Sensitivity of Normalized Difference Vegetation Index (NDVI) to Seasonal and Interannual Climate Conditions in the Lhasa Area, Tibetan Plateau, China

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Abstract

The Normalized Difference Vegetation Index (NDVI) derived from NOAA AVHRR Global Vegetation Index (GVI) for Lhasa area in the central Tibetan Plateau from 1985 to 1999 and its relationship with climate conditions (precipitation and temperature) are established in this study. Climate data from the Lhasa meteorological station provided by the Tibet Climate Data Center are used for this analysis. The NDVI-derived vegetation growth patterns show very strong seasonal cycles and interannual variations. The growing season length varies between years. The correlation between NDVI and precipitation ($r = 0.75$, $P < 0.01$) in Lhasa area is higher than the correlation between NDVI and temperature ($r = 0.63$, $P < 0.01$), suggesting that NDVI is more sensitive to precipitation than temperature in this semiarid climate zone. Furthermore, the time series of NDVI demonstrate a positive trend from 1985 to 1999, which means that the vegetation biomass present on land surface is increasing. This trend is strongly correlated to increased rainfall and temperature from mid-1980s to 1990s in the Lhasa area of the Tibetan Plateau.

Introduction

The spatial distribution of vegetation cover is strongly related to mean climatological conditions (Saugier, 1996). The growing season length, the total amount of biomass, and the ecosystem composition are strongly influenced by interannual climate variations (Roerink et al., 2003). At the same time, vegetation changes can feed back to the atmosphere by modifying the surface roughness, evapotranspiration, and albedo (Rasool, 1993).

Recently, satellite observations have been used to quantitatively describe vegetation growth patterns (Justice and Hiernaux, 1986; Menenti et al., 1993). The Advanced Very High Resolution Radiometer (AVHRR) on board National Oceanic and Atmospheric Administration (NOAA) satellites is most commonly used for vegetation-related research due to its global spatial scope and continuous long-term temporal coverage. The NOAA satellites have been operating globally on a daily basis since the 1970s, primarily at 1.1-km pixel scale. Based on AVHRR, scientists from NOAA and other research facilities derived global vegetation index (GVI) products at 16-km resolution since 1982 (NOAA GVI User's Guide, 2001). In fact, the AVHRR normalized difference vegetation index (NDVI) is the basic GVI product, and has been routinely used to monitor vegetation growth at global scale (Burgess et al., 1995).

Many studies have been carried out to investigate relationships between NDVI and climate conditions. Using data from the AVHRR sensor on NOAA's operational series of meteorological satellites, Tucker et al. (1985) classified land cover and monitored vegetation dynamics for Africa over a 19-mo period. The seasonal

variations in the density and fractional coverage of green-leaf vegetation closely follow the patterns of rainfalls that are associated with the movement of the Intertropical Convergence Zone (ITCZ). Richard and Poccard (1998) analyzed the relationship between rainfall and the NDVI in southern Africa, and their study showed that the strongest correlations occur when NDVI monthly values are compared with preceding bimonthly rainfall amounts, attesting to a 1- to 2-mo lagged vegetation growth response to rainfall. While sensitivity to seasonal rainfall is observed in southern Africa where mean annual rainfall varies from 300 to 900 mm, and where the contrast between wet and dry season is strong, sensitivity to interannual rainfall anomalies is observed only for the relatively dry area of southern Africa, where mean annual rainfall varies from 300 to 500 mm. Potter and Brooks (1998) analyzed the empirical relationship between annual climate variables (precipitation, temperature, and surface radiation) and NDVI seasonality, where the seasonality is defined as the difference between the beginning and peak NDVI value during growing season. They found that three climate indexes—degree days, annual total precipitation, and an annual soil moisture index—together account for 70 to 80% of the geographical variation in the NDVI seasonal extremes for the calibration year 1984. The monthly timing of NDVI extremes is closely associated with seasonal patterns in maximum and minimum temperature and rainfall, with lag times of 1 to 2 mo. Milich and Weiss (2000) investigated the relationship between NDVI and rainfall in the northern and southern Sahel. Their study shows that the relationship between NDVI and rainfall is fairly good for the growing season, where annual rainfall is between 250 and 500 mm;

however, in desert border zones such as the African Sahel, with rainfall significantly lower than 250 mm yr^{-1}, this relationship becomes unpredictable. Recent study in western China shows that rainy season NDVI (May to October NDVI) has increased in most areas of arid and semiarid regions over the past two decades (Piao et al., 2005). Compared to the early 1980s, the area of arid and semiarid regions decreased by 230,000 km^2 (6.9%) and 70,000 km^2 (7.9%) by the end of the 20th century, implying a reversal of desertification processes in these two climate regions. Stöckli and Vidale (2004) studied the vegetation phenology in Europe using AVHRR NDVI products from 1982 to 2000. They found that the starting and ending, as well as the growing season length display remarkable interannual variabilities.

