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Assessment of differences between near-surface air and soil temperatures for reliable detection of high-latitude freeze and thaw states

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A B S T R A C T

Near-surface air temperature and the underlying soil temperature are among the key components of the Earth's surface energy budget, and they are important variables for the comprehensive assessment of global climate change. Better understanding of the difference in magnitude between these two variables over high-latitude regions is also crucial for accurate detections of freeze and thaw (FT) states. However, these differences are not usually considered and included in current remote sensing-based FT detection algorithms. In this study, the difference between near-surface air temperature at the 2-m height and soil temperature at the 5-cm depth is assessed using ground-based observations that span a three-year period from 2013 to 2015. Results show noticeable differences between air and soil temperatures over temporal scales that range from diurnal to seasonal. The study also suggests that the ground-based upper layer soil temperature may be a better surrogate than the near-surface air temperature for the reliable detection of FT states at high-latitudes. Furthermore, the results from this study are particularly useful for better understanding the surface energy budget that ultimately drives the land surface processes that are embedded within weather and climate models.

1. Introduction

Near-surface air temperature and soil temperature are among the key variables for the assessment of global climate change and surface energy budget (Zheng et al., 1993; Chudinova et al., 2006). These variables also control soil moisture content, which in turn plays a critical role in ecosystem conditions through the exchange of heat and water fluxes between the atmosphere and the land surface (Brown et al., 2000; Betts, 2009). Soil temperature is also crucial for agricultural practices and vegetation health (height and density), and it is influenced by geographic, climatic, and environmental features. Since in-situ observations of soil temperatures are rather sparse at the global scale, they can be estimated through the energy balance equation and empirical methods. However, the relationships among soil temperature, soil moisture, skin temperature and air temperature are still not adequately explored. These relationships are currently being copiously studied by the research community.

Although both air and soil temperatures have considerable differences, they are oftentimes used interchangeably for some specific applications and in algorithms used to detect high-latitude freeze and thaw (FT) states. Nearly one-third of the global land areas exhibit seasonal freezing and thawing transitions, and these transitions play vital roles in hydrological activities, vegetation dynamics, terrestrial carbon and methane budgets, and in land-atmosphere trace gas exchanges (Jin et al., 2009; Wu et al., 2011; Shahroudi and Rossow, 2014; Du et al., 2015). Accurate detection of regional FT states and their variability is also vital for several land surface process applications. Since ground-observations of FT states in boreal regions are generally sparse and inconsistent, the effective monitoring of FT processes in these regions is difficult. However, remote sensing applications in the active and passive microwave bands have produced reliable FT monitoring over this region (Zhang and Armstrong, 2001; Podest et al., 2014). In the recent decade, several remote sensing-based FT detection algorithms have been developed. For instance, long-term (starting from 1979) daily FT records at the global scale (Kim et al., 2011, 2017) were developed from passive microwave brightness temperatures. Some of these algorithms use ground-based near-surface air temperature observations as reference, while others use upper layer soil temperature as reference. The community, therefore, has yet to reach consensus about which of the two temperatures (or some combination of both) to use in FT algorithms, and the lack of agreed consistency on this issue may have far reaching impacts not only on the detection of FT states, but also on the myriad of other geophysical phenomena that rely on these interactions.

A main objective, therefore, of this study is to assess the differences between in-situ near-surface air temperatures and soil temperatures

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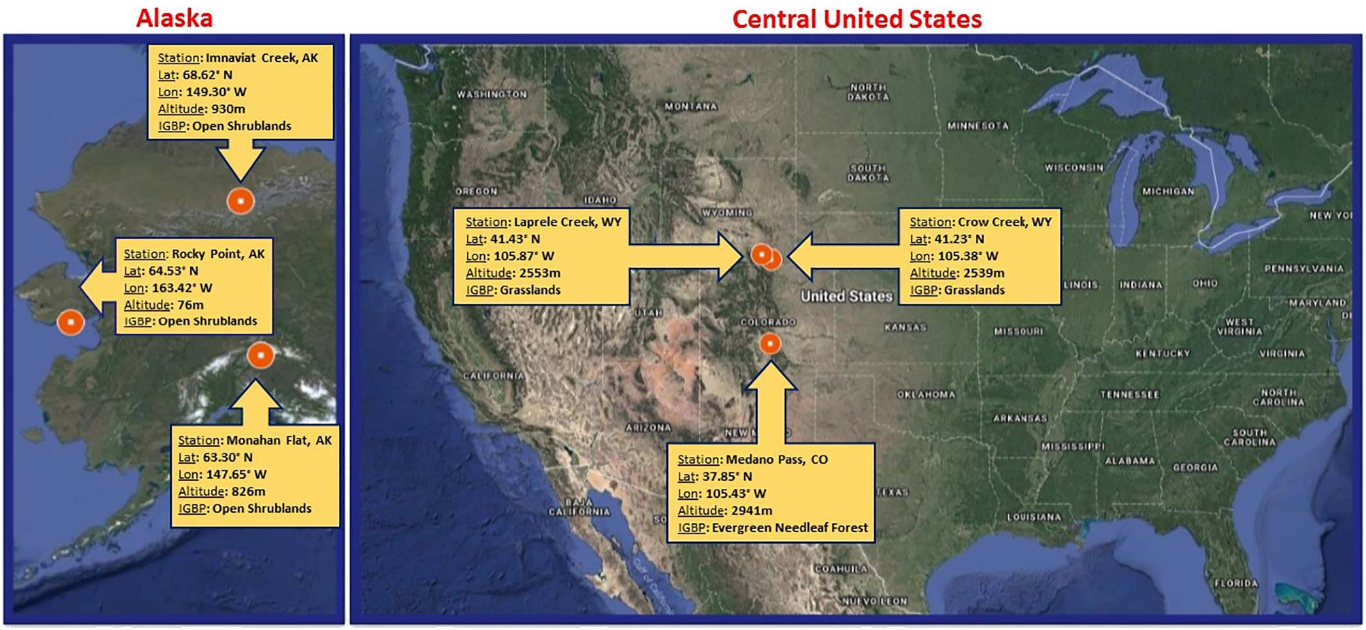

