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Response of vegetation growth and productivity to spring climate indicators in the conterminous United States derived from satellite remote sensing data fusion

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ABSTRACT

Spring temperatures strongly influence plant phenology, including budburst, canopy development, and crop planting period. Recent spring warming coincides with earlier and longer non-frozen season trends, and generally earlier spring canopy onset and vegetation productivity increases over the conterminous US (CONUS). However, earlier spring onset increases frost damage risk, with potential negative impacts to productivity. Frost sensitivity and vulnerability is heterogeneous over the CONUS domain, while the occurrence, intensity and regional impact of frost events are difficult to monitor from sparse weather stations. To enhance regional frost risk monitoring capabilities, we developed spring frost day (SFD) and spring frost damage day (SFDD) metrics spanning a long-term (>30 year) record by integrating a satellite microwave remote sensing record of daily landscape freeze-thaw (FT) status and optical-IR sensor based phenology record of start of season (SOS) and day of peak (DOP) canopy cover.

We find a decreasing regional SFD trend (−1.6 days decade^{-1}; $p<0.1$) coincident with spring warming, while the SFDD is generally increasing (1.5 days decade^{-1}; $p<0.1$). Spring warming is reducing frost occurrence, but an earlier SOS trend is paradoxically increasing vegetation frost damage risk. The ecological significance of the SFD and SFDD changes were evaluated using satellite derived vegetation gross primary production (GPP) and vegetation greenness (EVI2) anomalies. Higher SFD and SFDD levels coincide with reduced vegetation growth in spring, but only the SFDD shows significant ($p<0.1$) correlation with EVI2 summer growth anomalies. Apparent vegetation sensitivity to the SFDD varies across regional biomes and elevation zones, while an increasing SFDD trend indicates potentially larger negative impacts on regional vegetation growth with continued warming.

1. Introduction

Spring temperature in temperate and northern climate zones is a major environmental constraint to a range of plant phenology attributes, including canopy budburst, vegetation dormancy and cold hardiness, start of season (SOS), and crop planting period (Karlsen et al., 2007; Kucharik, 2008; Melaas et al., 2013; Vitasse et al., 2009). Recent widespread warming trends are promoting earlier seasonal thawing and longer frost-free days in spring (Burrows et al., 2011; Martin et al., 2010; Yang et al., 2012). Precocious dehardening and faster physiological recovery related to warmer springs are also leading to earlier seasonal onset of photosynthetic activity (Beier et al., 2008; Ensminger et al., 2008; Schwartz and Reiter, 2000). In seasonally frozen environments, a rapid rise in spring temperatures promotes snowmelt, landscape thawing and associated shifts in the surface radiation budget, which help to determine leaf expansion (Ault et al., 2011; Morin et al., 2009; Wesolowski and Rowinski, 2006), flowering (Ellwood et al., 2013; Menzel, 2002), net photosynthesis (Hollinger et al., 2004; Richardson et al., 2009; Urbanski et al., 2007), crop planting dates and seedling development (Mann et al., 2002; Shimono, 2011).

Recently, earlier spring onset and lengthening vegetation growing seasons associated with regional warming trends have been found across the Northern Hemisphere (Cleland et al., 2007;

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Schwartz et al., 2006; Tebaldi et al., 2006). In the continental USA (CONUS), surface air temperature records indicate a reduced number of frost days and earlier date of the last-spring freeze (Easterling, 2002), and a longer frost-free season (Cooter and Leduc, 1995; Kunkel et al., 2004). Several studies have reported earlier CONUS spring vegetation greening trends attributed to spring temperature warming (Wang et al., 2011), and commensurate changes to forest productivity (Augspurger, 2009; Hufkens et al., 2012), phenological responses (Schwartz et al., 2012), and agricultural yields (Hu and Buyanovsky, 2003; Schooley and Proctor, 2003; Tubiello et al., 2007). However, reductions in spring frost days do not necessarily indicate reduced risk of frost damage to vegetation (Meehl et al., 2000; Gu et al., 2008; Rixen et al., 2010) and associated fruit and crop production (Shimono, 2011; Warmund et al., 2008). An earlier spring bud-burst may enhance risk of damage if frost occurs following dehardening and canopy leaf-out (Augspurger, 2013; Ault et al., 2013; Inouye, 2008; Norby et al., 2003; Rigby and Porporato, 2008). Unseasonably late spring frosts may lead to flaccid shoots, root damage, plant cellular dehydration, low stomatal conductance, and ice crystal formation within plant cells (Lamontagne et al., 2000; Pearce, 2001; Warmund et al., 2008; Wipf et al., 2006). Frost damaged plants may also lose photosynthetic carbon and nutrients, resulting in reduced productivity and leaf area, and increased mortality risk (Gu et al., 2008; Martin et al., 2010).

