Analyzing phenological changes with remote sensing data in Central Asia

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Abstract. Based on NOAA/AVHRR NDVI biweekly time-series data, the start and end of the growing season of Central Asia from 1982 to 2006 were estimated. Trend analysis results indicate an earlier green-up and a later dormancy over the entire area during the study period. For seven main vegetation types, the largest advance of greenup onset (0.597 days/year) occurs in cropland and the longest delay of dormancy (1.109 days/year) in open shrubland. The smallest advance (0.164 days/year) occurs in evergreen needleleaf forest and delay (0.443 days/year) in crop/natural vegetation mosaic. These results imply enhanced vegetation activity in the Central Asia region over last decades.

1. Introduction

Central Asia is the core region of the Asian continent and stretches from the Caspian Sea in the west to China in the east and from Afghanistan in the south to Russia in the north. In this study, the definition of Central Asia includes the five republics of the former Union of Soviet Socialist Republics (USSR): Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan. Central Asia constitutes a particularly vulnerable region due to its physical geography (dominated by temperate deserts and semi-deserts), its relative underdevelopment resulting from an economic focus on agricultural exports from monocultures (wheat and meat in Kazakhstan, cotton in Uzbekistan, Tajikistan, and Turkmenistan, wool in Kyrgyzstan) before 1991, and the dramatic economic and institutional upheavals following the collapse of the USSR [1,2]. Despite its vulnerability to global climate and environmental change, there are still numerous gaps in our understanding of the contingent and nonlinear interactions between global climate change, regional land changes, and human vulnerabilities and adaptations to environmental change in this region [3].

Vegetation phenology is the study of cycling of vegetation growth and development events throughout the year and can measure the response of plant systems to changes in temperature [4,5]. With the increasing length of the available satellite data record, land surface phenology as the seasonal pattern of variation in vegetated land surfaces observed from remote sensing has proved to be an

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effective tool for vegetation monitoring \cite{6,7}. Phenological phases, such as onset (green wave) or dormancy (brown wave) of vegetation can be detected and monitored with NDVI time series.

For Central Asia, the dynamic of vegetation development and its possible causes such as climate and human activity have been investigated with remote sensing NDVI datasets in several studies. The changes in the observed land surface phenology of the agricultural area in Kazakhstan are analyzed using the advanced very high resolution radiometer (AVHRR)/normalized difference vegetation index (NDVI) biweekly time-series data collected between 1985–1988 and 1995–1999 and observed differences in the northern regions in the temporal development of NDVI were found to result from changes in agricultural practices \cite{2}. With AVHRR dataset from 1982 to 2003, a significant increase in NDVI with a value of 11.35\% over the growing season has been reported, which indicated an increasing carbon stock in biomass of ecosystems in Central Asia \cite{8}. A refinement analysis of the seasonal Kendall trend method to the NDVI image series at a 0.05° (≈5.6 km) and 500 m spatial resolution and a 16-day temporal resolution from 2000 to 2008 with MODIS product revealed drought as the proximal cause of significant declines in NDVI in Kazakhstan \cite{9}. Environmental drivers such as elevation, temperature and precipitation which can be used to explain the spatial-temporal variability of vegetation phenology in Central Asia were identified in three regional landscapes (desert, steppe, and mountainous) \cite{10}. Based on the analyses of NDVI time-series and gridded precipitation datasets (GPCC Full Data Reanalysis) for the years 1982–2006, vegetation development was found to be sensitive to precipitation anomalies for nearly 80\% of the Central Asian land surface \cite{11}. However, the changing trend of vegetation phenology over the entire region has rarely gone through a comprehensive investigation.

In this study, we used NOAA/AVHRR NDVI data set to estimate the plant phenology and its variability in Central Asia from 1982 to 2006. The objective of this study is to quantify changes in vegetation phenology for main vegetation types in order to better understand the dynamic of vegetation activity in Central Asia over the study period.

2. Study area and dataset

Central Asia is characterized by a variety of vegetation and land cover types according to the MODIS Land Cover Type product (figure 1). The semi-steppe and steppe area dominate the territory of Kazakhstan. In the northern, there are mainly croplands after a transition zone including shrublands, grasslands and forests. Agriculture is also practiced along rivers, mainly along Amu Darya and Syr Darya in other countries. The semi-desert and desert regional landscape comprises the considerable parts of Turkmenistan and Uzbekistan. Mountainous regional landscape incorporates the territories of Tajikistan and Kyrgyzstan. The snow pack and glaciers in the high mountains of the Tien Shan and Pamir are origins for numerous rivers meandering through the Central Asian terrain and supplies fresh water resources for the Central Asian region \cite{12}. In this study, seven major land use/cover classes are analyzed, namely ‘evergreen needleleaf forest’, ‘deciduous needleleaf forest’, ‘mixed forest’, ‘open shrubland’, ‘grassland’, ‘cropland’ and ‘crop natural vegetation mosaic’. As in figure 2, the seven vegetation types occupy about 80\% of the land surface in Central Asia in total.

The climate of Central Asia is a distinctive continental arid to semi-arid climate \cite{1}. Temperatures and precipitations follow a gradient from north to south and from lowlands to mountains \cite{11}. Mean summer temperatures range between 20 °C in the north and more than 30 °C in the south. During the winter months, average temperatures range less than –20 °C in the north and around +5 °C in southern Turkmenistan and southern Uzbekistan \cite{13}. Yearly mean precipitation varies between 80 and 150 mm in the desert region, between 200 mm/year in the south and 400 mm/year in the north in the steppe and between 600 and 800 mm in the mountainous zones \cite{14}. The vegetation growing season begins in April/May and lasts until September/October in most area of the study region \cite{11}.

