

Research Article

Analysis of Long-Term Meteorological Observation for Weather and Climate Fundamental Data over the Northern Tibetan Plateau

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Meteorological observation plays a critical role in climatic study, and in situ measurements are the foundation of meteorological observation, especially in the Tibetan Plateau, the surface of which is fairly complex. Several field stations in the Northern Tibetan Plateau, which features relatively homogeneous surface, were selected as the study area. A detailed description on the significance of site observation for climate prediction was given in this paper. Data from weather stations can be used to verify satellite data and provide parameters for initial mode field in the study of weather and climate changes. The field observation data in the Northern Tibetan Plateau from 2001 to 2013 is analyzed. The results show that in El Nino year, values of land surface temperature (T_s), air temperature (T_a) and wind speed are all greater than their mean values and that soil moisture values are lower than the averaged, while the opposite is the case in La Nina year. The warming rate in the Northern Tibetan Plateau is greater than that in global areas. The diurnal variations of T_s and T_a are various in different seasons and underlying surfaces, with the diurnal variations greater in spring, and less in summer and autumn. Furthermore, the diurnal variation in the area with drier underlying surface is more obvious than that in area with moist surface.

1. Introduction

It is well recognized that the Tibetan Plateau plays an important role in the East Asian and global climate because of its high elevation and complex surface conditions. The land surface of the Tibetan Plateau reaches elevations of greater than 4000 m above sea level, which is about a third of the height of the troposphere. It interacts with the atmosphere through radiation, sensible heat flux, and latent heat flux, and because of its topographic condition, the Tibetan Plateau exerts profound dynamical and thermal influences on Asian monsoon, the atmospheric circulation, and global climate change [1–3]. The huge heat source certainly has an effect on the vertical circulation over the plateau and its surrounding areas. The heat source can impact Chinese precipitation in

summer by changing the intensity of the East Asian monsoon [4].

Decades of research on the Tibetan Plateau indicates that the plateau plays a vital part in the East Asian and global weather and climate prediction. Then the long-term meteorological observation in the plateau is essential and crucial for the research. Scientists have started to observe the atmospheric condition over the Tibetan Plateau systematically since 1970s. The first atmospheric science experiment on the Tibetan Plateau in 1979 (QXPME-1979) was performed by Ye and Gao. In that field experiment, the variation and distribution characteristics of each component in the land surface radiation balance and heat balance were analyzed, and the changing process of the heat source has been well understood [5–9]. Afterwards, the second atmospheric

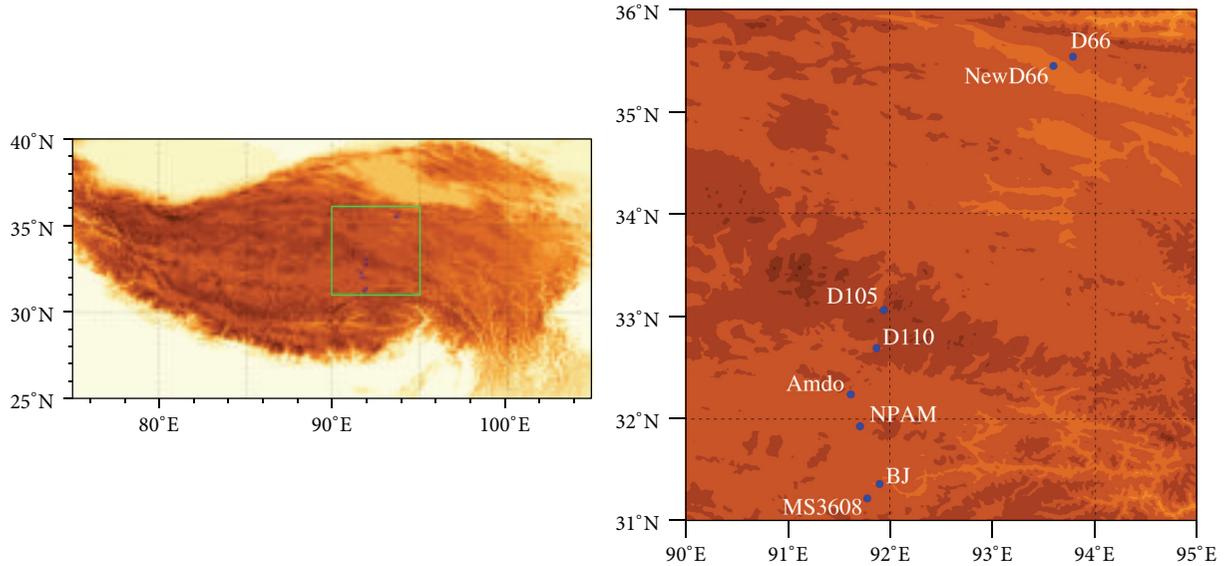


FIGURE 1: Map for the observation area and locations of stations in the Northern Tibetan Plateau.

science experiment on the Tibetan Plateau (TIPEX) was started in 1998. With the attention for the influence of the atmospheric hydrological process on the Asian monsoon increasing, the global energy and water cycle experiment (GEWEX) included the experiments called “GAME/Tibet” and “CAMP/Tibet,” which mainly aimed for researching the energy exchange between land and atmosphere in the Tibetan Plateau [10]. And in order to recognize the interaction between land and atmosphere further and quantitatively, these experiments covered the observation for the solar radiation, soil temperature and soil moisture, air temperature and pressure, soil heat flux, sensible and latent heat flux, and so on. Moreover, radiosonde observation has provided amount of data for the meteorological observation. The wind speed and direction, air temperature, moisture, and pressure data in the upper air are used to judge the atmospheric stratification and circulation situation [11].

