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ARTICLE

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Characterization of site-specific vegetation activity in Alaskan wet and dry tundra as related to climate and soil state

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Abstract

We present discrete (2-h resolution) multi-year (2008–2017) in situ measurements of seasonal vegetation growth and soil biophysical properties from two sites on Alaska's North Slope, USA, representing dry and wet sedge tundra. We examine measurements of vertical active soil layer temperature and soil moisture profiles (freeze/thaw status), woody shrub vegetation physiological activity, and meteorological site data to assess interrelationships within (and between) these two study sites. Vegetation phenophases (cold de-hardening start, physiological function start, stem growth start, stem growth end, physiological function end, cold hardening completion) were found to have greater interannual day of year (DOY) occurrence variability at the dry site compared with the wet site. At the dry site, vegetation activity begins on average ~7 days earlier and ends ~11 days earlier. The mean active stem growth window lasts ~54 days for the dry site and ~51 days for the wet site. Vegetation, in both tundra environments, began cold de-hardening functions (warm season prep) prior to atmospheric temperatures warming above 0°C. Similar results were found related to the critical soil freeze/thaw/transition dates; the dry site had a DOY phenophase occurrence range that was 8 days larger than that of the wet site. A longer continuous summer thaw period was captured at the wet site by ~26 days throughout the active layer. In addition, the dry site was measured to have longer spring and fall soil isothermal conditions than the wet site by ~9 and 5 days throughout the active layer. These results show that the dry site's willow shrub vegetation physiology and soil condition phenology is more variable than the wet site. Alongside the in situ data, a remote sensing product from NASA's MEaSUREs program was utilized; our research indicates that the AMSR-derived satellite product is more precise over the wet tundra site with critical date alignment between remote sensing observations and in situ measurements ranging from ~4 to 11 days. Furthermore, the AMSR product was shown to preemptively estimate land surface condition change during the spring transition for both tundra types while lagging during the fall transition and freeze-up periods.

KEYWORDS
Alaska, Arctic ecology, climate change, ecophysiology, freeze/thaw, growing season, phenology, soil moisture, tundra, vegetation

INTRODUCTION

The Arctic tundra is a narrow circumpolar terrestrial ecozone that begins at the northernmost reaches of the boreal forest tree line and extends to the Arctic Seas. The harsh environmental conditions in the tundra ("ET" climate in the Köppen classification system; Kottek et al., 2006) limit biodiversity to a small number of frost and drought/flooding-tolerant perennial and annual plant species and few animal species. Tundra vegetation is characterized by low stature and often-sparse plant cover including graminoids, drought-resistant woody herbs, and mosses (i.e., *Poaceae* (grasses), *Salix* (willow shrubs), and *Sphagnum* (mosses)) (Bliss & Feng Sheng, 2017). Some animals found in the tundra are birds such as Arctic terns and snowy owls, large herds of herbivores, such as muskox and caribou, and predators, including wolves and foxes, all of which roam the open landscape (Callaghan et al., 2004; Meltofte et al., 2013). Arctic ecosystems predominately exist on top of continuous permafrost zones (French, 1980), and in winter, the soils and aboveground biomass are covered with a continuous layer of snow. In the warmer summer months, the active (seasonally thawed) soil layers thaw but reside on top of a continuous permafrost layer, leaving the thawed soil layers shallow and nutrient poor with limited drainage. These regions have an annual rainfall of ~38 cm, but this varies region to region. There are indicators that these conditions (both biotic and abiotic, i.e., the tundra ecosystem itself) are changing (Mishra & Riley, 2014) in response to a warming climate.

The Arctic experiences change in climate more rapidly than the lower latitudes do due to associated changes in the net planetary radiation budget. This effect, known as "Arctic Amplification" (Serreze & Barry, 2011), was first discussed in 1969 (Budyko, 1969); discussions on the topic began gaining momentum in 1980 (Manabe & Stouffer, 1980). Research in the high latitudes has been irresistibly interesting due to the occurring biotic and abiotic changes, and these changes beckon for a higher number of interdisciplinary studies at an increased frequency (Seneviratne et al., 2010). However, the boreal-Arctic is still a statistically under-studied and under-reported realm when compared to lower latitudes, even though these high-latitude ecosystems play a substantial role in global climate modulation (Berner et al., 2005). The boreal-Arctic biome is acknowledged by the scientific community as an early-warning indicator for anticipated global climate change; yet, the region's role and impact in global climate modulation is not fully understood (Berner et al., 2005; Diepstraten et al., 2018).

