.05	–0.001	0.06★

Note: superscripts △, ▲ and ★ denote, respectively, the significance at the 10%, 5%, and 1% levels.

3.2 The largest potential evapotranspiration

According to the climatic LPE tendency rates in 1971–2005 for all the stations except Purang (Fig. 2a), a decline at –4.6— –71.6 mm per decade is shown, with the results for 76% of the stations being significant at the <10% levels, and the maximal decline observed at Tesdang station (–71.6 mm per decade), next being at Zayul (–52.9 mm per decade).

From the space distribution of LPE trends on a seasonal basis, it is found that insignificant increases (1.6–3.8 mm per decade) appear in Ngari and Nyingri prefectures as well as Chali county in spring, in contrast to the decreasing trends of –1.3— –23.2 mm per decade for most of the other parts of the Tibetan region, with the biggest drop at Tesdang (significant at the 1% level). In summer (Fig. 2b), all the stations show reducing LPE trends (–1.9–17.2 mm per decade) except the Purang and Tsona counties that witness the unchanged LPE, with the biggest drop of 17.2 mm per decade at Tesdang. In autumn, little change in LPE is seen in the southern part of the Shannan prefecture and Bome county, but the LPE decreases by –1.2— –18.4 mm per decade for the other areas, with the maximum drop at Tesdang (–18.4 mm per decade) that is significant at the 1% level. In winter, the LPE trends increase by ∼1.5 mm per decade in the Nyingri prefecture and Purang county, and for most of the other parts declining trends occur by –2.2— –14.2 mm per decade, with 70% of the stations passing the significance tests at the 10% level and beyond.