The most exciting breakthrough in atmospheric and land-surface process modeling since 1980s has come from the recent integration of biophysical and biogeochemical processes, plant physiology, and remote-sensing products. These researches are interdisciplinary in nature and help us to further understand the Earth system.

In this article, we will investigate changes of NDVI and its relationship with climate conditions in the Lhasa area of the Tibetan Plateau over the period from 1985 through 1999. First, we introduce the study area, including its geographic features and climatological conditions, and follow with a description of data sets used. The major results are then presented, followed by the discussion and conclusions.

Study Area

GEOGRAPHIC FEATURES AND GENERAL CLIMATOLOGY

The Lhasa area, a prefecture level administrative unit in Tibet Autonomous Region, is located in the central part of the Tibetan Plateau, China, extending from 29°14′26″N to 31°03′47″N, and from 89°45′11″E to 92°37′22″E. It extends 202 km north to south and 277 km east to west, including an area of 29,518 km^2. The average elevation is approximately 4000 m above sea level. In addition to the city of Lhasa there are seven counties in our study area, namely, Tolung Dechen, Chushur, Nyemo, Taktse, Lhundup, Damshung, and Medro Gongkar (Fig. 1).

The north and northwestern part of the Lhasa area is higher than the south. As part of Tibetan Plateau, the Lhasa area is characterized by Plateau monsoon climate (The Scientific Expedition to the Tibetan Plateau, 1984). Because of its high elevation, the Lhasa area possesses unique climatological conditions that are characterized by strong solar isolation, long sunlight hours, generally low annual mean surface temperatures, large diurnal surface temperature variations, distinct dry and wet seasons with strong wind in dry seasons, high rate of nocturnal rainfalls, low annual precipitation, and high annual evaporation (Lhasa City Agricultural and Pastoral Bureau, 1993). Occasional droughts, frosts, and gales are the major forms of climatic hazards in this region. The Lhasa area is in the semiarid climate zone of Tibetan Plateau; winters are cold and dry, and summers are semihumid, receiving most of its annual precipitation.

Precipitation

Precipitation in the semiarid Lhasa area plays an important role in driving ecological processes and in determining the vegetation distribution and its productivity. The precipitation regime is characterized by complex spatial and temporal patterns. Because the Lhasa area is located in the central part of the Tibetan Plateau, where plateau monsoon climate dominates, rainfall has marked seasonality. At the same time, the interannual variations in precipitation are strong.

According to climatological records from 1955 through 1995 (Lin, 2001), the mean annual rainfall amount in the Lhasa area is 427.6 mm, with a maximum of 796.6 mm in 1962 and a minimum of 229.6 mm in 1983. The maximum precipitation amount is about 3.5 times the minimum. The mean monthly maximum rainfall in the Lhasa area occurs in July or August. The long-term precipitation record demonstrates strong seasonality, with 75% of precipitation in the summer months (June to August), 16% in the autumn months (September through November), 8% in spring months (March through May), and about 1% in the winter months (December through February).

Besides the strong seasonal variations in precipitation, diurnal variations are also apparent. Most of the precipitation occurs at night: in the Lhasa area more than 85% of annual rainfall falls at night. The wet season in the Lhasa area usually begins in the early June and ends in the late September, lasting 120 d on average; the dry season lasts about 235 d, nearly twice as long as the wet season.

Temperature

Temperature plays a significant role in vegetation growth over the Tibetan Plateau, where high elevation leads to relatively low temperature values year round. Both the distribution and production of vegetation are strongly influenced by temperature. The mean annual temperature in the Lhasa area is about 7.6°C, with the mean annual maximum of 15.5°C and minimum of 1.0°C. The absolute maximum temperature recorded in Lhasa is 29.6°C, and the minimum is −16.5°C, though lower temperatures may have occurred at higher elevation, but are not recorded. The mean monthly temperature maximum occurs in June and the minimum in January. These seasonal variations of temperature are mainly driven by annual solar angle (Lin, 2001).

