文章编号：1001-8166(2006)12-1254-06

Response of Vegetation Photosynthetic Activity to Net Radiation and Rainfall: A Case Study on the Tibetan Plateau by Means of Fourier Analysis of MODIS fAPAR Time Series

JIA Li[1], M. Menenti[2,3]

(1. Alterra, Wageningen University and Research (WUR) Centre, Wageningen, The Netherlands;
2. Universit Louis Pasteur (ULP), Strasbourg, France;
3. Istituto per i Sistemi Agricoli e Forestali del Mediterraneo (ISAFOM), Naples, Italy)

Abstract: Climate variability has a large impact on the vegetation dynamics. To quantify this impact in the Tibetan plateau a study was carried out using time-series of MODIS fAPAR satellite data products and NCEP net radiation and rainfall re-analysis data. The data set spanned over the years between 2000 and 2005. The NCEP data are used to construct a time series of a radiational indicator of drought: daily net radiation and rainfall data for each NCEP grid are integrated over a period of eight days to match the temporal sampling interval of MODIS data products. The ratio of net radiation over rainfall for a given period of time is a measure of excess energy relative to available water and is therefore a measure of drought hazard. Fourier analysis of time series of the MODIS fAPAR provides two indicators of the response of vegetation photosynthetic activity to drought, as measured by the indicator just described. The two indicators used in this study are the mean yearly fAPAR value and its annual amplitude. The algorithm used (HANTS) fits iteratively a Fourier series to a set of irregularly spaced observations, after elimination of outliers, such as due to cloud-contaminated observations. The relationships between photosynthetic activity of vegetation and the radiational drought hazard indicator are determined and quantified spatially and temporally. The response during the wettest respectively driest year during the period covered by available observations was compared. The drier areas prove to be the most sensitive to climate impact. The analysis should be extended over a longer period of time to obtain a more robust assessment of climate impact on vegetation dynamics, particularly as regards the response of vegetation to temporal respectively spatial variability of climate.

Key words: Tibetan plateau; Drough; Phenology; MODIS, fAPAR; Time series; Fourier.

CLC Number: P467; Q948 **Document code:** A

Receive date: 2006-10-23.

Biography: JIA Li E-mail: li.jia@wur.nl

1 Introduction

Climate variability has a large impact on terrestrial ecosystems, but impact is not the same for every region and it is stronger for regions with a delicate balance between water availability, radiative forcing and ecosystems. This applies in particular to arid and semi-arid regions, like the Sahel, parts of the Mediterranean region and many regions in China. Terrestrial vegetation in arid and semi-arid zone is very sensitive to fluctuations in water availability. The effect of water deficits on vegetation depends strongly on radiative forcing, since excess radiant energy at the surface must be dissipated as either convective heating or heat of vaporization of water in both soil and foliage. Accordingly a good measure of climate forcing and variability for the study of terrestrial ecosystems response should combine a measure of water availability with a measure of radiative forcing.

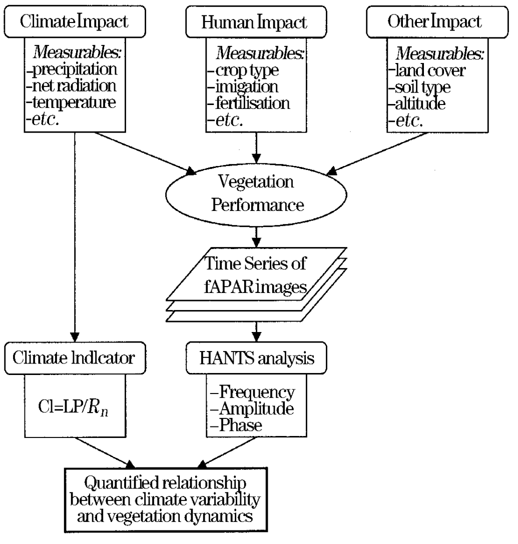

Fig.1 Schematic description of the approach proposed in this paper to study the response of terrestrial vegetation to climate variability; CI is the ratio of precipitation times the latent heat of evaporation to net radiation

To characterize climate and its variability, in terms of the relation between water availability and radiative forcing, we chose to use the Budyko Aridity Index[1~3], i.e. the ratio of net radiation over precipitation (multiplied by the latent of vaporization of water). This ratio was originally meant to be applied to long term climatologies, but we propose here to use it for short term (weekly in this study) total values of net radiation and precipitation. Our hypothesis[3] is that the indicator is still meaningful over short periods of time, since it measures the ratio of the evaporative demand of the atmosphere (i.e. net radiation) to available water (precipitation), which are the climate determinants of vegetation growth.