Table 1 shows that for the whole region, the yearly

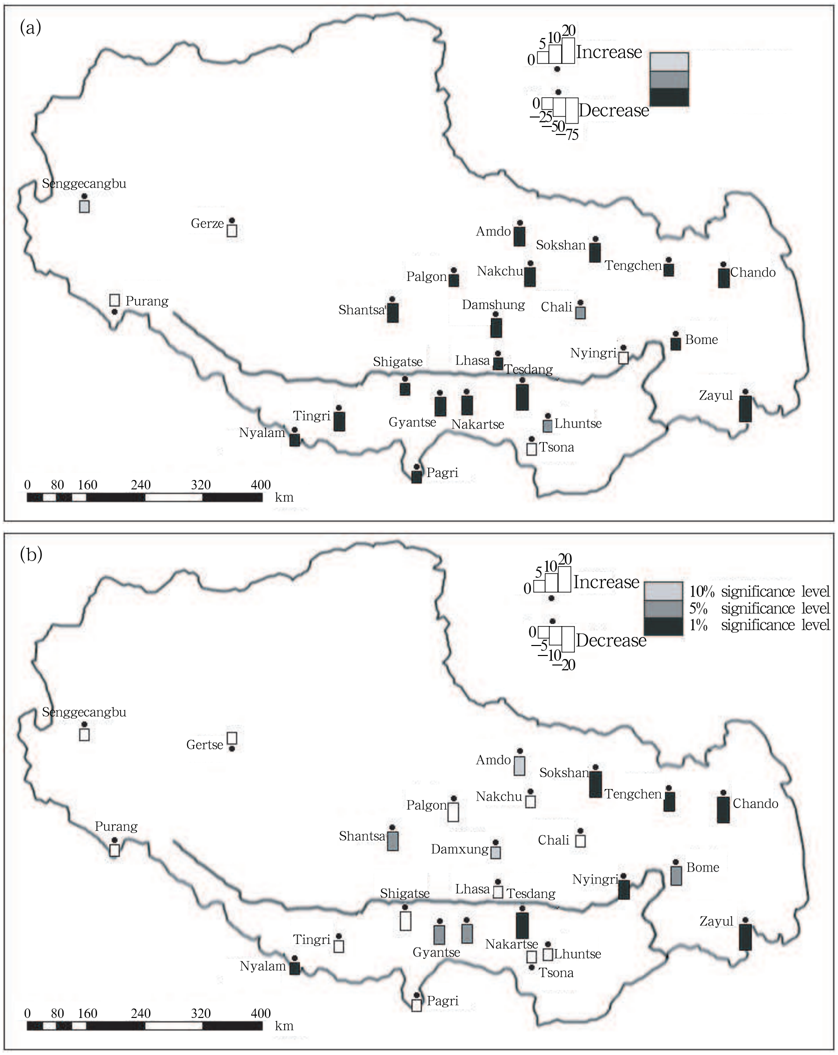

Fig. 2. Yearly (a) and summer (b) mean distributions of the 1971–2005 LPE climatic tendencies (mm per decade) over the Tibet.

averaged LPE in 1971–2005 is decreased by –24.0 mm per decade and the seasonal trends are all negative (decreasing), with the largest drop in winter at –7.5 mm per decade. All the seasons but winter in 1981–2005 show that the LPE decrease is enhanced by –5.9— –13.3 mm per decade, with the maximum in summer, and the annual LPE is decreasing by –34.3 mm per decade, suggesting that the LPE declining trends in the Tibetan Plateau are quite strong.

3.3 Variation of the surface wettability index

Figure 3 depicts the change of SWI over 1971–2005, indicating that in southwestern Ngari prefecture and Nyalam county the SWI exhibits marginally decreasing trends at –0.01— –0.02 per decade in contrast to the increasing trends (0.02–0.09 per decade) for other zones (the figures from 13 stations are significant at the 10% level and beyond). The pronounced increase of > 0.06 per decade in SWI is found over the Nyingchi, northern Qamdo, and eastern Nakchu prefecture.

According to the seasonal mean tendency rates of SWI, Purang in spring shows a decrease at –0.05 per decade (significant at the 10% level); in much of the Ngari prefecture, western Nakchu prefecture and SW Shigatse, the SWI changes little in contrast to 0.02–0.12 per decade for other zones of the Tibetan region (four stations with figures significant at the <10%

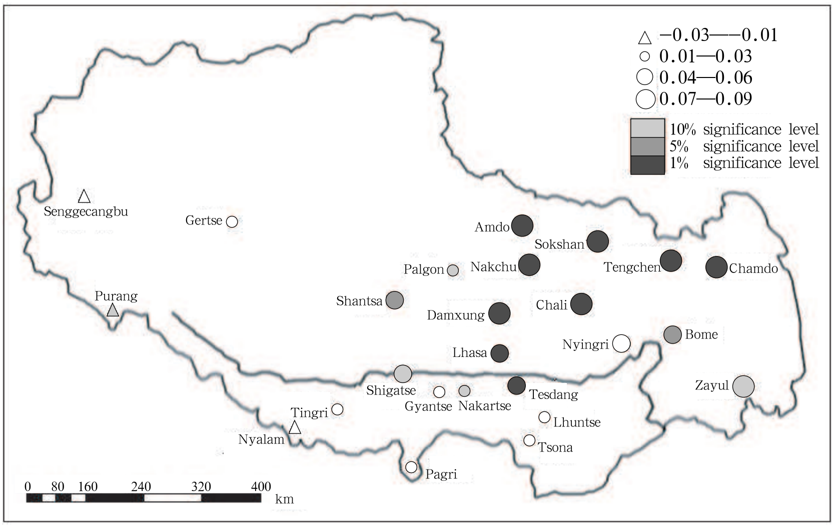

Fig. 3. The distribution of 1971–2005 climatic tendencies of SWI over the Tibet.

level), with 0.12 per decade for Bomi county. In summer, the SWI of southwest Ngari, Nyalam and Tsona shows decreasing trends (–0.01— –0.03 per decade), with the maximum drop at Purang, while other stations display increasing trends ranging over 0.02–0.26 per decade (the maximum rise is significant at the 1% level at Nyingri station). In autumn, no great change of SWI occurs in Ngari and Bome but an insignificant drop happens in Ngari, with –0.18 per decade as the biggest drop in Nyalam, the increases of 0.02–0.21 every decade at other stations, and the largest increase at the 1% significance level at Tengchen. In winter, for Ngari and the Yarlung Zangbo River, Lhasa River, and Nianchu River basin as well as in Nyingri, the SWI changes within ±0.01 by contrast to the increasing trends in other zones at 0.02–0.19 per decade, the largest figure being for the Pagri station.