Since the 1950s, the mean annual temperature in the Lhasa area has been gradually increasing. The increasing trend is more obvious since the 1980s (Chu, 2003), and the temperature increases in cold season are greater (Chu, 2002). At the same time, there are marked interannual variations in temperature in the Lhasa area.

LAND USE

Over the total study area, there are seven major different land-use types (Lhasa City Agricultural and Pastoral Bureau, 1993). They are cultivated land, forestland, grassland, residential land, transportation land, water bodies, and bare soil. Among these, grassland is the dominant land-use type in this region, covering 71.75% of the total area. The second largest land-use type is bare soil, which covers 17.01% of the total area. The other land-use types—cultivated land (1.18%), forestland (3.43%), residential land (0.30%), transportation land (0.09%), and water bodies (5.53%)—cover a small percentage of total area.

VEGETATION

The vegetation types and distribution in the Lhasa area result from interactions between climate and topography, along with long-term adaptation to the environment, and evolution over the time. There are 10 vegetation cover types in the Lhasa area, namely, high mountain sparse cushion vegetation, high mountain meadow, high mountain shrub meadow, high mountain grassland,

sub-high mountain meadow, sub-high mountain shrub meadow, sub-high mountain grassland, mountain shrub grassland, meadow and marsh, and desert. Among these the high mountain meadow is the dominant vegetation type, which covers over 50% of the total vegetated area. Because of the unique plateau climatic conditions, and the strong influences of elevated topography, the vegetation distribution presents a strong vertical gradient. Consequently, the vegetation cover in this area is characterized by complex three-dimensional distributions.

Data

VEGETATION DATA

The data set used in this study is the NOAA third-generation Global Vegetation Index (GVI) weekly composite product. It consists of NDVI images created from Channel 1 (0.58–0.68 μm) and Channel 2 (0.725–1.00 μm) of the NOAA AVHRR sensors. The original data are processed temporally and spatially to create weekly maximum-value composite images with a spatial resolution of 0.144 degrees (around 16 km at the equator). In this study we averaged the weekly NDVI values from 1985 to 1999 covering our study area into monthly NDVI values. In the maximum-value compositing process, the highest daily value recorded in a week is retained for each pixel location (Holben, 1986). This technique has the advantage of minimizing cloud contamination and off-nadir viewing effects since these factors tend to reduce the NDVI values over green surfaces (Holben and Frazer, 1984; Holben, 1986).

The study area boundary used here is based on a 1:100,000-scale Gauss-Krüger projection. To meet need for weekly NDVI data scale, the boundary was converted into Plate Carrée (latitude/longitude) projection that GVI data uses. The Plate Carrée (latitude/longitude) was selected as the map projection for GVI NDVI images, because it provides a reasonable representation for the problematic polar region, where the Mercator and the Equal Area projections will be more distorted.

All GVI data have been processed using IDRISI 3.2, a software system for remote-sensing products developed by Clark Labs of the George Perkins Marsh Institute at Clark University (www.clarklabs.org). There are 2500 × 904 pixels in a primary GVI image. Weekly GVI data provides 52 images per year and 770 images for the 15 years of our interest. The main processing procedures are as follows. First, we extracted NDVI data from GVI for our study area; then we calculated monthly-mean NDVI values from averaging the weekly maximum NDVI composite for each pixel; finally, the domain-averaged monthly-mean NDVI values are obtained by spatially averaging all the pixels. These domain-averaged monthly-mean NDVIs reflect the general vegetation growth states for the entire study area.

METEOROLOGICAL DATA

The meteorological data we used for this study were provided by Tibet Climate Data Center. There are four meteorological stations available within the study area, as shown in Figure 1. Considering the sparse distribution of meteorological stations, and the contamination of typical climate information as a result of spatial averaging, we chose Lhasa meteorological station, located at latitude 29°40′N and longitude 91°08′E (Fig. 1) to represent the climate condition for the study area. These daily data are then post-processed to monthly mean values of temperature and precipitation.

Results

DOMAIN-AVERAGED MONTHLY-MEAN NDVI TREND ANALYSIS

Most land-cover mapping studies using AVHRR NDVI data have focused on the spatial patterns. However, trend analyses of AVHRR NDVI data from specific regions are fundamental to such mapping. This is because the time series of point data analysis can help us understand the factors that influence the AVHRR NDVI phenologies before land-cover mapping commences (Giles et al., 1994).

