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Characterizing hydrologic changes of the Great Dismal Swamp using SAR/InSAR

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ABSTRACT

The Great Dismal Swamp (GDS), one of the largest, northernmost peatlands on the Atlantic Coastal Plain, is underlain by a thick water-logged organic soil layer (peat) made up of dead and decaying plant material. The peatland functions as a main sink for a large amount of soil derived organic carbon. The disturbance of this wetland has negatively impacted the ecosystem and contributed to climate change through the release of the stored greenhouse gases. Surface water level and soil moisture conditions are critical information about peatlands, but monitoring these hydrologic changes has been a challenging task. With a lack of in situ soil moisture measurements, we first explored yearlong Soil Moisture Active Passive (SMAP) data to find the close relationship (R-squared value: 0.80) between soil moisture and groundwater table from March 2015 to March 2016. Based on synthetic aperture radar (SAR) backscattering returns and interferometric SAR (InSAR) phase measurements from C-band Radarsat-1 and L-band ALOS PALSAR datasets, we then analyzed the hydrologic changes in the peatlands. We compared averaged C/L-band SAR backscattering intensity (mid 1998–early 2008 for Radarsat-1, late 2006–early 2011 for ALOS PALSAR) with groundwater level changes and found that the SAR backscattering is significantly responsive (R-squared value: 0.76 and 0.67 for Radarsat-1 and ALOS PALSAR, respectively) to soil moisture changes through a three-way correlated relationship of soil moisture, groundwater level, and SAR intensity. Using InSAR coherence observations, we delineated the inundated area (western and northern regions of GDS) during the wet season, subject to double-bounce backscattering. We measured the relative water level changes in the inundated areas through the InSAR phase measurements, and estimated the groundwater level changes corresponding to soil moisture changes using time-series InSAR analysis. Our comprehensive study has demonstrated that time-series SAR backscattering returns and InSAR analysis can be used to gauge soil moisture conditions and to monitor the hydrologic and vegetation changes in the GDS.

1. Introduction

A peatland is wetland with a thick water-logged organic soil layer (peat) made up of dead and decaying plant material. Peatlands cover <3% of Earth's surface area, but they contain the equivalent of half of the carbon that is in the atmosphere as CO_2 (Dise, 2009). Peatlands are unbalanced systems where production rates exceed decomposition rates, leading to the accretion of carbon, and ultimately functioning as a sink of a large amount of organic carbon (Fenner and Freeman, 2011). The Great Dismal Swamp (GDS) is one of the largest, seasonally flooded, and nonriverine swamp on the Atlantic Coastal Plain (Mitsch and Hernandez, 2013). The impounded water from seasonal flooding boosts the accumulation of the organic soils (peats) in forested wetlands that are highly acid, impermeable, and combustible. For centuries the peatland has been exposed to intense human activities and has experienced drastic changes to the ecosystem and hydrology. The swamp, not far from the first permanent English settlement in the Americas, Jamestown, Virginia, was initially developed by George Washington and drained for agricultural use in many areas. Ditches and canals were constructed throughout the swamp to promote drainage and transport harvested timber. Due to intensive development, the area has been reduced from an estimated 202,350 ha in precolonial times to 85,000 ha today (Day, 1982). Recent scientific studies have revealed vital factors effecting the disturbance and storage processes in peatlands (Fenner and Freeman, 2011; Ise et al., 2008). Hydrology is the driving force controlling most surface and subsurface processes in peatlands. The GDS is not a riparian environment, so the flooding regime is clearly the dominant influence. The frequency, timing, depth, and duration of inundation are all critical factors affecting vegetation distribution patterns and processing rates through the regulation of soil properties such as

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nutrient availability and oxygen content (Day et al., 1988). These hydrologic changes to the soil layer are a key factor in the biochemical processes regulating greenhouse gas fluxes (carbon dioxide and methane) and the storage of carbon (Ise et al., 2008).

Methane is produced in the anaerobic conditions of saturated peatlands and with shallow ground water conditions methane is released into the atmosphere. Methane emissions are reduced when the ground water surface drops, forcing the gas to travel through aerobic soils where methanotrophic bacteria consume the gas (Harriss et al., 1982; Fenner and Freeman, 2011). This relationship to ground water can influence the regulation of soil decomposition processes and greenhouse gas fluxes, and periodic, seasonal water inputs to the GDS have created an anoxic environment where decomposition of organic material is slowed, effectively storing the carbon within the saturated soils. These unique soil conditions also support a limited range of vegetation species that increase the uptake of atmospheric carbon dioxide, including Atlantic White Cedar, Cypress Gum, Maple Gum, and Pine Pocosin (Sleeter et al., 2017).

Preserving the natural hydrologic changes in peatlands is crucial for regulating the negative impacts associated with the disturbance of peat soils. Because the GDS is primarily influenced by seasonal fluctuation of surface water and groundwater flow, extensive anthropogenic drainage efforts have resulted in significant drying of the near-surface peat layers. These conditions have progressively converted the wet, organic rich soils into dry, granular soils. Soil transformations of this nature are usually irreversible and can accelerate the greenhouse gas flux and make peat soils more susceptible to natural ignition during lightning or human-ignited fires, where the peats burn through smoldering combustion. This flameless form of combustion occurs more readily than flaming combustion, but can be coupled with flaming combustion under drought conditions (Turetsky et al., 2014). The sensitivity of peatlands to hydrologic conditions in the soil and resulting contributions to climate change have been identified and defined (Ise et al., 2008), however, monitoring these hydrologic changes, such as water table and soil water content, has been a challenging task. The spatial extent of hydrologic effects can be both localized and regional, requiring substantial in situ measurements to adequately define changes taking place. The wet, remote, and expansive nature of peatlands, make in situ measurements both difficult and costly to obtain, often resulting in a lack of information.