Foliar phenology, i.e. the seasonal change of vegetation cover and its conditions, is an extremely sensitive indicator of many factors, such as climate, soils and land management, determining the temporal evolution of terrestrial vegetation. Satellite data provide the opportunity to monitor continuously foliar phenology, but such monitoring over a period of time of climatological relevance, i.e. 10-15 years, requires processing and analyzing a considerable quantity of satellite data.

The method applied in this study has been described by Menenti, et al.[5~7], Verhoef, et al.[8], Azzali[9] and Menenti[3], Roerink, et al.[10,11]. These previous studies make clear that climate impact on vegetation growth has to be analyzed on a yearly basis. On the other hand these earlier studies used time series of NDVI as obtained from multi-spectral AVHRR. Since the launch of the Terra satellite, the high quality radiometric data acquired with the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used to produce global observation geo-biophysical variables. In the study described here we have used five years of MODIS observations of the fraction Absorbed Photosynthetic Active Radiation (fAPAR), which is a much better measure of vegetation growth closely related to Gross Primary Production.

2 Method

The conceptual framework and research method are presented schematically in Fig.1. Vegetation performance is determined by two major impact sources, climate and human activity. The Earth surface can be monitored on a daily basis by space borne imaging radiometers (AVHRR, VIRS, AATSR, MODIS, MISR, etc). Several of these sensors provide measurements of red and near-infrared reflectance which is sufficient to provide a measure of light absorption by leaf chlorophyll, thereby providing an indication of vegetation vigor and growth. These reflectance measurements are most commonly combined into spectral indices like the commonly used Normalized Difference Vegetation Index (NDVI), which gives an indication of vegetation functioning[12]. A time series of NDVI image data document the temporal behavior of vegetation functioning[13] and provides suitable data for bio-climatological studies. The vegetation dynamics can be quantified by applying pixel-wise Fourier analysis to the time series of NDVI images[4]. If the resulting NDVI Fourier components are coupled to climate parameters, the relationship between vegetation dynamics and climate can be analyzed[14].

In this study of the Tibet plateau (Upper Right UR: 40.00°N 104.43°W; Lower Left 30.00°N 80.83°W) we have applied the same method to time series of MODIS fAPAR available over the period January 1st 2001 through December 31st 2005 at 8 days temporal resolution.

2.1 Satellite observations

The Fraction of Absorbed Photosynthetically Active Radiation (fAPAR) absorbed by vegetation measures the proportion of available radiation in the photosynthetically active wavelengths (0.4 to 0.7 mm) that a canopy absorbs. The MODIS FAPAR is derived directly from MODIS Reflectances (MR) and ancillary data on surface characteristics such as land cover type, background etc, by using a three dimensional formulation for the LAI/fAPAR inverse problem. MODIS fAPAR (MOD15A2) is Level4 products at 1 km spatial resolution provided on a 8-day basis by compositing maximum fAPAR over the 8 days period[15].

2.2 Climate observations

We have used the daily National Center for Environmental Prediction (NCEP) data products on precipitation (P), net shortwave radiation and net longwave radiation. Net radiation is derived from net shortwave radiation and net longwave radiation (R_n). The 8-day precipitation is obtained as the sum of the daily values over each 8-day period, matching the temporal coverage of the MODIS fAPAR. The R_n values were daily averages over the same 8 days period.

2.3 Climate indicator

Evapotranspiration is the key process in plant development. It is mainly controlled by two meteorological parameters, net radiation and precipitation; either one of them is the limiting factor. The Budyko Aridity Index is the ratio between net radiation over precipitation times the latent heat of evaporation[2,3]. In other words, it defines aridity as the amount of energy in excess of the heat necessary to vaporize all precipitation, for any period of time. Values of BAI >1 indicate a potential water stress, since net radiation (a simple measure of the evaporative demand of the atmosphere) is in excess of precipitation.