Growing Season Length

Shown in Figure 2a are the monthly-mean domain-averaged NDVI for the Lhasa area from April 1985 through December 1999. Because natural grassland and bare soil covers most of the area, the domain-averaged monthly-mean NDVI values of this region represent the states of natural vegetation. Large interannual variations in vegetation growing season lengths, identified by NDVI values >0.13, are evident. The associated peak values of greenness also vary on an interannual basis.

The vegetation phenology clearly responds to the seasonal atmospheric forcings, demonstrating strong seasonal cycles. The vegetation in the Lhasa area starts to grow around late May/early June, achieving peak NDVI values around July or August. Then, the NDVI value slowly decreases as vegetation senescence takes over. The lowest NDVI values occur between March and April. The maximum monthly-mean domain-averaged NDVI value from 1985 through 1999 is 0.32, which occurred in June 1999, while the minimum value was 0.01 in March 1997. The average value of maximum and minimum monthly-mean NDVI of each year from 1985 through 1999 is 0.21 and is 0.09, respectively. Mean value from 1985 through 1999 calculated by using monthly-mean NDVI is 0.14.

Comparison of the meteorological and NVDI data in Figure 2 shows that maximum precipitation is not always accompanied by maximum vegetation growth (see 1988 for example). The total accumulated annual precipitation seems to relate more to the magnitude of NDVI than any specific monthly maximum. Temperature also plays an important role; elevated temperature if combined with increased rainfall can lead to prolonged and maximized vegetation growth, as shown in year 1999.

The Positive Trend in NDVI

Besides the strong seasonal cycle, the vegetation in the Lhasa area also shows large interannual variations (Fig. 3a). The domain-averaged monthly mean NDVI shows a positive trend from 1985 through 1999, with a slope of 0.024 per decade. The positive NDVI trend indicates that the overall vegetation biomass has been increasing, which implies an improving physical environment for vegetation growth. In fact, vegetation status is one of the most important and sensitive indicators of physical environment changes.

Coincident with the positive trend in NDVI, the monthly-mean temperature and monthly total precipitation at Lhasa meteorological station also show positive trends for this time period (Fig. 3b, c). The slopes are 0.69°C/decade for monthly-mean temperatures, and 6.35 mm/decade for monthly-total precipitations. Both variables demonstrated consistent seasonal cycles. The winter is dry and cold, while the summer is warm and receives most of the annual precipitation. Precipitation appears to have more interannual variability than temperature.
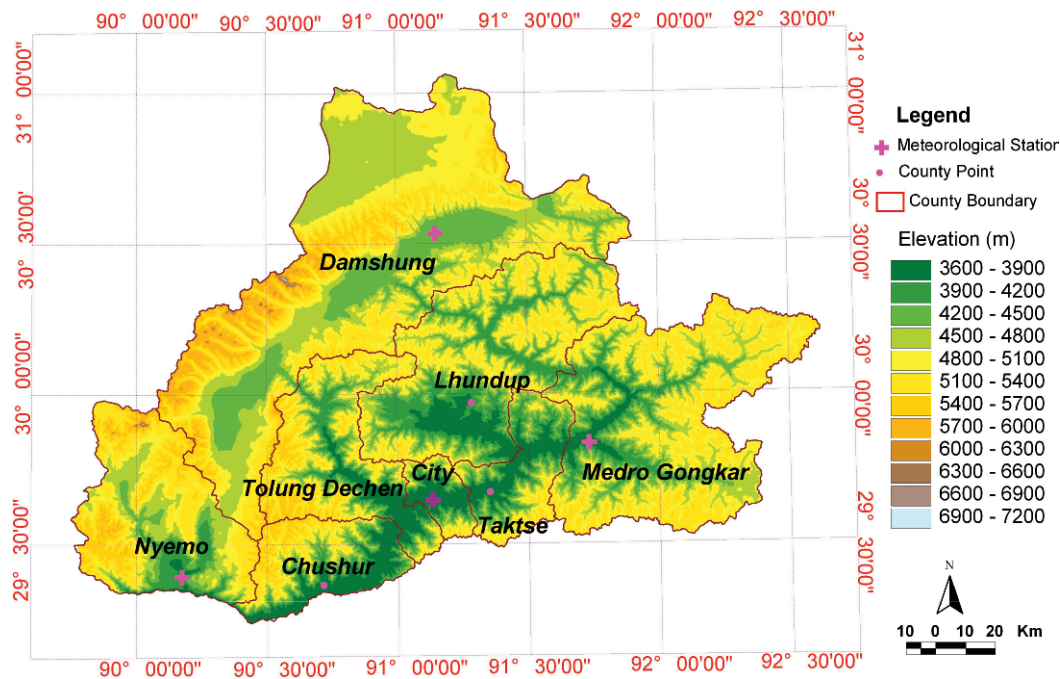
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FIGURE 1. Topography of the Lhasa area, the domain for this study. Also shown are county administrative boundaries and the surface meteorological station locations.