The tundra has been thought to have limited ecological inter-relational connectivity because of the relatively low biodiversity (i.e., fewer species results in less complex relationship webs); however, recent studies indicate that the ecological interconnectedness is higher than previously assumed (Diepstraten et al., 2018) due to ecological dependency of Arctic trophic levels upon one another and on environmental conditions. This heightened biotic dependency, due to lower biodiversity, results in ecosystem-wide changes from even small variations to the current abiotic ecological architecture (Post et al., 2009); current abiotic changes to the Arctic architecture refers to, among others, reduced permafrost cover and deepening active layers (Mishra & Riley, 2014), increases in wildfires (Hu et al., 2015), heightened glacial melt (Winski et al., 2018), and lowered surface albedo (Andry et al., 2017). The concept of a changing climate affecting biological communities has been known for over a century (Grinell, 1917). Historic phenology events are well documented and provide evidence of how phenology and phenophases are shifting (Pau et al., 2011) in relation to geologic and pre-industrial records (Ciais et al., 2013). Understanding the links between phenology and climate is necessary in order to produce authentic predictions pertaining to climate-induced changes, especially in high latitudes (Karami et al., 2017).

For example, sap flow in Arctic plants may occur only when the plant tissue has thawed and the plant has exited the winter dormancy state (cold hardened). This requires some time after complete thaw and is related to complex biochemical processes that reinstate membrane functions, cell hydration, organelle reconfiguration, and enzyme production. In addition to the vegetation leaving its dormancy state, the soil must be thawed so that main roots are able to develop fine roots for osmotic water and nutrient uptake (carbon and nitrogen). Net photosynthetic carbon uptake in leaves occurs when air temperature is well above zero degrees Celsius and photosynthetic active radiation (PAR) is sufficiently available to compensate for plant tissue respiration. Overall plant growth may occur only when net carbon production takes place in the leaves and surplus carbohydrates are distributed from leaves to within the entire plant by phloem transport to be allocated in stems, stalks, and roots. The resulting radial growth of stems is a proxy for the duration of the allocation phase, as well as its magnitude. Changes or shifts to the duration of these phases across Arctic vegetation influence global carbon and nitrogen cycling directly through changes in this way (Barichivich et al., 2013; Westergaard-Nielsen et al., 2013).

Vegetation phenology also influences atmospheric water and energy exchanges through various feedbacks (Kasurinen et al., 2014; Zhang et al., 2014). Climate-induced shifts in phenology and ecological boundaries may disproportionately affect species (i.e., response and adaptation to the same initial environmental perturbation differs across species) globally, but especially in the Arctic domain, thereby potentially resulting in drastic ramifications for botanical and zoological inter-species interactions (Schmidt et al., 2016). Arctic phenology is a critical driver of global climatic and ecological transformations (i.e., the sum effect of shifting phenological patterns), and continued study is needed to strengthen conceptual knowledge of these ecosystems (Osipov et al., 2017). Currently employed climate mitigation strategies have yet to arrest the accelerating rate of Earth's changing climate (Pachauri et al., 2014), with the rate of Arctic warming being nearly three times greater than the global rate of warming (Andry et al., 2017; Berner et al., 2005). The threat of a near-future large-scale synoptic shift in the overall function, structure, boundary, and global influence of the Arctic is possible as this region will continue to experience exaggerated climatic temperature warming trends while simultaneously being the most vulnerable region to such changes (Berner et al., 2005; Pachauri et al., 2014).

Through this study, we intend to contribute to the scientific body of knowledge on site-specific in situ analysis on wet and dry tundra ecosystems; wet and dry tundra were selected since these two Arctic land cover types comprise most of the terrestrial surface on Alaska's northern slopes (Muller et al., 2018). We expect this study to prove useful in the near future for advancing remote sensing methods of high-latitude terrestrial land surface transitional changes as well as potentially aiding in modeling efforts for carbon fluxes (i.e., through providing soil decomposition windows across the active layer and vegetation carbon sequestration at the surface). In order to accomplish this, we take the approach of assessing relationships between plant stem growth, soil thaw depth, soil moisture regime, and seasonal air temperature. We also examine differences in phenological timing day of year (DOY) between these sites. As seasonal surface states are not only identifiable on the ground but also through spaceborne remote sensing observations, we compare our findings from the in situ datasets collected with data records of surface freeze/thaw fields derived from microwave remote sensing products made available through NASA archives. Our specific points of examination include assessment of (1) the active plant stem growth window as related to the upper soil layer thaw window, (2) the active plant stem growth window as related to the upper soil layers soil moisture availability, (3) site comparison of vegetation phenophase timing between wet versus dry tundra sites, and (4) an initial comparison of in situ-based timing seasonal transitions with freeze/thaw transitions determined from NASA data records.