The averaged annual SWI in 1971–2005 displays a noticeable increasing trend (Table 1) of 0.04 per decade. Particularly in 1981–2005, the increase is 0.06 per decade. The seasonal SWI shows increasing trends, too, especially in summer (0.07 per decade). The seasonal SWI (with exclusion of winter) in 1981–2005 increase to different degrees, with 0.14 per decade in summer.

In addition, through the analysis of departures (Fig. 4) found by an 11-yr moving method for summer, winter and annual SWI (denoting the dryness or wetness) and also temperature (for cold or warm air), we come to the following conclusions:

(1) In the summers of the 1970s, the Tibetan SWI is lower and temperature is cooler, displaying the interannual variations featured mainly by a cold and dry climate. In the early and mid 1980s, temperature is normal and SWI is in negative departures. From the late-mid 1990s to the first 5 yr of the 21st century, both temperature and SWI are higher than the mean, exhibiting an interannual feature dominated by a warm and moist climate.

(2) In the 1970–1974 winters, there occurred higher temperature and lower humidity, while SWI and temperature were in negative anomalies in the late 1970s, suggesting a type of dry and cold climate. From the mid-late 1980s to the 1990s higher temperature and humidity occurred as an interannual feature. Over 2000–2004, temperature and SWI are higher than normal, showing the dominance of a warm and wet climate in the plateau.

(3) For anmual mean, from the 1970s to 1980s the interannual climatic properties are dominantly lower temperature and humidity. From the mid-late 1990s to 2005 temperature is increased and SWI is higher than the mean, indicating a warm and wet climate.

