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# Circumpolar vegetation dynamics product for global change study

Alemu Gonsamo *, Jing M. Chen

*Department of Geography and Planning, University of Toronto, Toronto, M5S 3G3, ON, Canada*

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ABSTRACT

Land surface phenology (LSP) and vegetation growth of the circumpolar north are changing in response to more pronounced warming in the region. We here introduce the first phenology index (PI) based vegetation dynamics product, comprising start (SOS), end (EOS), length of growing season (LOS), and growing season integrated annual normalized difference vegetation index (NDVI), specifically designed for the entire circumpolar north (>45°N) using SPOT VGT data starting from 1999. PI combines the merits of NDVI and normalized difference infrared index (NDII) by taking the difference of squared greenness (from NDVI) and wetness (from NDII) to remove the soil and snow cover dynamics from key vegetation LSP cycles. The results show that the circumpolar vegetation dynamics and their spatial distributions are realistically detected. Further validation based on North American and European deciduous broadleaf, evergreen needleleaf and mixed forests, and wetland flux tower sites shows good agreements between the LSP dates from the circumpolar vegetation dynamics and ground phenology estimates from $CO_2$ flux measurements. The validation also proves that the circumpolar vegetation dynamics product is an improvement over the operational global MODIS Combined Land Cover Dynamics (MCD12Q2) product for the circumpolar region. The results are further compared with the interannual variability of sea ice extent and leading teleconnection patterns in the region. The circumpolar averaged results show that, the growing season integrated annual NDVI is significantly increasing (0.68% $\text{year}^{-1}$, $p = 0.006$) and well correlated with the growing season sea ice extent trend ($p = 0.007$). The circumpolar vegetation dynamics is more related to Polar/Eurasia pattern (i.e., indicator of circumpolar vortex) than to Scandinavian Pattern (SCA) and North Atlantic Oscillation (NAO). In view of the considerable scientific and policy importance of the circumpolar region, particularly the arctic ecosystems, the presented circumpolar vegetation dynamics product will greatly contribute to study changes in plant growth, phenology, photosynthetic capacity, and associated feedbacks under climate change.

## 1. Introduction

Land surface phenology (LSP), the study of the timing of recurring seasonal pattern of variation in vegetated land surfaces observed from synoptic sensors (de Beurs & Henebry, 2004; Gonsamo, Chen, Wu, & Dragoni, 2012b), has received much attention due to its role as a surrogate in detecting the impact of climate change on terrestrial ecosystems. LSP and vegetation growth of the northern hemisphere circumpolar region are changing (Bhatt et al., 2013; Jeganathan, Dash, & Atkinson, 2014; Tucker et al., 2001; Xu et al., 2013; Zeng, Jia, & Epstein, 2011; Zhang, Friedl, Schaaf, & Strahler, 2004) in response to disproportionately pronounced warming, and, by inference, its effect on natural physical and biological systems in this region (Hinzman et al., 2005; Post et al., 2009; Serreze et al., 2000; Stroeve et al., 2012). Knowing how the circumpolar vegetation ecosystems are responding to recent and persistent climate change is paramount to understanding the future state of the Earth system. The circumpolar region is experiencing pronounced warming (Polyakov et al., 2002) and the warming is expected to be enhanced in the future through the Arctic amplification process (Miller, 2013). This has also been reflected in severe changes in LSP of the circumpolar region (Buitenwerf, Rose, & Higgins, 2015). The observed pronounced contemporary shifts in climate and LSP in the circumpolar region help understand changes that may come in the decades ahead on other regions of the Earth. LSP is a sensitive and valuable indicator of the dynamic responses of circumpolar vegetation ecosystems to climate change. LSP changes may exacerbate or moderate rates of climate change by altering energy and gas exchanges between the land surface and the atmosphere. Several adverse consequences of circumpolar LSP changes for land-surface–climate feedbacks (Bonan, 2008), ecosystems (Post et al., 2009) and species with synchronized life cycles (Both, Bouwhuis, Lessells, & Visser, 2006) have already been observed. Therefore, to better understand and predict circumpolar ecosystems dynamics related to global change, it is important to reduce uncertainties in detecting vegetation growth and LSP changes.