The driest year was 1986 (288.6 mm), while the wettest year was 1990 (613.8 mm).

In order to further examine vegetation growth patterns in the Lhasa area, we plotted weekly maximum NDVI for the driest year 1986 and wettest year 1990 (Fig. 4). The lowest NDVI value occurred at the 14th week in 1986, but at the 18th week in 1990. The 1-mo difference between the two minima was determined by when the rainy season started. Immediately after the rainy season commences, vegetation growth increases rapidly and reaches the peak NDVI value by late July to early August both in 1986 and
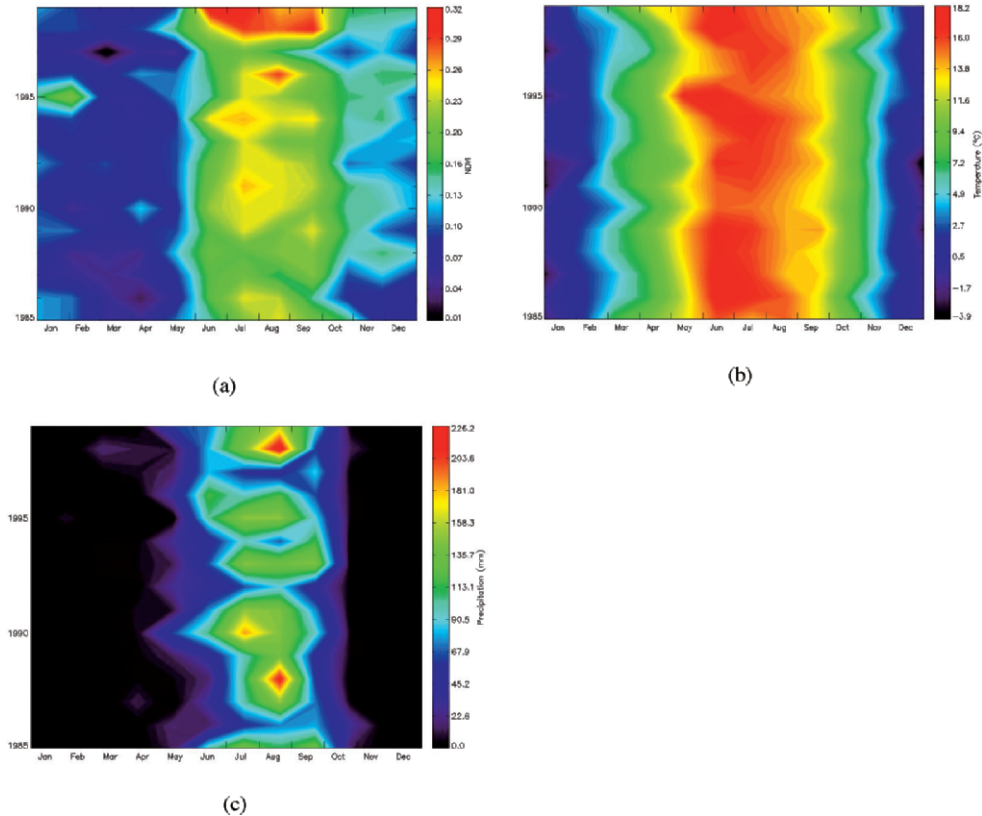