2.4 Time series analysis

In order to extract concise characteristics of the

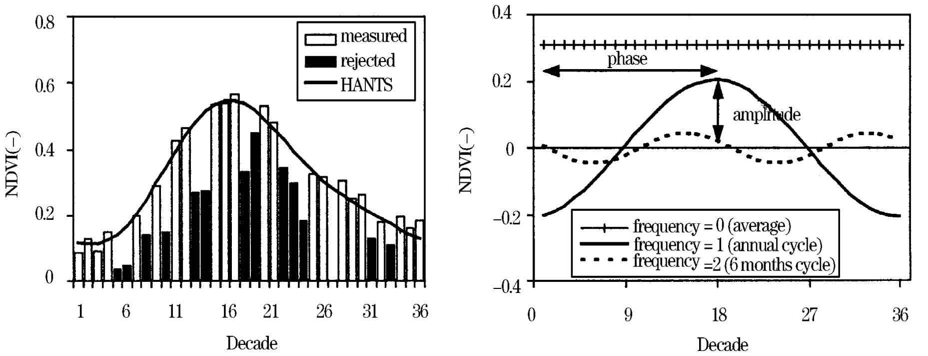

Fig.2 Schematic description of the HANTS algorithm: (left) identification and removal of outliers and (right) resulting Fourier parameters of the filtered time series

vegetation dynamics, Fourier analysis is applied on the time series of image data: earlier work used a Fast Fourier Transform algorithm [6]. Later on a more flexible method was developed: the Harmonic ANalysis of Time Series (HANTS) algorithm [8]. This algorithm considers only the most significant frequencies expected to be present in the time profiles, and applies a least squares curve fitting procedure based on harmonic components (sines and cosines). For each frequency the amplitude and phase of the cosine function is determined during an iterative procedure. Input data points, which have a large positive or negative deviation from the current curve (like cloudy and missing pixels), are removed by assigning a weight of zero to them. After recalculation of the coefficients on the basis of the remaining points, the procedure is repeated until the maximum error is acceptable or the number of remaining points has become too small. For a detailed description of the HANTS algorithm one is referred to Roerink and Menenti and Roerink, et al [10].

An example of the HANTS procedure is given in Fig. 2 which represents an annual temporal profile of an arbitrary pixel. Cloud affected observations are identified as large negative outliers and filtered out during the iterative HANTS procedure, using only three frequencies (frequency 0 = yearly mean value; frequency 1 = annual harmonic component, frequency 2 = 6 months component). The rest of the points have a maximum deviation from the fitted curve of, in this case, 0.05 NDVI units. Fig. 2 (right) shows the Fourier components (cosine functions) of the three individual HANTS frequencies; the arrows represent the amplitude and phase values of the annual NDVI cycle (frequency = 1).

3 Results

The simplest way to present the results obtained by applying HANTS to a yearly time series of fAPAR observations is by combining the dominant Fourier parameters, i.e. the yearly mean value and the amplitudes of the yearly and half-yearly components into a RGB color composite (Fig. 3, Plate IX). Green indicates here vegetation cover with relatively high mean fAPAR and moderate seasonality, while red indicates vegetation cover with relatively low mean fAPAR and significant seasonality. This concise representation of phenology makes it much easier to study the impact of climate variability on vegetation phenology.

The basic principle of the approach is illustrated in Fig. 4: although the overall shape of the fAPAR signature remains a simple periodic function, subtle differences in timing of minimum and maximum values and in the overall yearly amplitude are observable. Such differences are measured by using the Fourier parameters determined with HANTS.

Our data analysis indicated that 2001 was the driest and 2005 the wettest year, so we focused our analysis on the differences between these two years (Table 1).

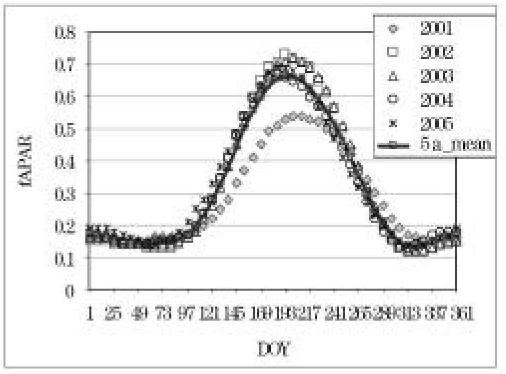

Fig. 4 Observed fAPAR values at a randomly selected pixel in the Tibetan plateau; Each observation applies to a 8-days sampling interval; Terra / MODIS, 2001-2005

Table 1 Descriptive statistics on observed differences (δ) between the driest (2001) and wettest (2005) year; A_{12} respectively A_6 is the amplitude of the 12 months respectively 6 months component; MODIS area coverage Tibet plateau (Upper right UR: 40.00°N 104.43°W; Lower left 30.00°N 80.83°W)

2001-2005	δfAPAR	δA_{12}	δA_6	$\delta(R_n/\lambda P)$
Mean	1.07	-0.06	0.4	4.1
Std. deviation	3.1	3.8	2.4	15.4

As indicated by the large values of the standard deviation for all variables considered the most significant feature is the very significant spatial variability both the Budyko ratio and of fAPAR Fourier parameters. Overall, the 2001 value of $(R_n/\lambda P)$ indicates significantly drier conditions than 2005, but the impact on vegetation functioning seems limited to a slightly lower amplitude of the winter-summer cycle and to a stronger 6 months component.