However, the Tibetan Plateau covers a vast geographic area with various landforms, and the research is largely deficient only by a few of weather stations. But the remote sensing observation features large coverage and can obtain different surface parameters simultaneously, and it makes up the deficiency for the conventional observation data. With the developing of the satellite remote sensing, using satellite data to research various weather systems over the plateau has been a popular way. Meanwhile, an important method of estimating the air temperature by satellite data has been put forward, and it benefits the research on the land-atmosphere interaction [12, 13]. In addition, the essential data for the weather forecast and climate modeling and prediction are the land surface parameters, such as the soil temperature and moisture, reflectivity, emissivity, and roughness. Since the values of underlying surface are generally constant in current numerical models, the models are hard to reflect the reality of climate change [14, 15]. On the other hand, the satellite remote sensing plays a unique role in terms of

TABLE 1: The basic information of all sites.

Stations	Longitude and latitude	Elevation	Underlying surface
NewD66	35.43°N, 93.59°E	4465 m	Alpine sparse grassland
D105	33.06°N, 91.94°E	5039 m	Alpine meadow
NPAM	31.93°N, 91.71°E	4620 m	Alpine meadow
BJ	31.37°N, 91.90°E	4509 m	Alpine meadow
MS3608	31.23°N, 91.78°E	4589 m	Alpine grassland

achieving the parameters on inhomogeneous surface in the plateau. The surface parameters can be retrieved by satellite data, and the new parameterization scheme from those data can be introduced in the numerical models [13]. Therefore, the accuracy of the prediction can be improved. Nevertheless, the data from satellites and models are all needed to be verified by the in situ observation data, so the meteorological observation stations on the Tibetan Plateau are essential for the weather and climate prediction.

2. Materials and Methods

2.1. Materials. As is shown in Figure 1, eight field weather stations [11, 16] spread along Qinghai-Tibet Railway and six of them are used in this paper. The characteristics of all stations are shown in Table 1 and the surface feature of the Northern Tibetan Plateau can be represented by the stations [16]. The elevations of these stations are all above 4500 meters; D66 and NewD66 stations are covered by alpine sparse grassland, located in north of the Northern Tibetan Plateau. The elevation of D105 station which is above 5000 m is the highest station among these stations. The experiment field in D105 station, covered by alpine meadows, is flat and wide, and some hills stand at the east of the field. Similarly,

the experiment field in NPAM station, covered by alpine meadows, which are 15 centimeters tall, is flat and wide, and there are hills that are 100–200 meters tall that are around the field. The experiment field in BJ station, covered by alpine meadows, is flat and broad. MS3608 station, located in south of the area and covered by alpine grassland, is relatively moist.

Data applied in this study come from the observational data of the six stations, D66, NewD66, D105, NPAM, BJ, and MS3608. Daily meteorological data were obtained from the six stations and all these stations had complete records of meteorological factors from 2001 to 2013. The daily meteorological data included air temperature, land surface temperature, soil moisture, wind speed, and long-wave radiation. A few missing data (mainly in 2004, 2005 at BJ station) were estimated by averaging the value of other years observed at the same station.

2.2. Methods. Because of the poor quality data of land surface temperature observed, long-wave radiation data were used to calculate land surface temperature, and the formula is as follows:

$$R_{lw}^{\uparrow} = (1 - \varepsilon_s) R_{lw}^{\downarrow} + \varepsilon_s \sigma T_s^4, \quad (1)$$

where R_{lw}^{\uparrow} is the upward long-wave radiation, R_{lw}^{\downarrow} is the downward long-wave radiation, T_s is the land surface temperature, $\sigma = 5.67 \times 10^{-8} \text{ W} \cdot \text{m}^{-2} \text{ K}^{-4}$ is Boltzmann constant, and ε_s is land emissivity. From (1) we can see that T_s is affected by the upward long-wave radiation (R_{lw}^{\uparrow}), the downward long-wave radiation (R_{lw}^{\downarrow}), and land emissivity (ε_s). The influences of these three factors on T_s have been discussed in some researches [17, 18]. The upward and downward long-wave radiation in this study were measured by radiation instruments in all stations. ε_s of each station changes along with seasons. The influence of ε_s was considered in this study. Normalized differential vegetation index (NDVI) was applied to calculate ε_s in all sites, and the values were fluctuant from 0.92 to 0.98. This result is consistent with the conclusion drawn by He et al. [19]. The formula used for calculating ε_s was proposed by Van De Griend and Owe in 1993 [20]:

$$\varepsilon_s = 1.0094 + 0.047 \ln(\text{NDVI}). \quad (2)$$

In addition, the data quality of other factors was proved to be good for the study, so the observed data were used to analyze the long-term changes and climate prediction.