Synthetic Aperture Radar (SAR), with all-weather and day-and-night observing capability, has become one of the best tools to monitor the freshwater wetlands in the world (e.g., Alsdorf et al., 2000, 2001; Lu et al., 2005, 2014; Lu and Kwoun, 2008; Jung and Alsdorf, 2010; Kim et al., 2009; Kim et al., 2013; Kim et al., 2014; Wdowinski et al., 2004, 2008). The SAR backscatter coefficient from a long wavelength sensor in wetlands is sensitive to soil moisture, surface inundation, vegetation type, and leaf-on/off condition. Radar waves can penetrate vegetation canopy and interact with ground surface, and thus observe the land and water surface beneath the forest canopy and soil moisture content that is correlated with groundwater table. With the capability of discriminating land cover types and delineating inundated areas in large river basins and wetland areas (Hess et al., 1990; Hess et al., 1995; Hess et al., 2003; Ramsey, 1995; Wang et al., 1995; Kwoun and Lu, 2009), SAR intensity can be used to retrieve the soil properties, such as soil moisture, for various hydrological and meteorological applications (e.g., Lu and Meyer, 2002; Kasischke et al., 2009; Kornelsen and Coulibaly, 2013). Furthermore, exploiting phase and coherence components through interferometric SAR (InSAR), we can measure the water level changes and observe the scattering characteristics of vegetation types in these wetland environments (Brisco et al., 2017; Kim et al., 2009; Jung and Alsdorf, 2010; Kwoun and Lu, 2009; Kim et al., 2013; Kim et al., 2014; Lu and Kwoun, 2008; Ramsey et al., 2006).

There has been a strong interest to find the correlation between SAR observations and soil moisture changes through analyzing hydrologic condition in land surfaces where human disturbance (i.e. drainage, deforestation) has put constant pressure on the environmental condition. There have also been numerous efforts to observe the soil moisture in agricultural fields, bare soil fields (Dubois et al., 1995; Le Hégarat-Mascle et al., 2002; Moran et al., 2000; Oh et al., 1992), and vegetation-covered regions (Ulaby et al., 1982; Romshoo et al., 2002; Wigneron et al., 2004; Joseph et al., 2010). Most of these studies relied on SAR backscatter models that utilized low/high order polynomials or exponential and logarithmic equations, that were defined from in situ soil moisture, biomass, and roughness measurements. However, the equations differ from sensor to sensor and site to site, and the SAR backscattering, particularly from spaceborne sensors, is heavily influenced by artifacts from speckles and noise. The coherent contribution of the returned SAR signal comes from independent scatterers randomly distributed in the range cell (e.g., Franceschetti et al., 1992), and the speckle can include the effects of diverse backscattering mechanisms induced by soil moisture, inundation conditions, and vegetation characteristics. To overcome such limitations, the interferometric phases with high coherence can been utilized to estimate moisture changes in bare soils and beneath vegetation. A recent study found that the interferometric phases from InSAR are highly correlated with soil moisture (Zwieback et al., 2015), and the phase consistency in triplets of interferograms was introduced for soil moisture estimation (De Zan et al., 2014).

In our study, the hydrologic changes in the GDS, composed of changes in the surface water and groundwater levels, are related to soil moisture variations. These changes were observed using C- and L-band SAR time-series change analysis in the backscatter coefficients and interferometric phase in low-lying peatlands. We adopted a top-down approach, from a large scale (the entire GDS area), to an intermediate scale (areas according to vegetation covers), and finally at a small scale (a point target in a non-inundated area). This method is adopted to reduce scale related limitations, for example the SAR products, at a large scale, cannot exclude the effect of surface water, but measurements, at a smaller scale in the non-inundated regions, are relatively independent of standing surface water and mostly influenced by changes in soil moisture. Exploiting all available data products (SAR intensity as well as interferometric phase and coherence) from SAR and InSAR maximizes the utility of the spaceborne SAR sensor, and provides better definitions of the spatiotemporal hydrologic changes beneath vegetation and delineations of the areas subject to the impoundment of surface water.

2. Characteristics of study region and data

2.1. Characteristics of study region

The GDS is located on the coastal plain in southeastern Virginia and northeastern North Carolina. The surface gradient is gradual and to the east with soils that consist of unevenly distributed mucky peat underlain by clay over a shallow aquifer (Day, 1982). Once peat covered, most of the swamp floor consisted of oak and hickory forests, but has slowly been replaced by gum, cypress, juniper, and a variety of other species (Bradley, 2013). The western part of the swamp is covered by Cypress Gum (Fig. 1(a, b)), which is a typical southern swamp community adapted to surface inundation for at least part of the growing season. This forest community, covering 12% of the wetland, prospers where standing water is abundant. Cypress Gum forests are characterized by frequent, prolonged flooding from January to June, on poorly drained soils. They are slowly growing, but long-living in comparison to the other forest communities in the GDS, reaching their maximum height at 200 years (average canopy height is 30–35 m). Mortality can occur naturally any time after 200 years, but disturbance often shortens this life span (Sleeter et al., 2017). In the GDS, the Cypress Gum forest, formerly the most extensive association in the swamp, has been transformed into Maple Gum forests due to the change of the hydrologic settings and the intrusion of outside species. The Maple Gum forests,