METHODS

Study sites

In situ measurements were acquired for two tundra sites on the North Slope of Alaska, USA (Figure 1). The region (Arctic tundra) is characterized by vast plains and rolling hills covered either densely (100%) or sparsely (~20%) with shrubbery of 10–100 cm height. Hearty grasses take hold where shrubbery does not densely cover the landscape. Streams and rivers (such as the Sagavarnirtok, Kuparuk, Ivishak, and the Colville) run north from the foothills of the Brooks Range toward the Arctic Ocean. A pronounced surface moisture gradient persists from south to north with ponds and seasonally occurring surface waters being common, particularly at more northern latitudes. Dry and wet sedge tundra conditions dominate. The Arctic temperature varies seasonally, ranging from ~30 to −50°C. The climate in this region is classified as interior continental Arctic tundra (Kottek et al., 2006).

We examine a dry sedge tundra site located at 69.424°N, −148.695°W, near Sagwon, and a wet sedge tundra site located at 69.891°N, −148.767°W, near Franklin Bluffs. The two sites are separated by ~33 miles (~53 km). The Dalton Highway serves as the only overland route that traverses the latitudes between Fairbanks and Prudhoe Bay, providing access to these field sites. The Sagwon site is categorized as a dry sedge tundra sub-ecosystem type with expansive rolling hills, gentle topographic slopes, and tussock vegetation covering the landscape. The Franklin Bluffs site is categorized as a wet sedge tundra sub-ecosystem type with periodic inundation. The site is situated in the lowland plains located to the west of the Franklin Bluffs proper.