3. Results

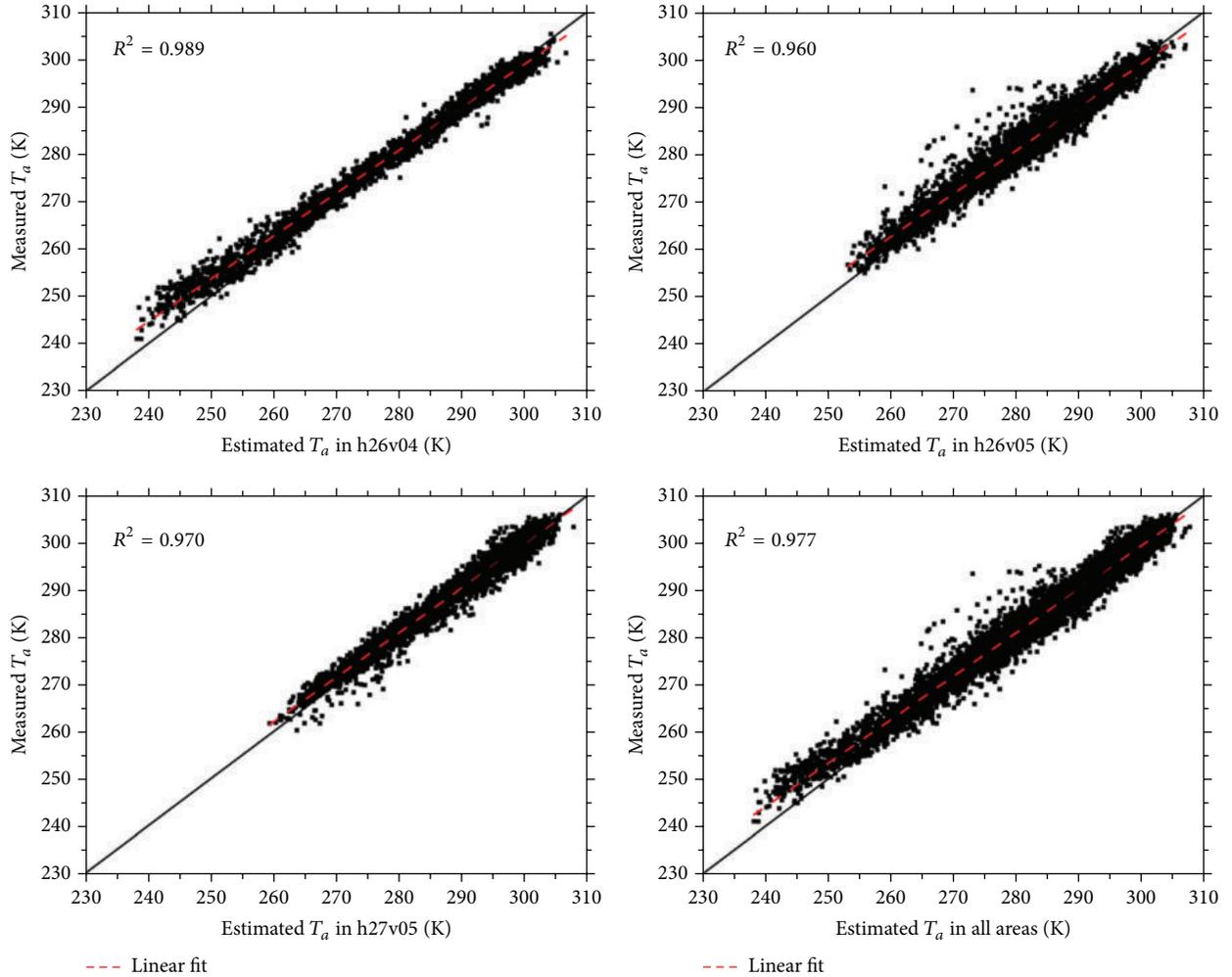
3.1. In Situ Measurements. Generally, the first-hand data for meteorology are provided by in situ measurements, and these data are widely used to validate the satellite data and model data for studying climate changes. For example, in situ measurements are compared with air temperature data estimated from the MODIS land surface data to verify the use of MODIS data for studying the spatial distribution of the air temperature by Sun et al. [21]. Three land areas covered by MODIS sinusoidal tile h26v04 (mountain area, average elevation 500–2000 meters), h26v05 (high mountain area, average elevation

2000–5000 meters), and h27v05 (plain area, average elevation 0–500 meters) were selected. Figure 2 shows the correlation of the estimated and measured air temperature. The in situ observations of air temperature are in good agreement with the estimated values from MODIS, with R^2 greater than 0.95 in all areas. In addition, the Mean Absolute Deviation (MAD) values of the estimated air temperature on the three areas are all lower than 2 K, and the Root-Mean-Square Error (RMSE) value in h27v05 area (1.84 K) is the lowest. According to Sun, the fact that the terrain in this area is relatively flat is the possible reason. This example has excellently shown that in situ measurements play a significant role in the validation of remote sensing data. And then, another example will prove the importance of weather station measurements for the weather and climate prediction. In recent years, it has been in the spotlight that numerical models are widely introduced to study the climate change, and hypotheses in models are based on observational facts. Radiosonde data can reflect the thermodynamic structure in the upper air. For example, Boos and Kuang [22] considered that the dominant control of the South Asian monsoon was the orographic insulation, and they demonstrated the hypothesis using numerical models. Before building the hypothesis and testing the models, radiosonde data were used to analyze the thermodynamic structure in the upper air. As is shown in Figure 3, the thermodynamic structure over Indian and Tibetan stations was accurately analyzed. Figure 3(a) shows the equivalent potential temperature within 25 hPa of the surface at radiosonde sites over and around the Tibetan Plateau. Figure 3(b) presents the daily mean profiles of temperature. Dashed lines are dry adiabats from the lowest sounding level up to the lifted condensation level and moist pseudoadiabats thereafter. Figure 3(c) represents the mean temperature difference between the Indian and Tibetan Plateau sites, with positive values denoting air that is warmer over Indian sites. The atmospheric conditions in the upper air were accurately analyzed by observational data, and reasonable hypotheses could be proposed. Based on the meteorological observation, the numerical simulated results are more dependable and accurate for the weather forecasting and climate prediction.

