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Capturing agricultural soil freeze/thaw state through remote sensing and ground observations: A soil freeze/thaw validation campaign

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ABSTRACT

A field campaign was conducted October 30th to November 13th, 2015 with the intention of capturing diurnal soil freeze/thaw state at multiple scales using ground measurements and remote sensing measurements. On four of the five sampling days, we observed a significant difference between morning (frozen scenario) and afternoon (thawed scenario) ground-based measurements of the soil relative permittivity. These results were supported by an *in situ* soil moisture and temperature network (installed at the scale of a spaceborne passive microwave pixel) which indicated surface soil temperatures fell below 0 °C for the same four sampling dates. Ground-based radiometers appeared to be highly sensitive to F/T conditions of the very surface of the soil and indicated normalized polarization index (NPR) values that were below the defined freezing values during the morning sampling period on all sampling dates. The Scanning L-band Active Passive (SLAP) instrumentation, flown over the study region, showed very good agreement with the ground-based radiometers, with freezing states observed on all four days that the airborne observations covered the fields with ground-based radiometers. The Soil Moisture Active Passive (SMAP) satellite had morning overpasses on three of the sampling days, and indicated frozen conditions on two of those days. It was found that > 60% of the *in situ* network had to indicate surface temperatures below 0 °C before SMAP indicated freezing conditions. This was also true of the SLAP radiometer measurements. The SMAP, SLAP and ground-based radiometer measurements all indicated freezing conditions when soil temperature sensors installed at 5 cm depth were not frozen.

1. Introduction

Nearly all of the Northern Hemisphere land area above 45 N undergoes a seasonal transition between frozen and thawed conditions each year, with even more regions experiencing short-term diurnal freeze/thaw (F/T) events. The spatial distribution and timing of these transitions are critical factors affecting the terrestrial water, carbon, and energy balance, with consequential effects on hydrological, ecological and biogeochemical processes. Koren et al. (1999) demonstrated the importance of ground F/T state in weather and climate models, particularly for use in flood forecasting applications, where frozen ground limits the infiltration of rainfall and snowmelt, increasing the potential for overland flow. The emission of nitrous oxide from agricultural fields has been well documented, but a recent study by Wagner-

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Riddle et al. (2017) suggests that neglecting the nitrous oxide emissions that occur when soils transition from frozen to thawed conditions results in an underestimation of this potent greenhouse gas by up to 28%. F/T state is also an important driver for vegetation growth and net ecosystem CO_2 exchange in perennial systems such as the boreal forest (Kimball et al., 2004) and grasslands (Kreyling et al., 2008).

The use of microwave remote sensing for F/T detection has been well documented using both active and passive systems. Rignot and Way (1994) used a change detection technique applied to C-band (5.3 GHz) synthetic aperture radar (SAR) data from ERS-1 (European Remote-sensing Satellite) to monitor F/T transition across a boreal forest region. Radar detection of F/T state using C-band data continued to be explored using ASCAT data from MetOp (available since 2007; *e.g.* Zwieback et al., 2015); while measurements from SeaWinds on QuikScat (in operation 1999–2009) allowed the use of Ku-band data for monitoring F/T and snow melt monitoring (13.4 GHz; Bartsch et al., 2007; Roy et al., 2010).

Utilizing higher frequency passive microwave radiometer measurements, Kim et al. (2011) used data from the Special Sensor Microwave Imager (SSM/I; 19 and 37 GHz) to estimate surface F/T state for both morning and afternoon passes over a period of 20 years. Relative to ground based measurements of temperature, the F/T product derived from SSM/I demonstrated accuracies > 80%, particularly for the afternoon overpasses, regardless of landcover type (Kim et al., 2017).

Lower frequency L-band measurements at 1.4 GHz have advantages for F/T detection such as reduced sensitivity to vegetation and greater penetration into the surface soil layer. Roy et al. (2015) found high accuracy retrieving the F/T state from NASA/CONAE Aquarius/SAC-D and ESA Soil Moisture Ocean Salinity (SMOS) L-band radiometer measurements over tundra (> 95%), forest (> 90%) and prairie regions of Canada (> 80%). Rautiainen et al. (2016) used SMOS measurements of brightness temperature to develop a F/T algorithm, but found ancillary air temperature information was necessary to mitigate obvious false positives in the freeze and thaw retrievals. In 2015, the NASA Soil Moisture Active Passive (SMAP) mission was launched, with a mission requirement of determining ground F/T state with an accuracy > 80% (Entekhabi et al., 2010). Originally, the F/T product was to be produced at 3 km resolution based on SMAP backscatter measurements, but with the failure of the SMAP radar in July 2015, the transition to a radiometer derived F/T product (36 km resolution) was necessary (Dunbar et al., 2016). Recent validation activities suggest good performance for the SMAP radiometer derived F/T product for Arctic tundra, grasslands and forested regions at northern latitudes (Derksen et al., 2017), but minimal evaluation over agricultural environments has occurred. Remote sensing based F/T studies have been conducted at multiple resolutions, from meter-scale for active remote sensing (*e.g.* Rignot and Way, 1994) or ground-based microwave radiometers (*e.g.* Roy et al., 2017; Rautiainen et al., 2014) to kilometer-scale (*e.g.* Roy et al., 2015; Zuerndorfer et al., 1990; Rautiainen et al., 2012; Xu et al., 2016), but there has been minimal evaluation of the agreement of the F/T state measured between these scales. There have also been few validation campaigns conducted specifically for satellite-derived F/T product development and validation, and even less with the use of multi-resolution airborne data useful for F/T studies.