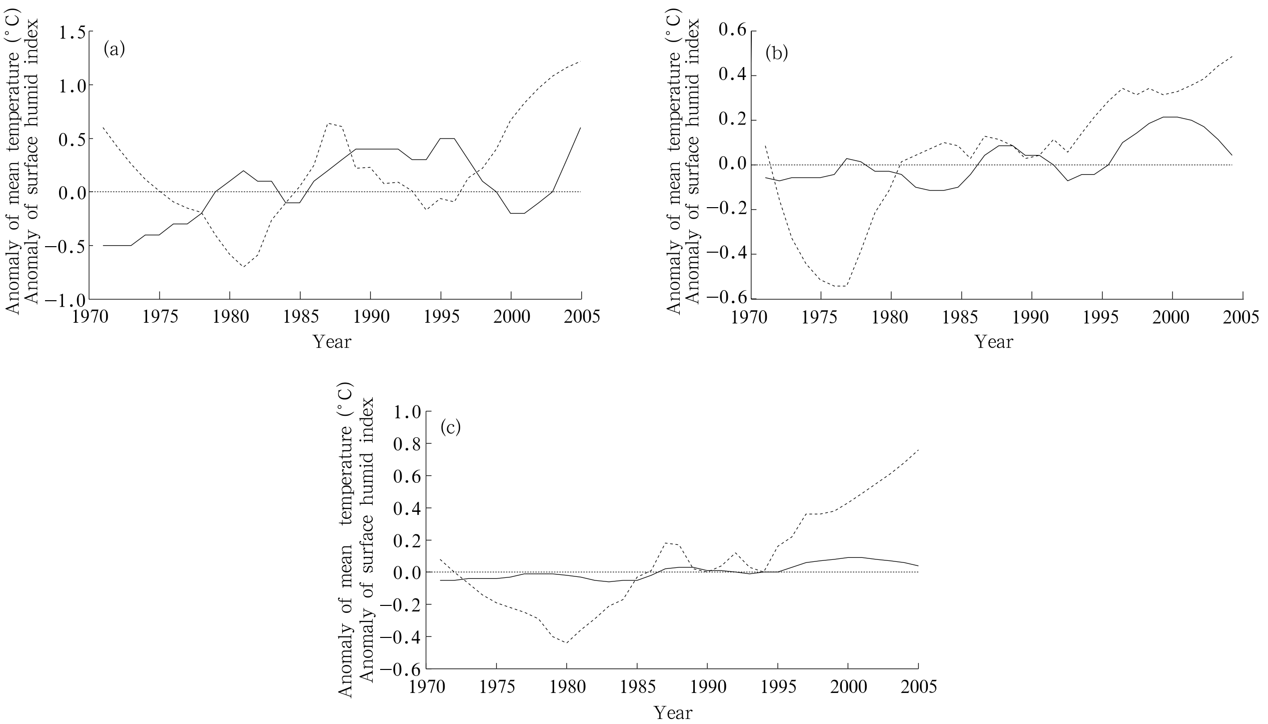

Fig. 4. 1971–2005 departures of SWI (full line) and mean temperature (dashed line) for (a) winter, (b) summer, and (c) annual mean over the Tibet.

3.4 Meteorological variables affecting the SWI

According to its definition, the SWI depends on precipitation and LPE. In 1971-2005, the two factors experienced appreciable variations. The climate regime (drying or wetting) hinges upon their changes. The LPE is influenced by interactions among relative humidity, temperature, radiation, and wind.

3.4.1 Changes in variables associated with LPE

Examining the climatic tendencies of factors affecting LPE (Table 2) yields that the annual sunshine duration (insolation) shows a great reducing trend at –31.1 h per decade, and except the winter case, the seasonal drop ranges over –3.52— –23.30 h per decade, with the maximum appearing in summer. The annual mean wind diminishes at –0.27 m s^{-1} per decade, with the seasonal trends ranging over –0.22— –0.32 m s^{-1} per decade mainly in winter and spring. The seasonal relative humidity shows increasing trends ranging over 0.70%–3.20% per decade and annual relative humidity increases at 1.66% per decade.

Table 2. Climatic tendencies (per decade) of meteorological factors contributing to Tibetan LPE

Period	Insolation h	mean wind m s^{-1}	RH %	MT °C	MT$_{max}$ °C	MT$_{min}$ °C	MDTR °C
Spring	–5.0	–0.29★	1.77★	0.25▲	0.15	0.39★	–0.24★
Summer	–23.3★	–0.22★	0.70	0.24★	0.10	0.40★	–0.30★
Autumn	–3.5	–0.23★	0.87△	0.26★	0.15	0.37★	–0.21△
Winter	0.9	–0.32★	3.20★	0.26△	0.15	0.41★	–0.26▲
Annual	–31.1★	–0.27★	1.66★	0.25★	0.15▲	0.39★	–0.24★

Note: RH=relative humidity, MT=mean temperature, MT$_{max}$=mean maximum temperature, MT$_{min}$=mean minimum temperature, MDTR=mean daily temperature range. For the meanings of △, ▲, and ★, refer to the note of Table 1.

Additionally, annual mean temperature in 1971–2005 displays a strong increasing trend at 0.25°C per decade, such being almost the case for the change in seasonal temperature (∼0.25°C). Increases in annual and seasonal mean minimum (maximum) temperature range over 0.37–0.41°C (0.10–0.15°C) per decade, with the winter increase in the minimum temperature being the greatest. The trend of annual (seasonal) mean temperature daily range is –0.24°C (–0.21— –0.26°C) per decade. Obviously, the air temperature change does not act as the main factor for LPE decrease but the pronounced reduction of temperature daily range has some association with the LPE drop.