3.2. Long-Term Meteorological Observations. As shown in Table 2, the land surface temperature (T_s) and air temperature (T_a) in all stations show uptrend along with time, except for T_s in NPAM in autumn, which show a decreasing trend with the seasonal rate 0.07°C . In NewD66 and D105, the annual increase rates of T_s are greater than that of T_a , and it means that the uptrend of T_s is more obvious than that of T_a in the north part of the Northern Tibetan Plateau. In spring and winter, the increasing trends of T_s are more obvious, while, in summer and autumn, the rising trends of T_a are greater than that of T_s . In BJ and MS3608, which are located in the south part of the Northern Tibetan Plateau, the annual increase rates of T_a are greater than that of T_s . The uptrends of T_a are remarkable in spring and summer, and the rising tendency of T_s and T_a in BJ is more apparent than that in MS3608. However, in NPAM, the annual increasing rates of T_s and T_a are both 0.01°C/a , and the warming trend

TABLE 2: The annual and seasonal linear trend of T_s and T_a in all sites.

	Annual		Spring		Summer		Autumn		Winter	
	T_s	T_a								
NewD66	0.12	0.03	0.11	0.04	0.02	0.08	0.01	0.08	0.09	0.03
D105	0.12	0.02	0.04	0.02	0.02	0.09	0.07	0.09	0.05	0.01
NPAM	0.01	0.01	0.01	0.02	0.01	0.07	-0.07	0.05	0.01	0.01
BJ	0.07	0.10	0.07	0.14	0.03	0.13	0.002	0.07	0.11	0.07
MS3608	0.01	0.03	0.02	0.06	0.06	0.10	0.03	0.01	0.01	0.01

FIGURE 2: Comparisons between the estimated and measured T_a values in three case study areas covered by the MODIS tiles h26v04, h26v05, and h27v05. (The figure is cited from Sun et al. [21].)

is not obvious compared with other stations. According to IPCC5 and some studies [23–25], the global averaged surface temperature shows a warming of 0.85°C over the period 1880–2012, and over the past 60 years the rate of warming is $0.12^\circ\text{C}/10\text{a}$. Since 2001, the increasing rate of T_a in these stations is between $0.1^\circ\text{C}/10\text{a}$ and $1.0^\circ\text{C}/10\text{a}$, which means that the warming rate in the Northern Tibetan Plateau is greater than that in global areas.

Take BJ station as an example. Figure 4 shows the interannual variations of annual mean T_s and T_a in different seasons.

As shown in the figure, the annual increasing rates of T_s and T_a are $0.07^\circ\text{C}/\text{a}$ and $0.10^\circ\text{C}/\text{a}$, separately. T_s and T_a have been climbing since 2001, and the change trend of T_a always keeps pace with that of T_s , but the uptrend of T_a is more obvious than that of T_s . The warming rate of BJ is $1.0^\circ\text{C}/10\text{a}$ since 2001, which is almost ten times compared to that in global range. The seasonal rising rates of T_s are 0.07°C , 0.03°C , 0.002°C , and 0.11°C , respectively, in spring, summer, autumn, and winter, while those of T_a are 0.14°C , 0.13°C , 0.07°C , and 0.07°C . The air temperatures show warming trend in all seasons,