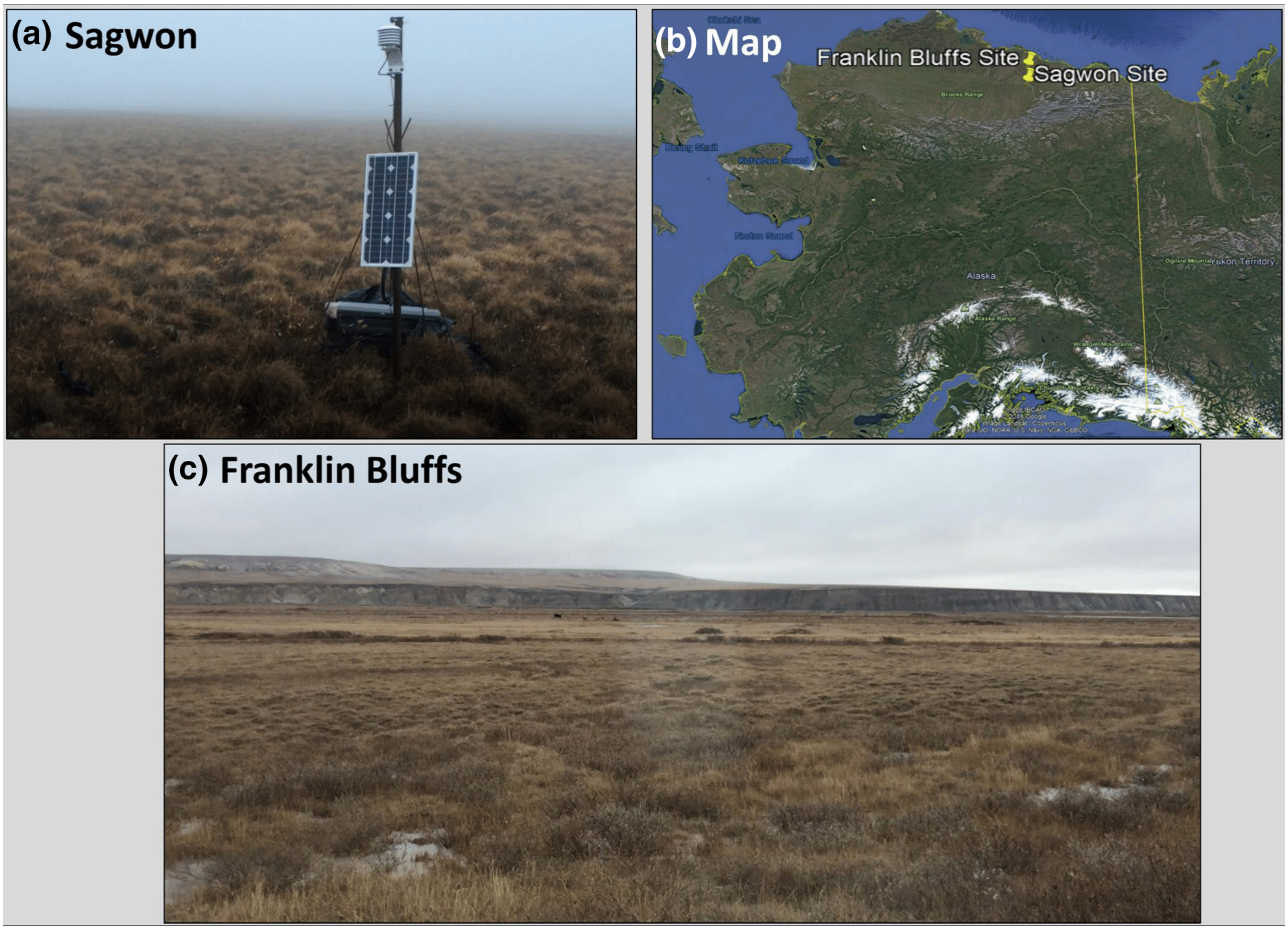


FIGURE 1 Photographs of wet and dry sedge Alaskan tundra study sites and a geographic map showing their locations in Alaska. The Sagwon site (a, dry) is shown on the upper left, general map (b) in the upper right, and the Franklin Bluffs site (c, wet) on the bottom. The general map in (b) was acquired from Google Earth and shows the relative geographic position of the sites in Alaska with yellow pins

In situ field stations and data collection

The in situ station locations were chosen for their respective representations of wet and dry sedge tundra ecosystem types in order to support characterization of soil conditions, vegetation physiology, and associated interrelationships within (and between) sites. At each site, we monitor vegetation and soil temperature, vegetation growth dynamics, soil moisture, and meteorology (relative humidity, air temperature, solar radiation). The years in which these data were collected were 2008, 2010, and 2013 through 2017 for the dry sedge tundra site and 2009, 2010, 2013, 2014, 2016, and 2017 for the wet sedge site. Sensors were set to collect data at a frequency of 2-h intervals. All data were collected in raw form (either voltage or resistance) in the field and converted into usable metrics in the laboratory. The following conversions were used on raw data retrieved from the data loggers: air temperature (via met sensor), $X = (y \times 0.1) - 40$, where x = air temperature in Celsius and y = sensor data in millivolts; relative humidity (percentage) $x = y \times 0.1$, where x = relative humidity in percentage and y = sensor data in; vapor pressure deficit, VPsat $= ce^{at/(b+T)}$, where $c = 6.1094$, $b = 243.04$, $a = 17.625$, and T is air temperature, VPair = VPsat × (RH/100), VPD = VPsat – Vpair; precision dendrometer, 5 kΩ = 1 cm, 1 Ω = 2 μm; soil moisture, raw data recorded in millivolts × 1000 = volts → proprietary Hydra software conversion → = volumetric estimations of soil water content; solar insolation, raw data recorded in millivolts × 5 = solar insolation in watts per square meter; thermistor temperature, temperature in degrees Celsius $= 87.2343 - 32.1338 \times (\ln[x]) + 2.6155 \times (\ln[x])^2 - 0.1914 \times (\ln[x])^3 + 0.0077 \times (\ln[x])^4$, where x = thermistor data in kilo ohms (kΩ).