Earth system and ecosystem process models require LSP modules to initialise photosynthetic processes in order to study the impacts of global warming on vegetated ecosystems. LSP parameterisation

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* Corresponding author.
*E-mail address:* gonsamoa@geog.utoronto.ca (A. Gonsamo).

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schemes included in Earth system and ecosystem process models, experimental warming, and contemporary climate-dependent processes such as growing degree days, underpredict plant phenological responses to global warming and do not reflect the changing climates (Arora & Boer, 2005; Gonsamo et al., 2013b; Migliavacca et al., 2012; Wolkovich et al., 2012). This is because global change has altered the phenology and distribution of many land and marine plant and animal species, evidenced in coherent fingerprint of climate change impacts across natural systems (Edwards & Richardson, 2004; Parmesan & Yohe, 2003; Poloczanska et al., 2013; Walther, 2010; Walther et al., 2002; Wolkovich et al., 2012). Therefore, observational studies are paramount to analyse climate change impacts across natural systems; in particular, terrestrial ecosystems provide a consistent picture of observed changes through retrieval of surface parameters from spatially and temporally continuous satellite observations.

In the last four decades, several LSP products derived from Advanced Very High Resolution Radiometer (AVHRR) (Justice, Townshend, Holben, & Tucker, 1985), Moderate Resolution Imaging Spectroradiometer (MODIS) (Zhang et al., 2003), and Medium Resolution Imaging Spectrometer (MERIS) (Dash & Curran, 2004) sensors were produced. They mostly use the normalized difference vegetation index (NDVI), but also enhanced vegetation index (EVI) and terrestrial chlorophyll index (MTCI), to extract start (SOS) and end of growing season (EOS) using vegetation index (VI) threshold or curve fitting algorithms (see comparison and reviews in: Atkinson, Jeganathan, Dash, & Atzberger, 2012; Fensholt & Proud, 2012; Fensholt, Rasmussen, Nielsen, & Mbow, 2009; Schwartz & Hanes, 2010; White et al., 2009). However, the application of a single VI is difficult for circumpolar vegetation due to limitations such as contaminations by background reflectances (e.g., from soil, leaf litter, dead branches, snow, soil thaw, snow thaw, and shadows), which also have distinct seasonal dynamics often misinterpreted as vegetation seasonal cycle (e.g. Boles et al., 2004; Delbart, Kergoat, Le Toan, Lhermitte, & Picard, 2005; Gonsamo, Chen, & D'Odorico, 2013a; Jackson & Huete, 1991; Jin & Eklundh, 2014; Shabanov, Zhou, Knyazikhin, Myneni, & Tucker, 2002; Todd & Hoffer, 1998). NDVI, EVI, and MTCI respond to greenness, wetness and dryness dynamics, from which LSP extraction in as predominantly snow covered areas as circumpolar region is far from trivial. These shortcomings are well documented in previous studies (D'Odorico et al., 2015; Delbart, Le Toan, Kergoat, & Fedotova, 2006; Delbart et al., 2005; Gonsamo, Chen, Price, Kurz, & Wu, 2012a; Jin & Eklundh, 2014; White et al., 2009).

Studies have shown the use of shortwave infrared (SWIR) reflectance in VI construction, such as, normalized difference infrared index (NDII), to improve LSP extractions from satellite reflectance observations (Delbart et al., 2005; Delbart et al., 2006; Delbart et al., 2008). However, NDII-based methods do not work well in regions where snowmelt and greenup processes overlap, and in conditions of abrupt increase in soil moisture before greenup, typical of circumpolar ecosystems. Gonsamo et al. (2012a) developed a new VI called phenology index (PI) which combines the merits of NDVI and NDII by taking the difference of squared greenness (from NDVI) and wetness (from NDII) to remove the soil and snow cover dynamics from key vegetation LSP cycles. PI based LSP estimates performed well in previous validations at northern $CO_2$ flux tower sites for both needleleaf and deciduous broadleaf plant forms (Gonsamo et al., 2012a; Gonsamo et al., 2012b; Gonsamo et al., 2013a). A recent site-level intercomparison study reveals that PI based LSP estimates agree with ground phenology estimates from $CO_2$ flux measurements and digital camera observations better than EVI based MODIS Global Land Cover Dynamics product (MCD12Q2) and NDVI based LSP estimates at 19 temperate and boreal deciduous broadleaf forest sites (D'Odorico et al., 2015). The next logical step is to apply PI over spatially and temporally continuous satellite observations and analyse the relationship between the resulting circumpolar vegetation dynamics product and the integrated anthropogenic and natural global change indicators in the region. The longest running modern satellite sensor, Satellite Pour l'Observation de la Terre Vegetation (SPOT VGT) with all required spectral bands (i.e., red, near infrared (NIR), and SWIR) provides operational level data to apply PI for LSP mapping. We use seasonally and annually averaged sea ice extent to represent the integrated anthropogenic global change and three leading circumpolar ocean-atmosphere oscillation patterns to represent the natural internal climate variability.

