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Using phase-spaces to characterize land surface phenology in a seasonally snow-covered landscape

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ABSTRACT

In seasonally snow-covered environments, snow significantly impacts upon vegetative phenology. As such, there is a need to derive land surface phenological descriptors that are free of the influence of snow-cover. The presence of on-ground snow-cover influences the phenological descriptors produced using some remotely sensed vegetation indices. This study proposes a method that uses both the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Infrared Index (NDII) to obtain dates for the start and end of the growing season. The method operates in the phase-spaces (sometimes referred to as feature- or band-spaces) created by the intersection of the NDVI–NDII data-space of individual pixels and can be used to derive descriptors for the start and end of the growing period as well as period corresponding with the end of green-up. This paper describes the origins and rationale for the method, which was applied to a MODIS image time-series of Australia's alpine bioregion for 2000–mid-2001. The results were validated against descriptors derived using the method of Delbart et al. (2005). For the start of the growing period, the validation indicated there was moderate correlation ($r = 0.51$, $p \leq 0.001$) between the descriptors. Noise in the NDII time-series used resulted in little, or no, correlation for the end of the growing period ($r = -0.13$, $p \leq 0.001$), and the correlation for the end of the green-up period was somewhat limited ($r = 0.24$, $p \leq 0.001$). In contrast to traditional NDVI threshold methods, the phase-space algorithm proposed here provided for a clear set of definitions that correspond with biophysical phenomena of the land surface, such as the offset and on-set of seasonal snow-cover.

1. Introduction

Phenological studies investigate relationships between the timing of recurrent biological phenomena and the forces driving these phenomena (Lieth, 1974). In recent years, interest in phenology has increased, as scientists are concerned that rising surface temperatures associated with climate change may result in a decoupling of interdependent species as seasonality shifts (Menzel, 2002, 2003; Walther et al., 2002). The concern is that increased decoupling will result in higher extinction rates for interdependent flora and fauna (Easterling et al., 2000; Root et al., 2003; Thomas & Williamson, 2012; Thomas et al., 2004). In the remote sensing literature, the Normalized Difference Vegetation Index (NDVI) and high temporal resolution optical imagery have been used to study phenological processes of vegetated land surfaces (e.g. Justice, Holben, & Gwynne, 1986; Tucker, Gatlin, & Schneider, 1984). The use of synoptic scale image time-series for phenological studies is increasingly referred to as land surface phenology (e.g. Dunn & de Beurs, 2011; Ganguly, Friedl, Tan, Zhang, & Verma, 2010; White & Nemani, 2006).

In environments where spatially extensive snow-cover is a recurring seasonal phenomenon, snow exerts a significant influence on vegetative phenology. Snow-cover impacts the aboveground microclimate, subsurface hydrology and soil geochemistry, thereby influencing vegetative growth (Pomeroy & Brun, 2001; Walker, Billings, & de Mollenaar, 2001). In these environments, the length of the growing season is determined by the duration of snow-cover (Körner, 2005). Although snow-vegetation interactions are complicated (Körner, 1998; Körner & Paulsen, 2004; Pomeroy, Holler, Marsh, Walker, & Williams, 2001), some interactions depend upon vegetation height in relation to the depth of the snow pack. For groundcover and low shrubs, snow can form a physical barrier preventing light from reaching foliage. Where this occurs, snow-cover impedes photosynthesis, shortening the duration of the growing period (Wielgolaski & Inouye, 2003). Although covering snow also insulates vegetation from colder ambient air temperature above the snow pack, which allows for limited plant development beneath snow-cover (Inouye & Wielgolaski, 2003), growth in these instances occurs through non-photosynthetic respiration pathways (Kirschbaum & Farquhar, 1984).

Snow-cover also interacts with taller vegetation, such as trees in forests and woodlands, where foliage exists above the snow pack. Although snow can still act as a photoinhibitor when it accumulates on canopy foliage, its main influence over vegetative growth in trees is through temperature. Due to its physical properties, snow-cover is highly reflective in the optical portion of the electromagnetic spectrum

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(Wiscombe & Warren, 1980). Surface temperatures above snow-covered surfaces are lower than they are over snow-free land because less energy is absorbed and retransmitted by a snow-covered land surface (Déry & Brown, 2007; Groisman, Karl, Knight, & Stenchikov, 1994). This reduction in temperature over snow is known as snow-albedo feedback. Because photosynthesis is temperature sensitive (Nobel, 2009), lower temperatures suppress plant growth by preventing the production of the enzymes required in photosynthetic processes (Kirschbaum & Farquhar, 1984), thereby impacting upon tissue formation (Körner, 1998). In this way, trees are more tightly coupled with atmospheric temperatures than other types of vegetation (Körner & Paulsen, 2004).