FIGURE 2. (a) Domain-averaged monthly-mean NDVI; (b) monthly-mean temperature; and (c) monthly-total precipitation. All data are from 1985 through 1999.
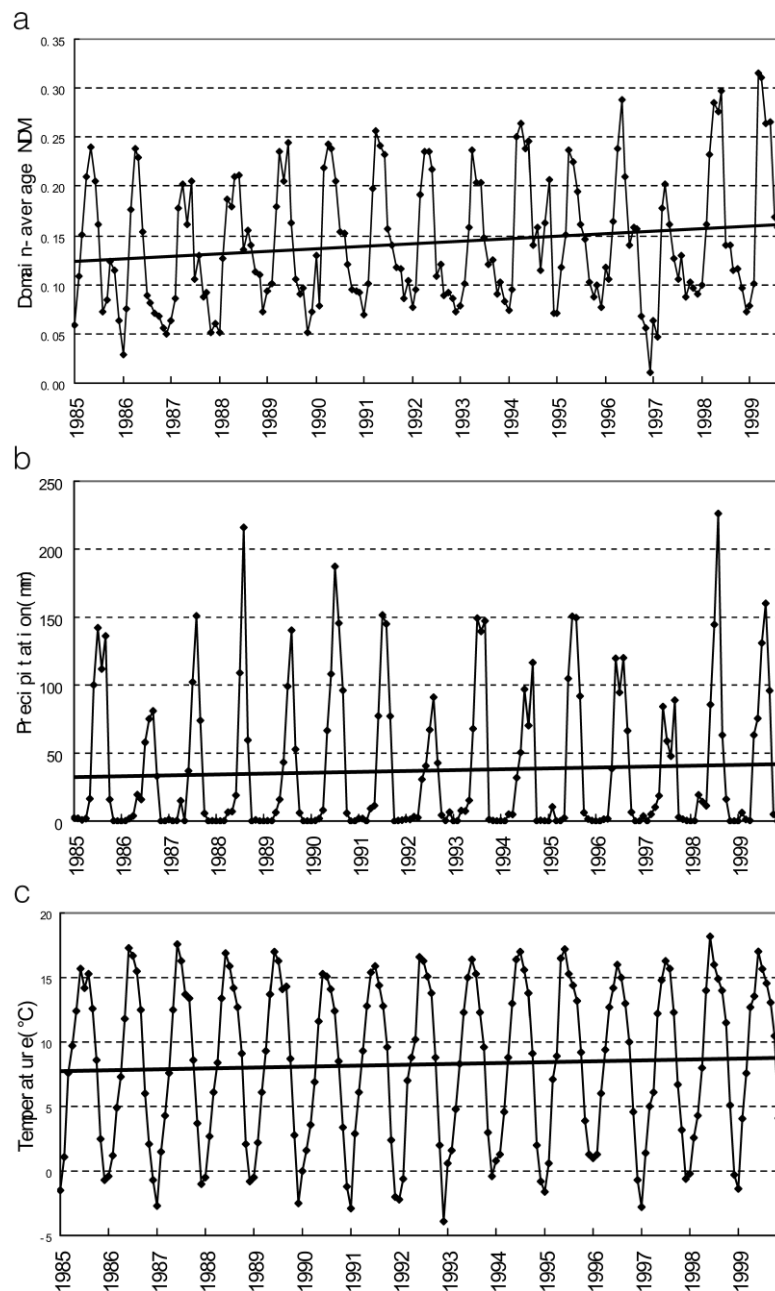
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FIGURE 3. **(a) Time series of domain-averaged monthly-mean NDVI from 1985 to 1999. The solid line shows a trend of 0.024/ decade. (b) Time series of monthly-total precipitation from 1985 to 1999. The solid line shows a trend of 6.35 mm/decade. (c) Time series of monthly-mean temperature from 1985 to 1999. The solid line shows a trend of 0.69°C/decade.**

1990. Because there was more rainfall in 1990 after the NDVI maximum, the NDVI decrease in 1990 was slower than that of 1986 (Fig. 4).

RELATIONSHIPS BETWEEN NDVI AND CLIMATIC ELEMENTS

The relationship between NDVI and precipitation in Lhasa has been analyzed from 1985 to 1999. As shown in Figure 3, the resemblance of interannual variation of precipitation and NDVI is remarkable. Both are characterized by high values during summer and low values during spring and winter. This is mainly because the precipitation in the Lhasa area is strongly influenced by warm and humid air mass coming from Indian Ocean, which is driven by the Southeast Asian monsoon system, and annual vegetation growth is very sensitive to rainfall patterns. A detailed correlation between NDVI and rainfall over the year, especially during the growing season, is summarized in Table 1. The results show that

NDVI is more sensitive to rainfall during the growing season (April to August) than that over the entire year.