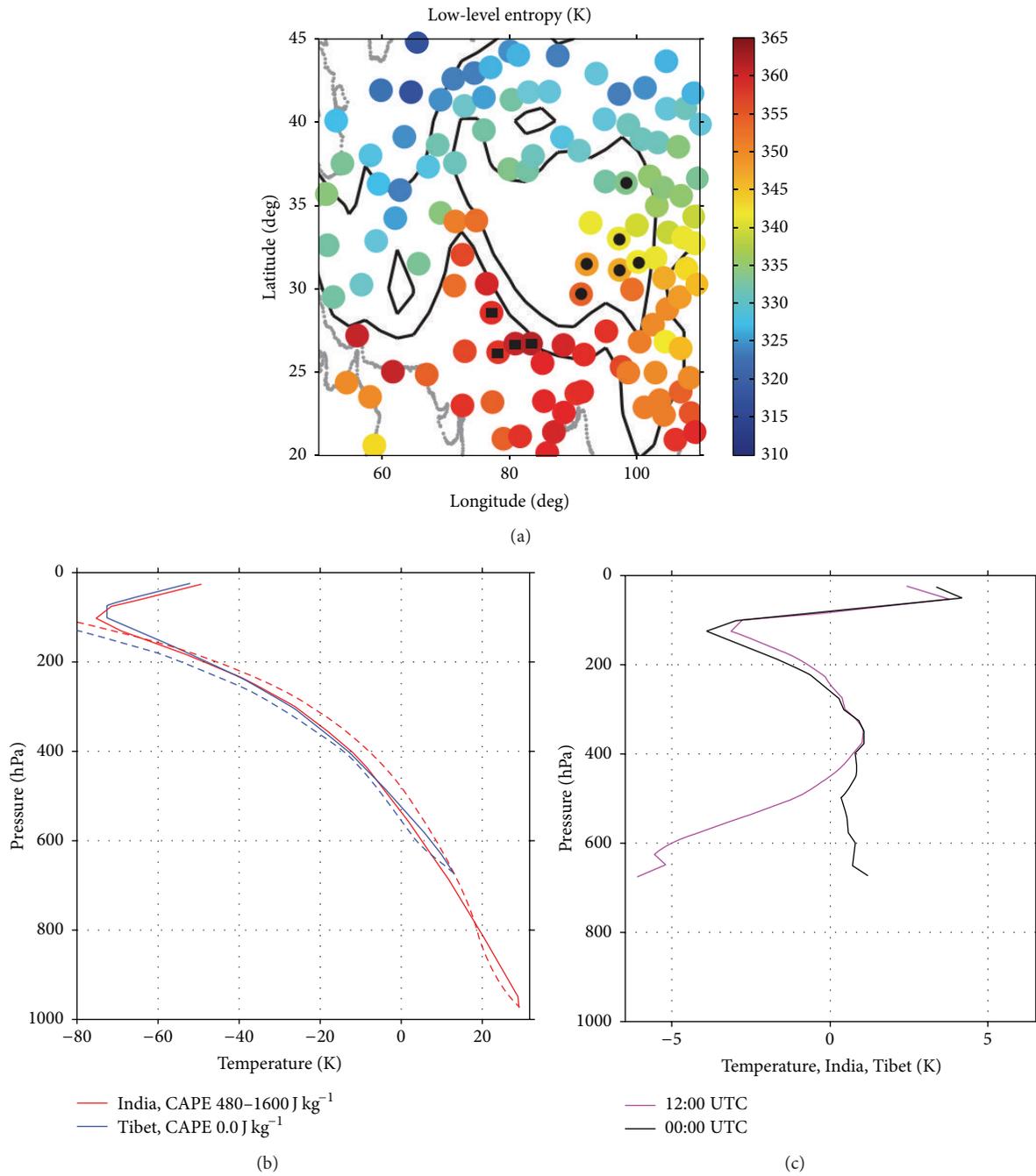


FIGURE 3: Thermodynamic structure from balloon soundings for June–August. (The figure is cited from Boos and Kuang [22].)

especially in spring and summer, while the land surface temperatures are rising in spring, summer, and winter, and T_s in autumn remains unchanged. Moreover, the rising trend of T_s is more obvious in winter. The increasing rate of T_s in winter is greater than that in summer, while the rising trend of T_a in summer is more remarkable than that in winter. On the other hand, the values of T_s are always greater than that of T_a , except for several winters. It indicates that the land surface is a long-term heat source for the atmosphere. Similarly, Figure 5 shows the interannual variations of annual mean

wind speed and soil moisture in each season. By comparing Figures 4 and 5, the impacts of wind speed and soil moisture on temperatures are revealed. In the winter of 2006, both T_s and T_a reached their maximum values -7.38°C and -8.13°C , while the value of wind speed was the greatest and the soil moisture value was the lowest. In 2008, the values of T_s and T_a were down to the bottom, especially in summer and autumn. Meanwhile, the value of wind speed was lower than the average value and the soil moisture value was greater than its mean value. It can be seen from the analysis that the changes