Fig. 1. Location of six selected SNOTEL stations considered in this study. Altitude and IGBP land cover type are also provided for each station.

over selected stations of North America, a region having appreciably good networks of simultaneous air and soil temperature observations. The study will also make the case that upper layer soil temperature, and not near-surface air temperature, should be used as the reference temperature in effective FT state detection algorithms and in the comprehensive study of related soil characteristics.

2. Data and methods

The relevant in-situ near-surface air temperature (at 2 m), soil temperature (at 5 cm), and snow depth data were obtained from the Snow Telemetry (SNOTEL) stations maintained by the National Resources Conservation Service and the National Water Climate Center (Serreze et al., 1999). Hourly data sets were collected over the span of a three-year period from 2013 to 2015. Several SNOTEL stations were used to investigate the differences between both temperatures for distinct weather conditions (e.g., snow versus no-snow). However, for brevity, only the results from six stations are shown and discussed in this study. The six stations were chosen so that they cover a wide range of geographic, topographic, and land cover features (e.g., Fig. 1). The International Geosphere-Biosphere Programme (IGBP) global land cover type product from the MODIS (e.g., MCD12C1 version 051) available at 0.05° spatial resolution (Friedl et al., 2010) is used to determine the vegetation type of the selected stations. Additionally, the land surface emissivity estimates, recently developed using the Advanced Microwave Scanning Radiometer – 2 (AMSR2), were used for the year 2015. These instantaneous land surface emissivity estimates are available at 0.25° spatial resolution (Prakash et al., 2016). To accurately compute the land surface emissivity from AMSR2 brightness temperatures at seven frequency channels, near simultaneous infrared-based land surface temperature, and profiles of air temperature and humidity were used. Furthermore, the discrepancy between the diurnal cycles of passive microwave brightness temperatures and infrared-based land surface temperature was minimized using a suitable statistical method (Norouzi et al., 2012, 2015; Prakash et al., 2016). It was recently demonstrated (Prakash et al., 2017) that due to its direct interactions with soil characteristics, remote sensing-based microwave land surface emissivity detects FT states better than brightness temperature.

Two specific times centered at 1:30 Local Standard Time (LST) and 13:30 LST were chosen for the analysis, because they were comparable to the AMSR2 equatorial crossing times. The linear average of 1:00 LST and 2:00 LST observations were calculated to get observations at 1:30 LST (nighttime/descending), and the linear average of 13:00 LST and 14:00 LST (the linear interpolation used does not affect the results considerably) were used to obtain observations of snow depth, air and soil temperatures at 13:30 LST (daytime/ascending). The differences between both parameters (e.g., soil and air temperatures) were studied for two different soil conditions, i.e., freeze and thaw states. These differences were computed for soil frozen states with soil temperatures less than or equal to 0 °C and simultaneously for air temperatures greater than 0 °C; they were also computed for soil thawed states with soil temperatures greater than 0 °C and simultaneously for air temperatures less than or equal to 0 °C. These differences show the uncertainty in FT state detection due to the use of near-surface air temperature rather than the use of upper soil temperature. The seasonal and diurnal variations of the differences between both temperatures were also examined in this study.

3. Results and discussions

Fig. 2 shows the three-year mean and standard deviation of the near-surface air temperature and the upper layer soil temperature during day and night times for the six selected stations. The three Alaskan stations show mean air temperature values less than 0 °C. Noticeable differences between the soil and the air temperatures are observed over all six stations. The differences between daytime and nighttime temperatures are higher for air than for soil. As expected, lower temperatures during nighttime as compared to daytime are observed from both variables. These differences are associated with the diurnal variation of surface energy flux. Typically, surface energy balance is positive when net shortwave absorption exceeds net longwave loss during the daytime. The surface emits energy during daytime, while it needs more energy at night due to no incoming solar shortwave radiation; this results in downward latent and sensible heat flux from the atmosphere to the surface. Air temperature exhibits larger magnitude of standard deviation as compared to the soil temperature. During the daytime, standard deviation is larger than nighttime in both air and soil temperatures.

In order to investigate the differences between air and soil