To address this gap, the SLAPEx (Scanning L-band Active Passive Experiment) F/T field campaign was conducted in the fall of 2015 to evaluate soil F/T at resolutions ranging from the point scale (using temperature and soil moisture sensors), meter scale (ground-based radiometers), field scale (field-based measurements and aircraft sensors) and satellite scale (SMAP measurements) during periods of diurnal F/T transitions. Measurement protocols were designed to address the following field campaign goals: 1) use of time series observations of F/T state to examine how high resolution surface modelling is able to capture F/T transitions; 2) perform validation of the SMAP F/T retrieval; 3) identify percentage of a grid cell that must be frozen to be detected by SMAP or airborne measurements; 4) evaluate field-scale variability of F/T and the impact of agricultural land use practices; and 5) evaluate the benefits/limitations associated with active and/or passive sensors to indicate soil F/T state. This paper will outline the overall field campaign, introduce the measurements, and provide preliminary results from manual ground-based sampling, *in situ* network, ground-based radiometers, airborne and SMAP measurements which collectively address objectives 2 and 3 of the overall SLAPEx campaign.

2. Study site

From October 30th to November 13th 2015, the SLAPEx F/T field campaign was conducted over the same domain as the Soil Moisture Active Passive Validation Experiment 2012 (SMAPVEX12) (McNairn et al., 2015), southwest of Winnipeg, Manitoba in an effort to capture diurnal soil F/T events. For this field campaign, 18 agricultural fields (15 fields that are annually cropped and three fields that are currently in pasture or forages) were selected for sampling. Fields were selected by considering soil type (in an effort to sample a range of soil texture) and permission from landowners was secured. These 18 fields are a subset of the fields sampled during SMAPVEX12, with the exception of one of the forage fields sampled, referred to as field 25 in this experiment. Further description of the SMAPVEX12 domain can be found in McNairn et al. (2015). It should be noted that apart from the pasture/forage sites, all annual crops had been harvested and all fall tillage activities were completed prior to the start of the campaign, ensuring residue and roughness characteristics did not change during the period of measurements.

3. Experimental design

The SLAPEx F/T campaign was conducted to evaluate the ability to detect F/T state at multiple resolutions ranging from the plot scale, as measured with ground sampling, *in situ* networks and surface-based radiometers, the field-scale as measured by airborne sensors, and large-scale (SMAP measurements at 36 km resolution).

Field measurements were collected by sampling teams on a total of 5 days between October 30th and November 13th, 2015. On each sampling day, teams would conduct ground measurements of temperature and soil relative permittivity (ε_r) twice a day (0500 to 0800; 1100 to 1400, local time) in an effort to capture both frozen (morning) and thawed (afternoon) conditions, coincident to the SLAP flights. Airborne observations were limited to 7 days during the period mainly due to above normal temperatures and rainfall, but included 5 days with paired morning and afternoon flights where soil conditions transitioned from frozen to thaw between the morning and afternoon flight times. Measurements from 17 SMAP overpasses (nine descending at ~0700 local time; eight ascending at ~1900 local time) also occurred during this time period.

3.1. Ground sampling procedures

3.1.1. In situ network

On October 25th and 26th an *in situ* network of Stevens Hydra II probes (Stevens Water Monitoring Systems Inc., Portland, OR; herein referred to as Hydra II probes) were installed on 18 agricultural fields (Fig. 1) within the SLAPEx F/T domain. The Hydra II probe instruments have four 5.7-cm-long tines (0.3 cm diameter) extending from a cylindrical instrument head which measure ε_r of soils using the principles of frequency domain reflectometry as outlined by Campbell (1990). These instruments have been used in many previous soil moisture campaigns within this region (*e.g.* Adams et al., 2015; Pacheco et al., 2015; Rowlandson et al., 2013, 2018). Laboratory validation studies of the instruments (*e.g.* Seyfried et al., 2005) suggest low inter-sensor variability.

To ensure that a range of soil types within the region were sampled,