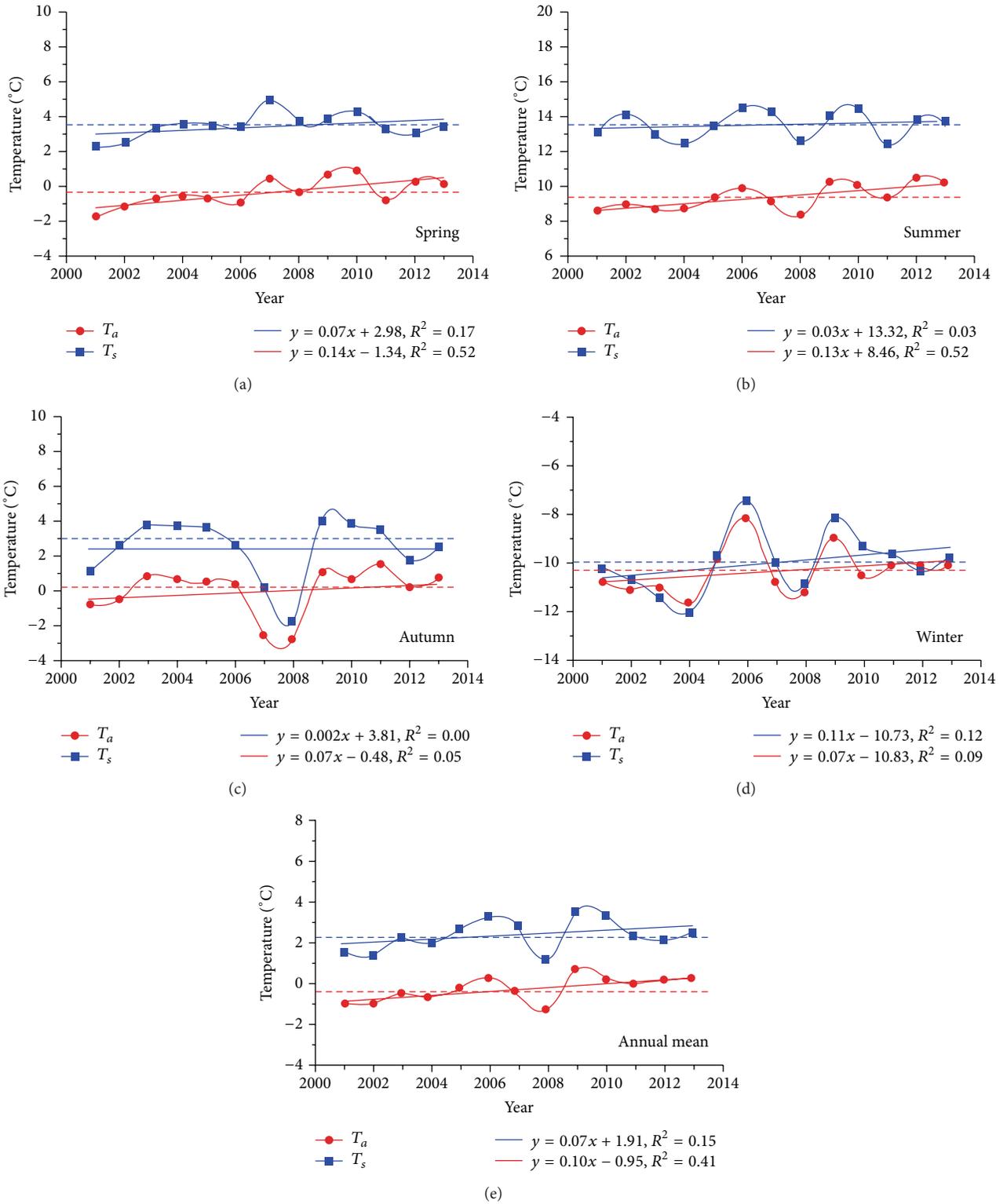


FIGURE 4: Averaged land surface temperature and air temperature change curves for seasons and years at BJ (curved lines are observed values, and straight lines are liner trend).

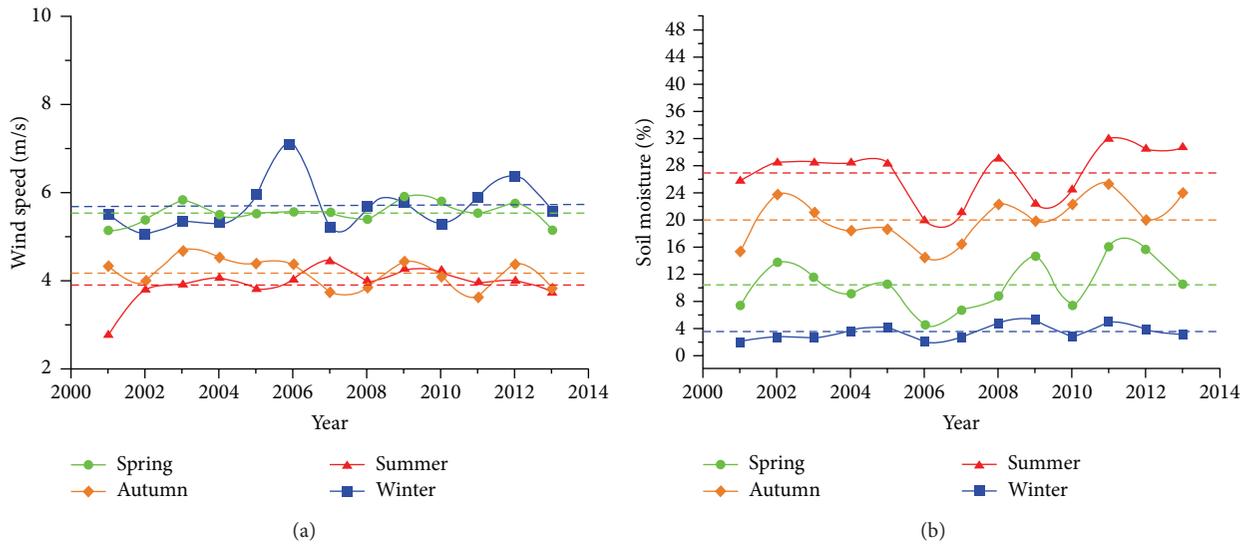


FIGURE 5: The interannual variation of wind speed and soil moisture in each season at BJ.

of wind speed and soil moisture make the difference to the temperatures on the Tibetan Plateau.

In addition, according to some researches [26, 27], El Nino and La Nina phenomenon separately occurred in 2006 and 2008. Based on some analysis [28], the surface heating field in the Tibetan Plateau has an increasing trend in El Nino year and weakens in La Nina year. Based on the above analysis, in El Nino year, the values of T_s , T_a and wind speed are greater than the averaged values, and the soil moisture values are lower than the averaged, while in La Nina year, the values of T_s , T_a and wind speed are less than the averaged values, and the soil moisture values are greater than the averaged. The variation of the previous surface heating field is a strong signal for the prediction of summer drought-flood anomalies at the east side of the Tibetan Plateau [29, 30]. It is thus clear that long-term observations in the Tibetan Plateau exert an important influence on the regional and global climate prediction.

3.3. Daily Observations at Different Sites. For the sake of monitoring the weather changes, a number of autoweather stations (AWSs) were set up in the Tibetan Plateau. Figure 6 shows the diurnal variations of T_s and T_a in D105, NPAM, and BJ stations mentioned in part 2, three stations in the Northern Tibetan Plateau. As can be seen from the figure, the variation trends are similar at all sites. T_s and T_a change significantly from daytime to nighttime; the fluctuation is larger in daytime than that in nighttime. Averagely, T_s reaches the peak value at 14:00, while T_a gets the maximum at 16:00–18:00. Obviously, the T_a diurnal variation falls behind T_s , and it is closely bound up with the solar radiation. Furthermore, the diurnal variation is various in different seasons, and what causes the differences may be the East and South Asian monsoon. The land surface in the plateau is relatively dry with less cloud cover and increasing solar radiation in spring, which is before the summer monsoon onset, so the surface

is cooled rapidly during the night and heated fast during the day. It can explain why the temperatures get the greatest diurnal change in spring. With precipitation increasing more, the soil moisture is growing in summer and autumn, which are after the monsoon onset, and the temperatures diurnal variation is the lowest. Besides, the changes are different in different latitudes and underlying surfaces. The diurnal variation and difference of T_s and T_a in D105, which is mainly covered by marsh, are less than that of NPAM and BJ with grassy marshland. The effect of T_a lagging behind T_s can give some information for the daily maximum air temperature forecast.