The GIMMS data set is a normalized difference vegetation index product available for a 25 year period spanning from 1981 to 2006. The data set is derived from imagery obtained from the AVHRR instrument onboard the NOAA satellite series 7, 9, 11, 14, 16 and 17. This NDVI dataset has been corrected for calibration, view geometry, volcanic aerosols, and other effects which were not related to
vegetation change. It is composited at a 15-day time step in an 8km Albers Equal Area Conic projection using the Clarke 1866 ellipsoid\textsuperscript{[15,16]}. The GIMMS data set of Eurasia continent from 1981 to 2006 is collected to analyze the spatial-temporal variation of vegetation phenology in the study area.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Land cover and land use map of Central Asia.}
\end{figure}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure2.png}
\caption{Main vegetation types in Central Asia.}
\end{figure}

3. Methodology

The software TIMESAT was used to smooth the time series of NDVI as well as to estimate the phenology metrics for the study area. Local Gaussian type of functions as following are fit to data in intervals around maxima and minima of the time-series\textsuperscript{[17, 18]}

\[ f(t; x_1, x_2, \ldots, x_5) = \begin{cases} 
 e^{\frac{-1}{2}(\frac{t-x_1}{x_2})^2}, & \text{if } t > x_1 \\
 e^{\frac{-1}{2}(\frac{t-x_1}{x_3})^2}, & \text{if } t < x_1
\end{cases} \]

For this function, $x_1$ determines the position of the maximum or minimum with respect to the independent time variable $t$, while $x_2$ and $x_3$ determine the width and flatness of the right function half. Similarly, $x_4$ and $x_5$ determine the width and flatness of the left half. The parameters are calculated using a separable Levenberg-Marquardt method. Two phenological metrics, namely the start of season (SOS) and the end of season (EOS) are calculated. The seasonal amplitude is the difference between the maximum value and the base level. The SOS is defined as time for which the left edge has increased to 30% of the seasonal amplitude measured from the left minimum level. And EOS is derived as the time for which the right edge has decreased to 30% of the seasonal amplitude from the right minimum level. In order to determine spatial patterns of directions and rates of change, overall trends of phenology parameters were computed using Ordinary Least Squares Regression (OLS). The linear functions were fitted through the time series of each pixel and the trend slopes were calculated. All trends described are statistically significant ($p<0.1$).

4. Results and discussion

4.1. Average phenological metrics
4.2. Spati-temporal variation of phenological metrics

Figure 3. Average (a) SOS and (b) EOS between 1982 and 2006 detected from GIMMS data. The spatial pattern of average SOS and EOS between the 25 years are shown in figure 3. The green updates spread from south (DOY 45) to north (DOY 180). In the eastern mountainous region, the SOS ranges from DOY 100 to 180. The end of the growing season (EOS) also varies in different regions. It spreads from south (DOY 120) to the north (DOY 290). In the eastern mountainous area, the vegetation begins dormancy from DOY 190 to 330.

Figure 4. Linear trend regression slope value of (a) SOS (b) EOS for pixels exhibiting trends at 90% confidence level between 1982 and 2006. Significant slope values (p<0.1) of SOS and EOS 1982–2006 based on linear trend analyses are shown in figure 4. Retrieved trends are generally towards earlier onset of spring and later occurrence of autumn, which may result in an extended growing-season length. Overall, the length of the growing season has increased by 1.16 days/yr from 1982 to 2006 for the entire area (figure 5). The trends retrieved from these results are generally in agreement with trends estimated from previous studies. The start of the season estimated using NOAA/AVHRR NDVI data have been reported to advance 0.2-0.4 days/year during the 1981–2000 period in Eurasia [19, 20, 21].
Figure 5. Interannual variations in the onset dates of (a) SOS (solid triangle), (b) EOS (solid square) for the entire study area from 1982 to 2006.

For the SOS date, there is an advance pattern across the study region. In particular, a sharp slope occurs in agricultural areas in Uzbekistan. This might be attributed to the transformation of agricultural practice of this area. For the EOS data, there is an obvious delay in the northern Kazakhstan and Kyrgyzstan. By contrast, an advance of end of season occurs in the croplands near the Aral Sea. The delay of SOS and advance of EOS occur in the steppe of western Kazakhstan, which may lead to a short season length and reduced vegetation activity.

Figure 6. Interannual variations in the onset dates of green-up (SOS, solid triangle) and vegetation dormancy (EOS, solid square) for different vegetation types from 1982 to 2006 in Central Asia.

For each vegetation type, figure 6 illustrates the trends of the onset dates of vegetation green-up and dormancy from 1982 to 2006 in Central Asia. All vegetation types exhibit advanced green-up and delayed dormancy. The largest advance of greenup onset (0.597 days/year) occurred in cropland and...
the longest delay of dormancy (1.109 days/year) in open shrubland. The smallest advance (0.164 days/year) of greenup onset occurred in evergreen needleleaf forest and delay (0.443 days/year) of dormancy in crop/natural vegetation mosaic.

5. Conclusions
Based on NOAA/AVHRR NDVI biweekly time-series data, we estimated the start and end of the growing season of Central Asia from 1982 to 2006. Trend analysis results indicate an earlier green-up and a later dormancy over the entire area despite regional disagreements. The same trends also occur for seven main vegetation types. These indicate the lengthening of growing season duration and enhanced vegetation activity in the Central Asia region in recent decades.

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