Although the NDVI has been amongst the most widely used remote sensing indices for studies of land surface phenological dynamics (e.g. Beck, Atzberger, Hogda, Johansen, & Skidmore, 2006; Justice et al., 1986; Myneni, Keeling, Tucker, Asrar, & Nemani, 1997; Reed et al., 1994; Tucker et al., 1984), the presence of on-ground snow is known to confound the derivation of land surface phenological descriptors. In particular, snow confounds those descriptors associated with the start and end of the growing period (Delbart, Kergoat, Le Toan, Lhermitte, & Picard, 2005; Reed, White, & Brown, 2003; Reed, Budde, Spencer, & Miller, 2009; White et al., 2009), as it exacerbates the seasonal dampening of the amplitude of an NDVI signal (Huete et al., 2002). This seasonal dampening makes it difficult to separate the dates associated with changes in vegetative phenology from the appearance or disappearance of snow-cover. Within the literature, several different approaches have been used to account for snow's influence on land surface phenological descriptors. These have included the use of fixed NDVI thresholds, where the start/end of the growing period is taken as the date when NDVI time-series values exceed/drop below a specified value (e.g. Jia, Epstein, & Walker, 2003, 2004; Markon, Fleming, & Binnian, 1995; Myneni et al., 1997; Myneni, Tucker, Asrar, & Keeling, 1998; Suzuki, Nomaki, & Yasunari, 2003; White et al., 2009). Both local thresholds, which are defined on a per-pixel basis (e.g. Høgda et al., 2007; Jönsson et al., 2010; Karlsen et al., 2007, 2008, 2009; Shutova et al., 2006), and global thresholds, where a single fixed value is used for every pixel in the time series (e.g. Jia et al., 2003, 2004; Markon et al., 1995; Myneni et al., 1997, 1998), have been used. Other studies have proposed the use of alternative vegetation indexes (i.e. not NDVI) for deriving land surface phenological descriptors (e.g. Delbart et al., 2005; Delbart, Le Toan, Kergoat, & Fedotova, 2006; Dunn & de Beurs, 2011) or they have proposed substituting snow-covered NDVI values with the snow-free NDVI values (e.g. Beck et al., 2006). In each of these studies, the aim was to derive land surface phenological descriptors that were free of the influence of appearing or disappearing snow-cover.

Despite the introduction of newer innovative methods, such as those proposed by Delbart et al. (2005) and Beck et al. (2006), methods that employ simple NDVI threshold remain amongst the most widely used for seasonally snow-covered environments. Research presented by White et al. (2009) indicated that there remains a need for algorithms that can obtain pure, or snow-free phenological descriptors, particularly in landscapes dominated by evergreen vegetation. While the phenological algorithm developed by Delbart et al. (2005) exhibited good correspondence with in situ phenological observations (Delbart et al., 2005) and modeled phenological descriptors (Dunn & de Beurs, 2011), some limitations with the method were reported. In particular, Delbart et al. (2005) noted that there was uncertainty in the phenological descriptors corresponding to evergreen forests, as the NDII time-series from these areas generally exhibited lower inter-annual variability relative to areas with deciduous vegetation. In this paper, we propose a new phenological method that overcomes this limitation and can be used to derive biophysically meaningful and snow-free phenological descriptors for landscapes dominated by evergreen vegetation.

In this study, we adopt a phase-space approach to deriving land surface phenological descriptors. In chemistry and physics, phase-space diagrams represent the set of all known possible states of a system. James Clerk Maxwell (1879) was the first scientist to use the term phase to describe systems, though this was based on his understanding of Boltzmann's work (1872). An accessible description of phase-space and its origins is presented by Nolte (2010). Phase-spaces are *n*-dimensional orthogonal data spaces that represent all possible states of the system. Examples include the phase-space comprised of data-spaces for position and momentum used to describe bodies in motion, or the temperature and pressure phase-space that describes state transitions of materials (i.e. transitions between solid, liquid, or gas phases). Because phase-spaces represent all known possible states of a system, movement and trajectories through phase-space can be used to characterize the behavior of the system. It should be noted that in the remote sensing literature, the terms feature-space, band-space, or spectral-space are often used to denote the phase-space concept employed here.

In the remote sensing literature several authors have used phase-space type approaches to study land surface dynamics and phenology. Amongst the earliest examples was the Tasseled Cap approach put forward by Kauth and Thomas (1976). Kauth and Thomas (1976) demonstrated that an orthogonal multi-dimensional space representing greenness, brightness, yellowness, and 'non-such' could be used to track phenological development of vegetation in agricultural systems using multi-temporal image sequences from Landsat. Another phase-space type approach was recently presented by Guerschman et al. (2009), who used the NDVI and the Cellulose Absorption Index (CAI) to identify the fractions of photosynthetic vegetation, non-photosynthetic vegetation and bare soil through time in a tropical savannah.

Here, we propose using phase-spaces defined by the orthogonal intersection of NDVI and Normalized Difference Infrared Index (NDII) observations to characterize the land surface phenology of seasonally snow-covered environments. In particular, we test the hypothesis that a pixel's trajectory through the snow-free period can be used to derive land surface phenological descriptors similar to those proposed by Delbart et al. (2005). The descriptors originally proposed by Delbart et al. (2005) included the onset of greening (start of growing period) and the onset of leaf coloring. Though useful for deciduous forests, the authors acknowledged there were greater uncertainties associated with their descriptors when applied to the evergreen forests of their study area, thus prompting the method proposed here.

In Section 2, the alpine study area located in south-eastern Australia is described and the MODIS data and remotely sensed indices used are also presented. Section 3 discusses the foundations for the NDVI–NDII phase-space partitioning and it details the algorithm used to identify the land surface phenological descriptors. The methods used to validate these descriptors are described in Section 4 and the results are presented in Section 5. Sections 6 and 7 provide a discussion and conclusion to the study.

2. Site and data description

2.1. Study area

Situated in the south-eastern corner of the continent, the Australian alpine bioregion encompasses an area of 12,147 km^2 (Fig. 1). The region is culturally, economically, ecologically and geographically significant. As such, much of the area within the alpine bioregion is protected as National Parks (Costin, 1989). The terrain is largely comprised of a dissected plateau. Elevation in the area ranges from 354–2228 m ASL at Mt. Kosciuszko. Significant land cover types within the area are open forests (45.8%), low open forests (33.3%) and woodlands (9.2%) that are primarily dominated by evergreen Eucalyptus species. Areas encompassing true alpine vegetation are mostly confined to Mt. Kosciuszko (Costin, Gray, Totterdell, & Wimbush, 2000). Although Australia's alpine bioregion is globally unique in that Eucalyptus species dominate the alpine landscape, it should be noted that the variability in the remotely sensed phenological signal is driven primarily by