Vegetation stem temperature and soil temperature profiles were monitored using thermistors implanted in the woody stems and buried at specified depths in the soil (−5, −10, and −20 cm from the soil surface). All thermistors were custom-built and potted in hollow brass cylinders (2.54 cm length × 6 mm outer diameter × 4 mm inner diameter) and sealed with epoxy and waterproof heat shrink wrap for protection from weather. Critical dates for soil temperature were selected based upon the timing of when soil layers warmed to 0°C exiting the winter, thawed to above 0°C entering the summer, cooled down to 0°C in the fall, and when soils cooled to below 0°C in the winter. The sensor beads utilized (Digi-Key brand) in building the thermistors have a temperature accuracy of ±0.01°C. Soil moisture profiles were monitored with Stevens Hydra probes at the same depths as the soil temperature thermistors and retrieved data readings from ~42 cm^3 of volumetric soil space. Accuracy of the three-tined soil moisture probes was ±0.03 wfv (water fraction volume). Critical dates for soil moisture were determined through consistent values equal to or less than 0.1 wfv (intermittent soil water availability) and greater than 0.1 wfv (consistent soil water availability). Custom-built precision spring dendrometers were constructed to document vegetation physiological activity as represented through changes in the stem radius. Dendrometers were able to capture vegetation physiology related to radial stem changes as small as 0.1 μm. Radial stem growth signals (critical vegetation phenophases) were recorded when stem measurements began fluctuating, began increasing consistently, stopped increasing consistently, end of photosynthetic functioning, and completion of winter prep. The meteorological sensor package collecting air temperature and relative humidity was the Vaisala HMP50-L. The Vaisala sensor was covered with a radiation shield so direct sunlight did not affect the data; accuracy of the sensor's measurements is ~0.5°C and 0.5% for humidity.

All sensors were connected through hard-lined electronic cabling to a Delta-T Devices DL2e data logger powered by a 12-V lead-acid battery and housed in a small Action Packer-style weather-resistant box placed near the sensors. The power supply is connected to a solar panel mounted on a pole or tripod. An example illustration of the layout for both sites is shown in Figure 2.

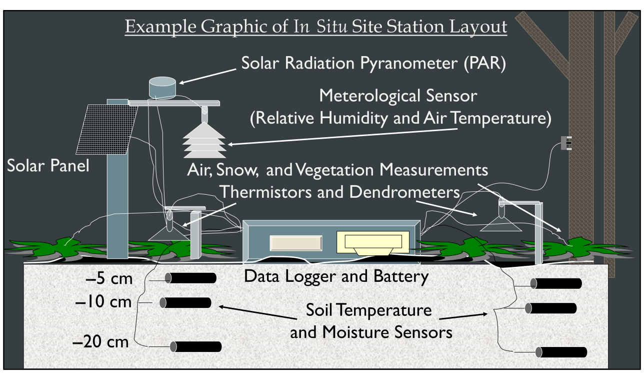


FIGURE 2 Representation of field site layout collecting in situ measurements

The data collected from this sensor suite were compiled into annual time series, manually checked for quality, and converted into metrics for ecological and physiological assessment. Critical dates representing seasonal state transitions in freeze/thaw condition, soil moisture, and vegetation growth metrics were manually determined based upon specific conditions for each parameter (i.e., when soil temperature was arriving or departing from zero degrees Celsius, variations and timing appearance of liquid soil moisture, and the occurrence of vegetation activity phases). Figure 3 shows the temporal breadth in situ data available with examples of collected ecosystem parameters plotted.

Remote sensing datasets of land surface freeze/thaw state

Spaceborne remote sensing observations have been analyzed extensively to assess changes in the Arctic (Bhatt et al., 2013; Karlsen et al., 2014; Vierling et al., 1997; Zhou et al., 2018). These methods have illuminated local and large-scale spatiotemporal change associated with the climate system (Bieniek et al., 2015; Young et al., 2016). In this study, we compare remote sensing measures of land surface freeze/thaw state, comparing with the in situ-based measures of seasonal freeze/thaw transitions. We examine the dates associated with the soil state changes (i.e., the land surface state changes of freezing, thawing, or transitioning between the two) as well as the number of days between such events.

The Advanced Microwave Scanning Radiometer on Earth Observing System (AMSR-E) microwave radiometer flew on-board NASA's AQUA spacecraft from 2002 to 2011. Launched in 2012, the successor instrument, AMSR-2, is currently operational on-board the Japanese Space Exploration Agency (JAXA) GCOM-W1 spacecraft. AMSR-E and AMSR-2 measure microwave brightness temperature and are useful for assessing the frozen or thawed state of the land surface. A global-scale daily landscape freeze/thaw state dataset has been developed from AMSR-E and AMSR-2 brightness temperature time series data (Kim et al., 2018) under NASA's Making Earth System Data Records for Use in Research Environments (MEaSUREs) program. The AMSR Ka Band (36.5 GHz) channel observations were employed to derive a daily temporal resolution time series from the combined AM and PM overpasses with the native spatial resolution of ~13.5 km × 7.5 km reprojected onto a 6-km spatial resolution EASE-Grid format. This dataset provides a remote sensing-based daily classification of the land surface state with four possible categories. These land surface state categories are frozen (AM/PM frozen), thawed, (AM/PM