Previous studies have proposed a variety of spring climate indicators in the CONUS domain using gridded estimates of climate parameters and in-situ field observations (Arguez et al., 2012; Diamond and Lief, 2009; Di Luzio et al., 2008; McCabe et al., 2012; Schwartz, 1997). Spring frost days determined from surface air temperatures have been used for studying temporal variability of the spring frost season (Easterling, 2002; Kunkel et al., 2004), determining management routines for agriculture and gardening (Kurtural and Wilson, 2008; USDA Plant Hardiness Zone Map 2012), and analyzing frost impacts on spring phenology (Augspurger, 2009). Common limitations of weather station-based climate indicators in the CONUS domain include observation time differences, sampling artifacts, temporal inhomogeneity due to instrument changes, and regionally sparse observations, particularly in the intermountain west, along the west and east coasts, and in the southeast (Easterling, 2002; Kunkel et al., 2004). Also, previous spring climate indicators have been produced using apparent surface air temperature thresholds (Cittadini et al., 2006; Kunkel et al., 2004; Marino et al., 2011; Terando and Easterling, 2012) without considering different low temperature tolerances associated with vegetation health conditions, genetic differences, plant functional types, and topographic conditions (Jolly et al., 2005; Pearce, 2001; Strimbeck et al., 2007). Global climate models often used to derive spring climate indicators can also show large differences depending on the type of land parameters, observation and assimilation schemes used (Kodra et al., 2011; Pierce et al., 2009).

Satellite passive microwave remote sensing brightness temperature retrievals from lower frequency (≤37 GHz) sensors can detect landscape freeze-thaw (FT) state transitions associated with temporal changes in surface dielectric properties between predominantly frozen and non-frozen conditions (Markus et al., 2009; Ulaby et al., 1982). These data have been used to classify the aggregate frozen or non-frozen status of surface soil and vegetation canopy layers, with reduced sensitivity to potential signal degradation from atmospheric aerosol and cloud contamination, and solar illumination effects (Han et al., 2010; Kim et al., 2011; Wang et al., 2013). In this study, we apply a global satellite microwave daily FT classification record to define a new spring climate indicator (SCI) associated with the number of classified frost days. The FT record is combined with synergistic land surface phenology (LSP) information from satellite optical-IR remote sensing to define the number of spring frost days occurring between spring canopy onset and peak seasonal canopy development. The long-term trend patterns of spring crop planting dates for maize and soybean determined from the United States Department of Agriculture (USDA), National Agricultural Statistics Service (NASS) are also used to evaluate the relative influence of the SCI on mean annual planting dates for these major cropland types. We use satellite optical-IR remote sensing derived spectral vegetation greenness indices and vegetation gross primary production (GPP) estimates to quantify annual productivity and vegetation canopy growth responses to changes in the SCI metrics. Empirical correlation and regression analysis is used to quantify regional SCI trends, spring climate variability and frost related impacts on vegetation productivity within the CONUS domain.

2. Data and methods

2.1. Satellite data

The primary remote sensing data used for this study is a global daily landscape FT Earth System Data Record (FT-ESDR) developed from calibrated overlapping satellite passive microwave remote sensing time series extending from 1979 to 2010 (Kim et al., 2011, 2013). The FT-ESDR provides global daily observations of the landscape FT state at coarse spatial resolution (~25 km) and was derived from a temporal classification of calibrated, overlapping 37 GHz, vertically polarized brightness temperature records from SMMR (scanning multi-channel microwave radiometer) and SSM/I (special sensor microwave imager) sensors (Kim et al., 2012). Four discrete FT classification levels are provided, including frozen (AM and PM frozen), non-frozen (AM and PM thawed), transitional (AM frozen and PM thawed) and inverse transitional (AM thawed and PM frozen) status; the morning (AM) and evening (PM) FT designations are defined relative to equatorial crossing times of the orbital brightness temperature retrievals from SMMR (~12 AM/PM) and SSM/I (~6 AM/PM). Kim et al. (2012) reported overall mean annual FT-ESDR spatial classification accuracies of 91.4 ± 1.05 (temporal standard deviation) and 84.2 ± 0.92 percent for the PM and AM overpass retrievals relative to in situ surface air temperature measurements from the global weather station network (Kim et al., 2012). The FT-ESDR has been used to quantify non-frozen season impacts on vegetation productivity, evapotranspiration and the terrestrial carbon cycle (Barichivich et al., 2013; Bi et al., 2013; Buermann et al., 2013; Xu et al., 2013; Zhang et al., 2011), and to validate the land component of the Community Earth System Model (CESM, Shi et al., 2013). The FT-ESDR product used for this investigation is publicly available (Kim et al., 2013) in a global cylindrical Equal-Area Scalable Earth grid (EASE-Grid; Brodzik and Knowles, 2002) projection format.

We used the MODIS (Moderate Resolution Imaging Spectroradiometer) MOD17A3 (Collection 055; Zhao and Running, 2010) global record to estimate annual GPP variability over the CONUS domain. The 30-arcsec (approximately 1 km resolution) annual GPP data were reprojected from the WGS geographic format to the 25 km global EASE-Grid of the FT-ESDR for this investigation.

The satellite optical-IR vegetation greenness index (VI) data include the NDVI (normalized difference vegetation index; Tucker, 1979) and EVI (enhanced vegetation index; Huete et al., 2002), which provide a relative measure of photosynthetic canopy cover. However, the NDVI shows a loss of sensitivity under high canopy biomass (e.g., forests) levels (Chen et al., 2005; Vina et al., 2004; Wang et al., 2005, 2010) and from atmosphere aerosol contamination (Kobayashi and Dye, 2005). Alternatively, the EVI is purported to have improved canopy sensitivity in higher biomass (e.g.,