Table 1 summarizes the statistical analysis between NDVI, annual total precipitation amount, and relationship between monthly NDVI and monthly precipitation amount for 1985 to 1999. Generally, the maximum monthly rainfall amount occurs in August or July, and the minimum monthly precipitation falls in November and December. The correlation coefficients between monthly NDVI and corresponding monthly precipitation from 1985 to 1999 are greater than 0.70 ($P < 0.05$) except for 1988, when the coefficient fell to 0.67 ($P < 0.05$). Correlation coefficients from April to August are greater than that from January to December. The correlation coefficient between monthly NDVI and monthly total precipitation from 1985 to 1999 is 0.75 ($P < 0.01$). In conclusion, in the semiarid climatic zone in Tibetan Plateau, the NOAA AVHRR NDVI and precipitation in the Lhasa area are highly correlated.
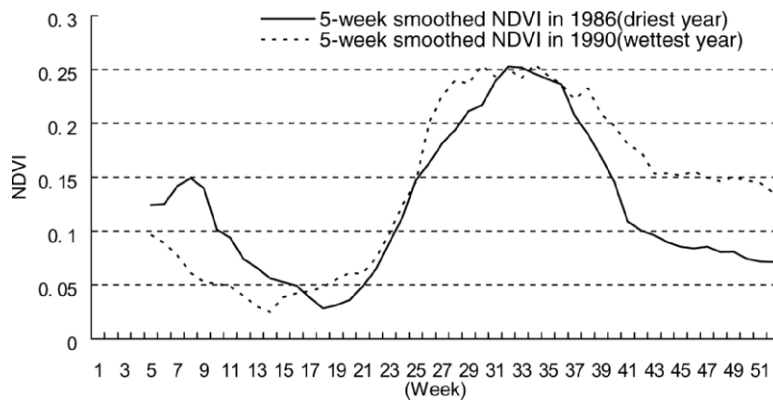
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FIGURE 4. Weekly maximum NDVI for 1986 and 1990.

Temperature also affects vegetation growth over the Tibetan Plateau. The monthly temperature changes also resemble monthly NDVI changes (Fig. 3). The correlation coefficient between monthly-mean temperature and NDVI over the period 1985 to 1999 is 0.63 ($P < 0.01$). The lower correlation coefficient between monthly temperature and NDVI, compared to 0.75 between the monthly precipitation and NDVI, implies that precipitation is the main factor affecting NDVI variations in the Lhasa area. Since the historical maximum temperature in the Lhasa area is lower than 30°C, the main impact of temperature on vegetation growth in the Lhasa area is minimum temperature. In particular, for mountain grasslands at lower altitude, the impact of minimum temperature during spring on growth is strong.

THE AVERAGE ANNUAL CYCLE

Shown in Figure 5 are composites of monthly-mean NDVI, monthly-total precipitation, and monthly-mean temperature averaged over 1985 through 1999. The average annual cycles demonstrate strong seasonal variations for the Lhasa area. The monthly-mean NDVI reaches its maximum in July (0.24), and minimum in March (0.07); August receives the largest rainfall amount of the year (132 mm mo^{-1}); the monthly-mean temperature is highest in June (16.2°C).

Discussion and Conclusions

We analyzed the domain-averaged monthly-mean time series of NOAA AVHRR NDVI products from 1985 to 1999 for the Lhasa area in conjunction with temperature and precipitation obtained from Lhasa meteorological station. Since nearly 90% of the Lhasa area is not human modified (i.e., natural grassland and bare soil), the NDVI variations represent seasonal and interannual dynamics of natural vegetation cover for this area. In the semiarid area of the Tibetan Plateau, vegetation has strong seasonal and interannual variations. The temporal NDVI analysis in the Lhasa area indicates that NDVI reaches its low point in March and April and its peak in July or August.

NDVI trend analysis for the Lhasa area shows a detectable positive trend; vegetation biomass represented by NDVI pixel values has been increasing since the mid-1980s. However, we realize that longer record might be needed to better evaluate this trend.

The NDVI value is more sensitive to precipitation variations than to temperature variations in the Lhasa area. A significant relationship exists between monthly-mean NDVI and monthly-total precipitation, and its correlation coefficient is 0.75($P < 0.01$), compared to a correlation coefficient of 0.63($P < 0.01$) between monthly-mean NDVI to monthly-mean temperatures. The maximum monthly NDVI ranges from 0.20 to 0.30 and minimum vary from 0.01 to 0.09 for 1985 to 1999.