The process of making weather forecast consists of observation, data acquisition, data processing, data analysis, and forecast. All of them are based on the observation, and surface observation is absolutely necessary and it provides initial and reference value for the numerical forecasting. It is obvious that daily observation has an effect on weather forecast in the Northern Tibetan Plateau.

4. Conclusions

The underlying surface in the Tibetan Plateau is complex and heterogeneous, and it makes all the difference to the East Asian and even global climate change. So based on the in situ measurements, weather and climate prediction is dependable and convincing. As the first-hand data, data from weather stations are widely used to validate the satellite data and model data for studying climate changes. And in situ measurements are essential to the climate and weather forecast.

Long-term observations in the Tibetan Plateau exert an important influence on the regional and global climate prediction. In the Northern Tibetan Plateau, T_s and T_a have been climbing since 2001, and the change trend of T_a always keeps pace with that of T_s , but the uptrend of T_a is more obvious than that of T_s , especially in spring. Compared with

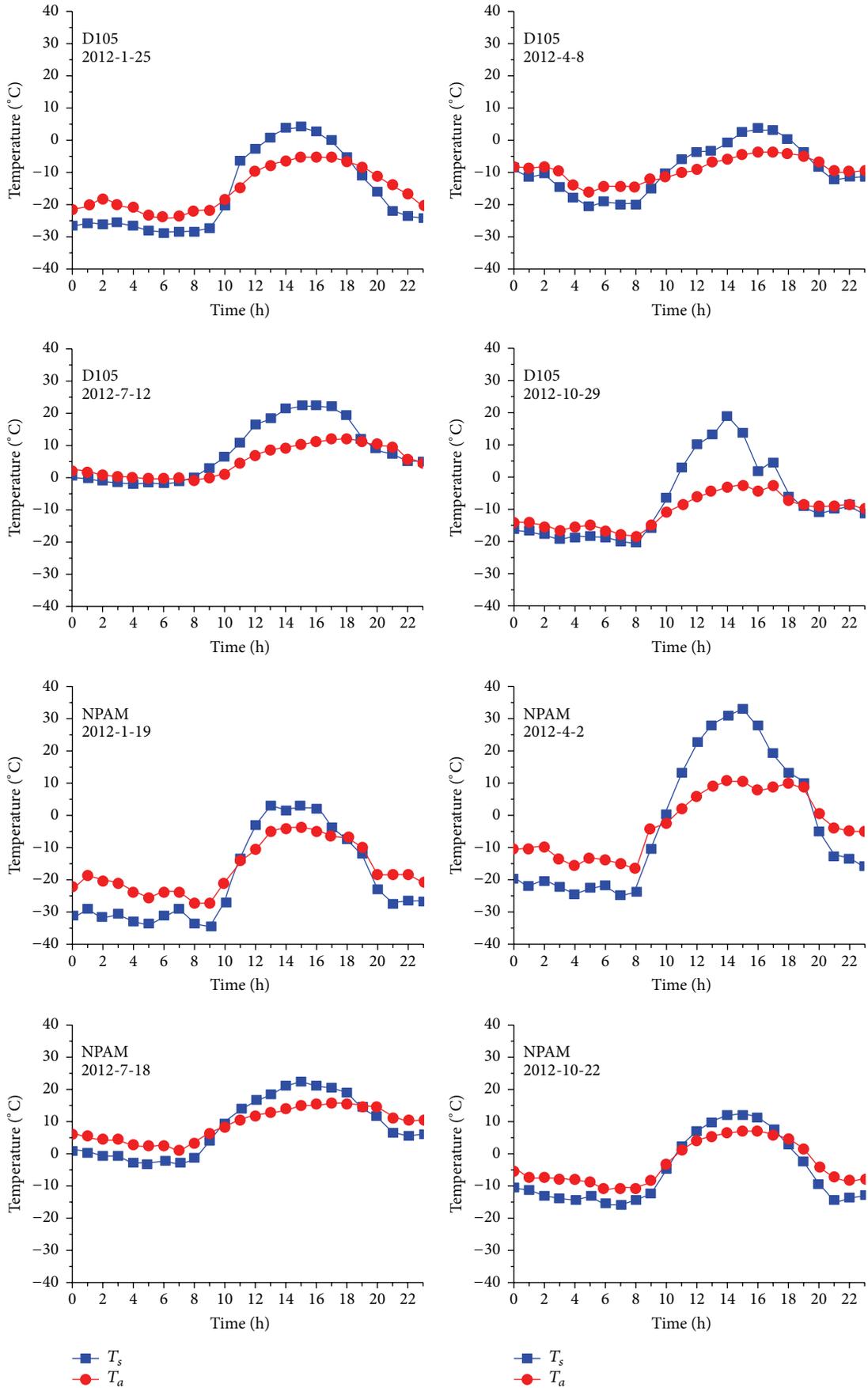


FIGURE 6: Continued.