In this paper, we present the first phenology index (PI) based circumpolar vegetation dynamics product, specifically designed for the entire circumpolar north (>45°N) using SPOT VGT data starting from 1999. The circumpolar vegetation dynamics product comprises four layers, i.e., start (SOS), end (EOS), length of growing season (LOS), and growing season integrated annual normalized difference vegetation index (NDVI) (Tables 1 and 2). As an example application for global change studies, we also present the responses of the circumpolar vegetation dynamics to long-term trend and interannual variability of dominant global change indicators in the region. Further validations are provided using citizen science phenology records and ground phenology estimates from $CO_2$ flux measurements.

## 2. Methods

### *2.1. Study area and SPOT VGT S10 data descriptions for circumpolar vegetation dynamics product*

The study area includes the entire circumpolar north (>45°N). In this work, we use the 1 km ten-day product (S10) from SPOT VGT Maximum Value Composite (MVC) Syntheses reflectance data (Maisongrande, Duchemin, & Dedieu, 2004) obtained from the VITO product distribution portal (http://www.vito-eodata.be/) for 1999–2013. The S10 10-day reflectance data are corrected for molecular and aerosol scattering, water vapour, ozone and other gas absorption based on a single best MVC data for every 10 days (Holben, 1986). The red (0.61–0.68 μm), NIR (0.78–0.89 μm) and SWIR (1.58–1.75 μm) reflectances are compiled from SPOT-4 (VGT1 sensor) until January 2003 and after that from the SPOT-5 (VGT2 sensor). SPOT VGT sensors offer the advantage over MODIS of longer data records going back to 1998 including the SWIR spectral band. The SPOT VGT sensors also offer better sun-synchronous navigation against orbital drift and improved radiometric sensitivity advantages over the most widely used AVHRR series of sensors. Some of the SWIR detectors are declared defective due to proton shocks and detector locations and consequently the data given by those detectors are ignored, and replaced by data obtained from an interpolation from the neighbours (http://www.vgt.vito.be/pages/VegetationSystem/dataprocessing.htm). However, a small number of stripes still remain after processing.

### *2.2. Rationale for vegetation index used for circumpolar vegetation dynamics product*

The red, NIR and SWIR S10 reflectances are averaged to 4 × 4 km (0.03571428 × 0.03571428°) in order to increase the convergence of the curve fitting algorithm with statistically sufficient data points with expected temporal pattern. The LSP algorithm described in Gonsamo et al. (2012a) is applied for the years 1999 to 2013 to extract SOS and EOS dates from PI times series. The PI is calculated from red, NIR and SWIR reflectances as follows:

$$PI = \begin{cases} 0, \text{if NDVI or NDII} < 0 \\ NDVI^2 - NDII^2 \\ 0, \text{if } PI < 0 \end{cases} \tag{1}$$

where from SPOT VGT red (0.61–0.68 μm), NIR (0.78–0.89 μm) and SWIR (1.58–1.75 μm) reflectances, NDVI = (NIR-red)/(NIR + red), and NDII = (NIR-SWIR)/(NIR + SWIR). NDVI is an indicator of the amount of greenness while NDII captures the amount of wetness over an observational unit such as a pixel. PI is constructed on the basis of