3.4.2 Reasons for the enhanced SWI

As shown in Tables 1 and 2, the LPE decrease rate exceeds the increase rate of precipitation in 1971–2005, and the enhanced SWI is linked less to increased rainfall than to the significantly diminished LPE, which is one of the main factors for climate wetting. As we know, wind velocity and insolation are important elements influencing LPE, so their appreciable decreases explain, to a great extent, the LPE declining trend. Noticeable increase (decrease) in relative humidity (temperature daily range) is crucial to the decrease in evaporation, too.

To expound the relationship between environmental factors and SWI, a general survey was conducted as to the correlations between SWI and associated climate variables (Table 3), where we see that SWI bears a negative correlation to sunshine hours, with the seasonal coefficients in excess of –0.53 (except winter), reaching –0.89 for summer. This suggests the innegligible effect of decreased sunshine duration on the increase of SWI. The SWI is positively correlated with rainfall and relative humidity, meaning that the increased precipitation associated with the increased relative humidity leads to higher SWI. The SWI bears a negative correlation with mean wind, implying that reduced wind causes increased SWI. Besides, a higher negative correlation is found between SWI and the temperature daily range, with the maximum correlation coefficient more than –0.59. It follows that the decreased mean temperature daily range is likely to play a dominant role in the increase of SWI.

Table 3. Correlation coefficients between SWI and a range of meteorological factors in 1971–2005 over the Tibet

Period	MSD	MW	RH	MT	MT_{max}	MT_{min}	MTDR	LPE	Rainfall
Spring	–0.53★	–0.39▲	0.57★	–0.11	–0.23	0.21	–0.59★	–0.51★	0.95★
Summer	–0.89★	–0.42▲	0.85★	0.08	–0.43★	0.62★	–0.87★	–0.80★	0.98★
Autumn	–0.74★	–0.31△	0.70★	0.03 ★	–0.27	0.45★	–0.77★	–0.65★	0.97★
Winter	–0.10	–0.29△	0.49★	–0.18	–0.37▲	0.08	–0.60★	–0.47	0.92★
Anumal	–0.66★	–0.54★	0.76★	0.46★	0.19	0.70★	–0.71★	–0.66★	0.94★

Note: MSD = mean sunshine duration, MW = mean wind; Others are the same as in Table 2. For the meanings of △, ▲ and ★, refer to the note of Table 1.

Analysis of the correlaton reveals that enhanced precipitation and relative humidity as well as marked reduction in temperature daily range bear a close relation to the SWI increase, while the diminution of sunshine duration and wind exerts less effect on the SWI.

4. Conclusions and discussion

The Penman-Monteith model is utilized to calculate the largest potential evapotranspiration (LPE), with which surface wettability index (SWI) is formulated and examined based on the 1971–2005 observations. An analysis is undertaken of their climate tendency rates, together with investigation of meteorological elements influencing SWI. The following conclusions are obtained.

(1) The 1971–2005 annual precipitation shows a marked increasing trend at 15.0 mm per decade, especially in 1981–2005. The seasonal rainfall also displays an intensifying trend, mainly in summer. The annual LPE indicates a great reducing trend at –24.0 mm per decade. The seasonal LPE exhibits declining trends, with the biggest drop showing up in winter.

(2) The annual SWI shows a noticeable increasing trend at 0.04 per decade, with 0.06 per decade in 1981–2005, a condition that favors the amelioration of the Tibetan ecology, especially for the arid and semiarid climate of the western Nakchu zone and western Shigatse district where the desertification may be thus suppressed to some degree.

(3) In terms of the annual mean, the Tibetan climate is marked mainly by lower temperature and humidity in the 1970s and 1980s. It is changing into a climate featured by a constant rise in temperature and a significant increase in SWI, suggestive of the occurrence of a warm and wet climate from the 1990s.

(4) In the period of 1971–2005, the pronounced increase in rainfall and relative humidity and the salient reduction of mean temperature daily range over the Tibetan region are the principal causes of the significantly enhanced SWI. In addition, the impacts of the significant decline of mean wind and sunshine duration on the increased SWI are by no means ignorable.

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