These results indicate that a meaningful analysis of the impact of climate variability on vegetation functioning cannot be done globally for a vast and complex region like the Tibetan plateau.

When looking at specific locations and vegetation cover, the relationship between changes in drought conditions, as measured by changes in $(R_n/\lambda P)$, and changes in vegetation phenology, as measured by the Fourier parameters computed from the fAPAR time series becomes much clearer (Fig.5). Within the Tibetan plateau we observe, for the same pair of years, both significantly drier conditions $[\delta(R_n/\lambda P) = 13]$ and slightly drier conditions $[\delta(R_n/\lambda P) = 0.7]$. The impact is very significant only in the former case, i.e. δfAPAR = -12.

4 Conclusions

We have described a preliminary case-study on the use of time series of satellite observations of biophysical variables and climate data to characterize vegetation response to climate variability. The advantage of the approach presented is two-fold:

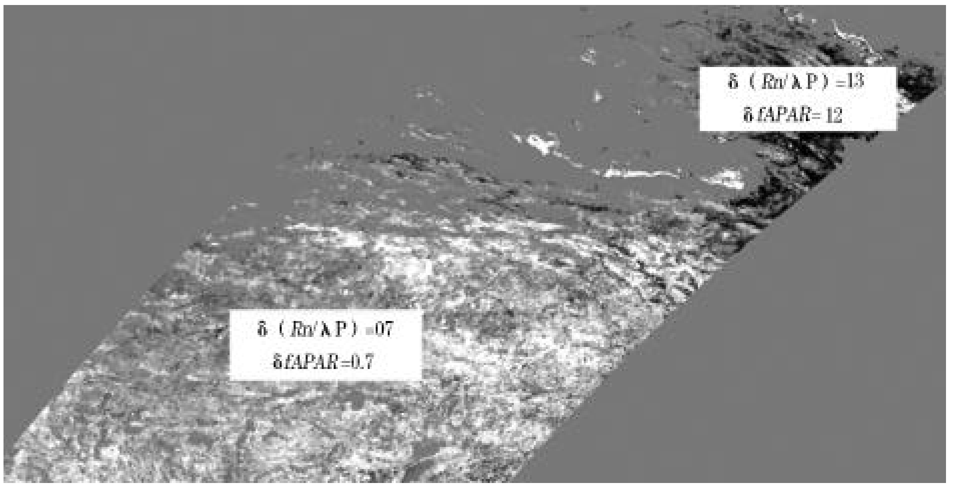

Fig.5 Map of change in mean yearly fAPAR between the driest (2001) and wettest (2005) year: black indicates lower values in 2001, white larger; labels show the corresponding changes in $(R_n/\lambda P)$ and fAPAR

(1) By using a Fourier series to model pixel-wise time serie of observations, the information is concisely represented in a very limited number of parameters.

(2) The satellite observations at 1 km spatial resolution capture subtle aspects in the spatial variability of vegetation response that would otherwise be rather difficult to capture by ground observations.

Even though the period of time spanned by the MODIS fAPAR observations was just five years, it was sufficient to capture significant changes in drought conditions between 2001 and 2005 and the corresponding response of plateau vegetation.

References:

[1] Budyko M I. The Heat Balance of the Earth's Surface [M]. Trs. Nina A Stepanova. Washington DC: US Department of Commerce, 1958.

[2] Budyko M I. Climate and Life [M]. New York: Academic Press, 1974.

[3] Henning D, Flohn H. Climate aridity index map [C] //Explanatory Note of United Nations Conference on Desertification. Nairobi, 1977, A/Conf, 74/31: 7-9.

[4] Azzali S, Menenti M. Mapping vegetation-soil-climate complexes in southern Africa using temporal fourier analysis of NOAA-AVHRR NDVI data [J]. International Journal of Remote Senssing, 2000, 21 (5): 973-996.