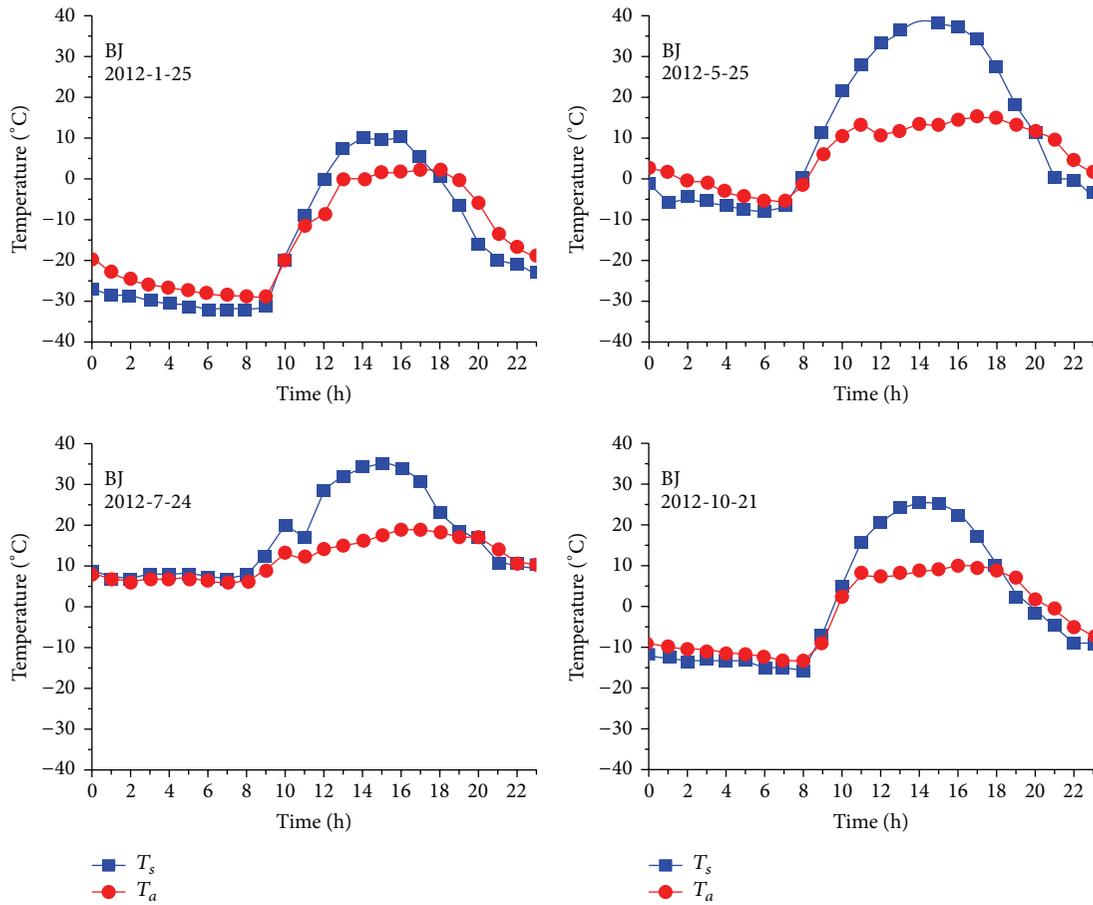


FIGURE 6: The diurnal variation of land surface temperature (T_s) and air temperature (T_a) in typical clear days in different seasons at D105/NPAM/BJ.

the global warming rate with $0.12^{\circ}\text{C}/10\text{a}$ over the past 60 years, the warming rate in the Northern Tibetan Plateau over the past ten years is greater than that in global areas. In El Nino year, the values of T_s , T_a and wind speed are greater than the averaged values, and the soil moisture values are lower than the averaged, while the contrary is the case in La Nina year.

The daily variations of T_s and T_a at all sites have similar trend, with obvious changes in the daytime and no significant changes in the nighttime. T_a changes lag behind that of T_s . The diurnal variations of T_s and T_a are the greatest in spring and are less in summer and autumn. The diurnal variation in the area with drier underlying surface is more obvious than that in the area with moist surface.

According to these observations, amount of weather and climate research in the plateau can be done continuously. As the foundation of climate prediction, long-term meteorological observations are worthy to be paid more attention.

Conflict of Interests

The authors declare no conflict of interests.

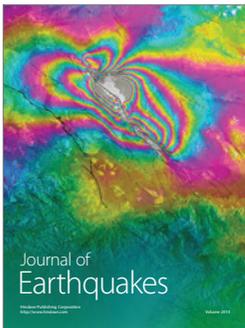
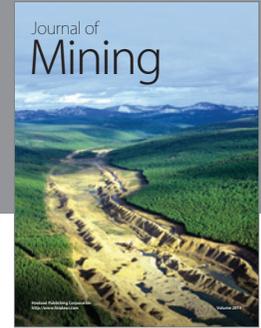
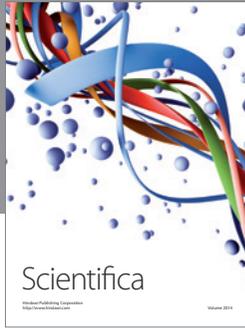
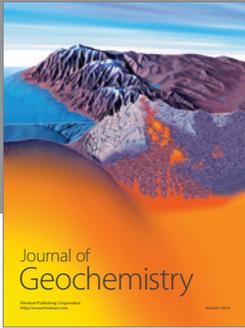
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