TABLE 1

Correlation coefficients ($P < 0.05$) between monthly-mean NDVI, and monthly total precipitation, and monthly mean temperatures.

| Time	Precipitation (mm)	Temperature (°)	Maximum and minimum monthly NDVI and corresponding months				Correlation coefficients between monthly total rainfall and monthly NDVI		Correlation coefficients between monthly mean temperature and monthly NDVI	
Year	Annual total precipitation	Annual mean temperature	Max NDVI	Month of max NDVI	Min NDVI	Month of min NDVI	January to December	April to August	January to December	April to August
1985	529.8	8.1	0.24	August	0.06	April	0.88	0.91	0.68	0.82
1986	288.6	7.8	0.24	July	0.03	March	0.72	0.84	0.68	0.91
1987	386.5	8.0	0.21	September	0.05	March	0.74	0.68	0.76	0.90
1988	418	8.3	0.21	August	0.05	February	0.62	0.67	0.57	0.88
1989	364.3	8.5	0.24	July	0.07	March	0.79	0.86	0.71	0.75
1990	613.8	7.6	0.24	August	0.05	February	0.81	0.80	0.75	0.71
1991	476.3	8.0	0.26	July	0.07	April	0.90	0.98	0.66	0.89
1992	291.7	7.7	0.24	Jul. Aug.	0.08	April	0.89	0.91	0.73	0.92
1993	535.9	8.2	0.24	July	0.07	April	0.90	0.98	0.72	0.91
1994	371.8	8.5	0.26	July	0.07	April	0.85	0.88	0.73	0.93
1995	517.8	8.8	0.24	July	0.07	March	0.71	0.94	0.21	0.48
1996	448.9	8.5	0.29	August	0.08	March	0.77	0.76	0.62	0.76
1997	321.5	7.5	0.20	July	0.01	March	0.70	0.88	0.64	0.80
1998	580.9	9.0	0.30	September	0.09	March	0.81	0.87	0.81	0.80
1999	538.1	9.2	0.32	Jun	0.07	April	0.79	0.74	0.57	0.91

a

b

c
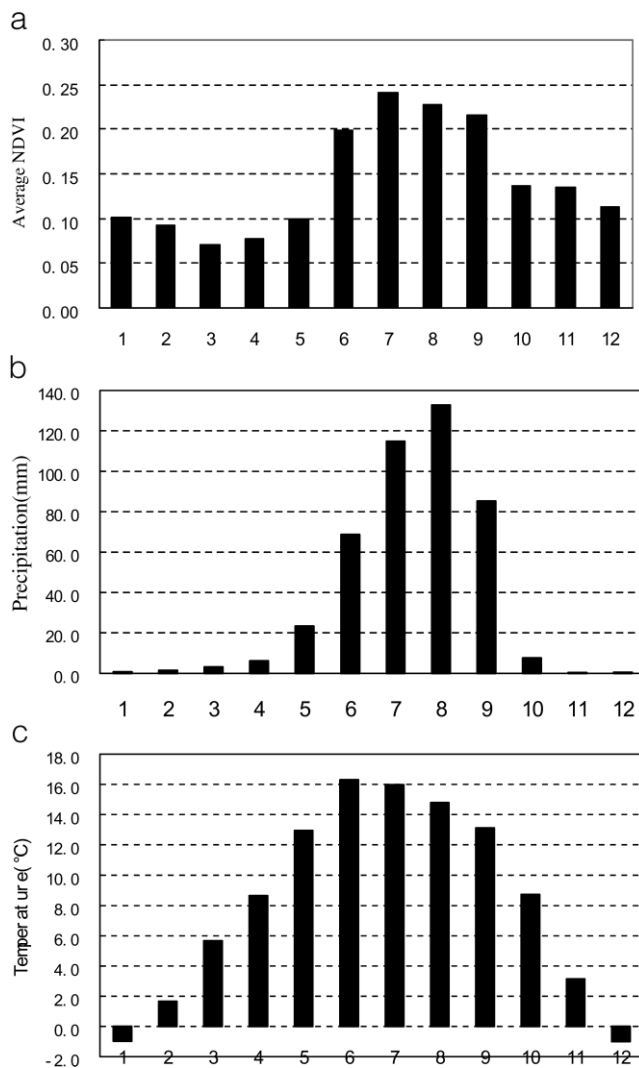
FIGURE 5. (a) Monthly-mean NDVI composite averaged from 1985 to 1999; (b) Monthly-total precipitation averaged from 1985 to 1999; (c) Monthly-mean temperature averaged from 1985 to 1999.

Although climate conditions (precipitation and temperature) are essential factors affecting natural vegetation growth, social and anthropogenic impacts also influence ecosystem dynamics. Higher resolution remote-sensing data are needed to understand this change.

Acknowledgments

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