[5] Menenti M, Bastiaanssen W G M, Hefny K, et al. Mapping of groundwater losses by evaporation in the Western Desert of Egypt.

Report 43 [R]. DLO Winand Staring Centre, Wageningen, The Netherlands, 1991: 116.
[6] Menenti M, Azzali S, Verhoef W, et al. Mapping agroecological zones and time lag in vegetation growth by means of Fourier analysis of time series of NDVI images [J]. Advances in Space Research, 1993, 13 (5): 233-237.
[7] Menenti M, Azzali S, Verhoef W. Fourier analysis of time series of NOAA-AVHRR NDVI composites to map isogrowth zones [C] // Zwerver S, et al, eds. Climate Change Research: Evaluation and Policy Implications. Amsterdam: Elsevier, 1995: 425-430.
[8] Verhoef W, Menenti M, Azzali S. A colour composite of NOAA-AVHRR-NDVI based on time series analysis 1981-1992 [J]. International Journal of Remote Sensing, 1996, 17: 231-235.
[9] Azzali S, Menenti M. Mapping iso-growth zones on continental scale using temporal Fourier Analysis of AVHRR-NDVI data [J]. International Journal of Applied Earth Observation and Geo-information, 1999, 1 (1): 9-20.
[10] Roerink G J, Menenti M, Verhoef W. Reconstructing cloud-free NDVI composites using Fourier analysis of time series [J]. International Journal of Remote Sensing, 2000, 21 (9): 1 911-1 917.
[11] Roerink G J, Menenti M, Soepboer W, et al. Assessment of climate impact on vegetation dynamics by using remote sensing [J]. Physical Chemical of Earth, 2003, 28: 103-109.
[12] Goward S N, Tucker C J, Dye D C. North American vegetation patterns observed with the NOAA-7 Advanced Very High Resolution Radiometer [J]. Vegetatio, 1985, 64: 31-40.
[13] Spanner M A, Pierce L L, Running SW, et al. The seasonality of AVHRR data of temperate coniferous forests: Relationship with leaf area index [J]. Remote Sensing of Environment, 1990, 33: 97-112.
[14] Roerink G J, Menenti M, Su Z. A method for assessment of interannual climate variability by using Fourier components [C] // Proceedings International Geoscience and Remote Sensing Symposium (IGARSS). Hamburg, IGARSS'99, 1999: 681-693.
[15] Myneni R B, Knyazikhin Y, Zhang Y, et al. MODIS leaf area index (LAI) and fraction of photosynthetically active radiation absorbed by vegetation (FPAR) product (MOD15) Algorithm Theoretical Basis Document, Version 4.0 [Z]. 1999.

利用 MODIS fAPAR 傅立叶时间序列分析研究植被光合作用活动对净辐射和降雨的响应:青藏高原个例研究

贾　立[1], M. Menenti[2,3]
(1. Alterra, Wageningen University and Research (WUR) Centre, Wageningen, The Netherlands;
2. Université Louis Pasteur (ULP), Strasbourg, France;
3. Istituto per i Sistemi Agricoli e Forestali del Mediterraneo (ISAFOM), Naples, Italy)

摘　要:气候变化对植被动力学有非常大的影响。为了定量描述气候变化对植被的影响,文章利用 MODIS fAPAR 数据和 NCEP 的净辐射和降雨再分析数据对青藏高原地区气候变化对植被的影响进行了时间序列分析。研究所用的数据时间跨度为 2000 年至 2005 年。首先利用 NCEP 再分析数据建立了干旱度因子的时间序列,为了与 MODIS fAPAR 具有相同的时间采样间隔,由 NCEP 的日净辐射和日降雨量得到每 8 天的平均净辐射和 8 日降雨的和。根据一定时间间隔的净辐射与降雨量的比可以用来衡量相对于可利用水分的剩余能量,因此该比值也是干旱灾害的度量。其次,对 MODIS fAPAR 的傅立叶时间序列分析提供了两个植被光合作用对干旱相应的因子,即 fAPAR 的年平均值及其年振幅值。在时间和空间尺度上对植被光合作用活动与干旱指数之间的关系进行了定量分析。对湿年和干年之间的响应差异进行了比较。研究表明较干地区对气候变化的响应最为显著。分析应该扩展到更长的时间跨度以便更加有效地在时间和空间尺度上评估气候变化对植被动力学的影响。

关　键　词:青藏高原;干旱;生物气候学;MODIS, fAPAR;时间序;傅立叶