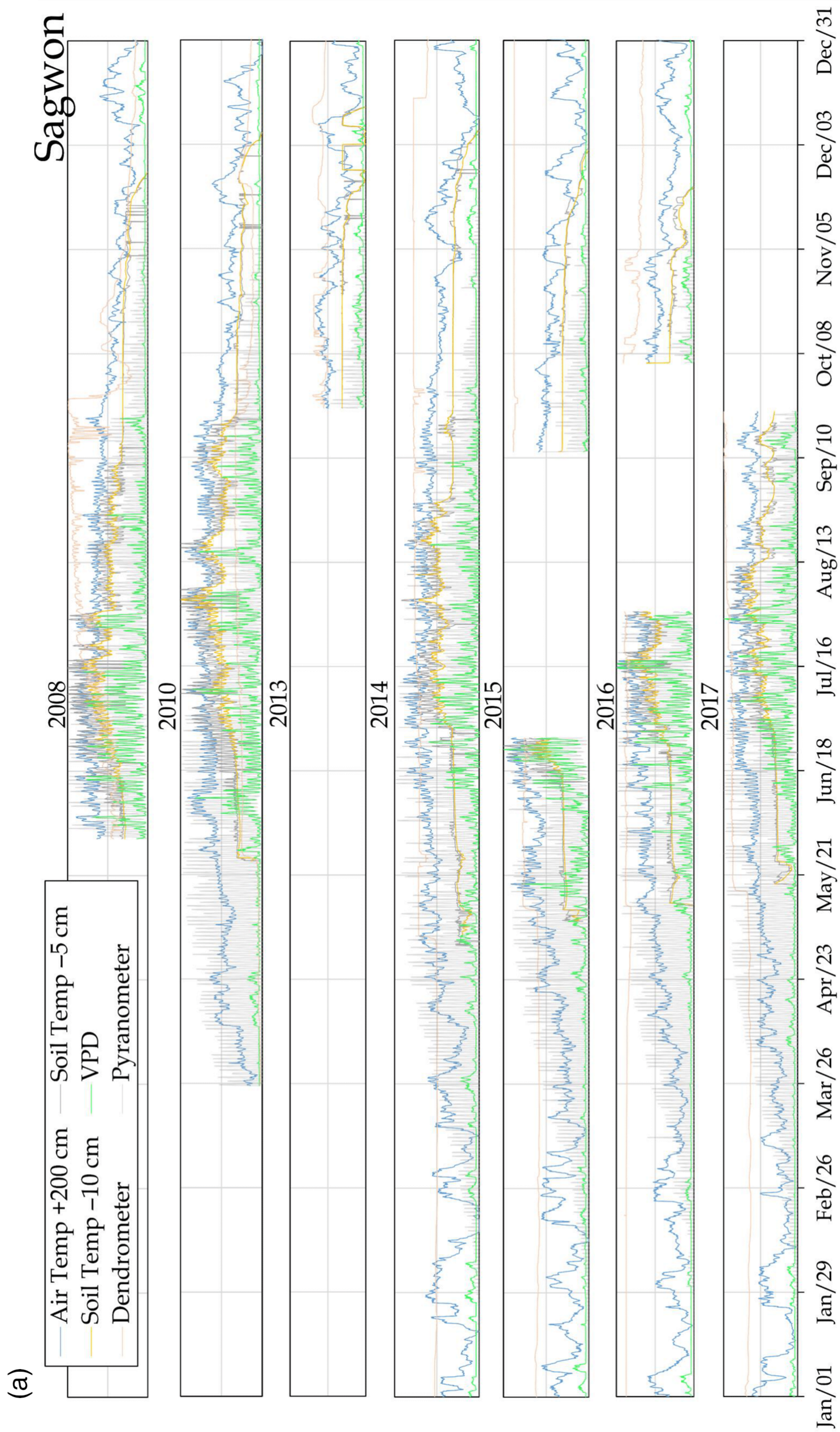


FIGURE 3 Availability of multi-year in situ data utilized for this study. Data are normalized (scaled 0 to 1 on the *y*-axis for both a and b) to illustrate when data were present and where gaps exist in the time series. Air temperature, soil temperature, dendrometry, and meteorological parameters are shown for Sagwon (a) and Franklin Bluffs (b). VPD stands for vapor pressure deficit, and PAR stands for photosynthetic active radiation (solar insolation)

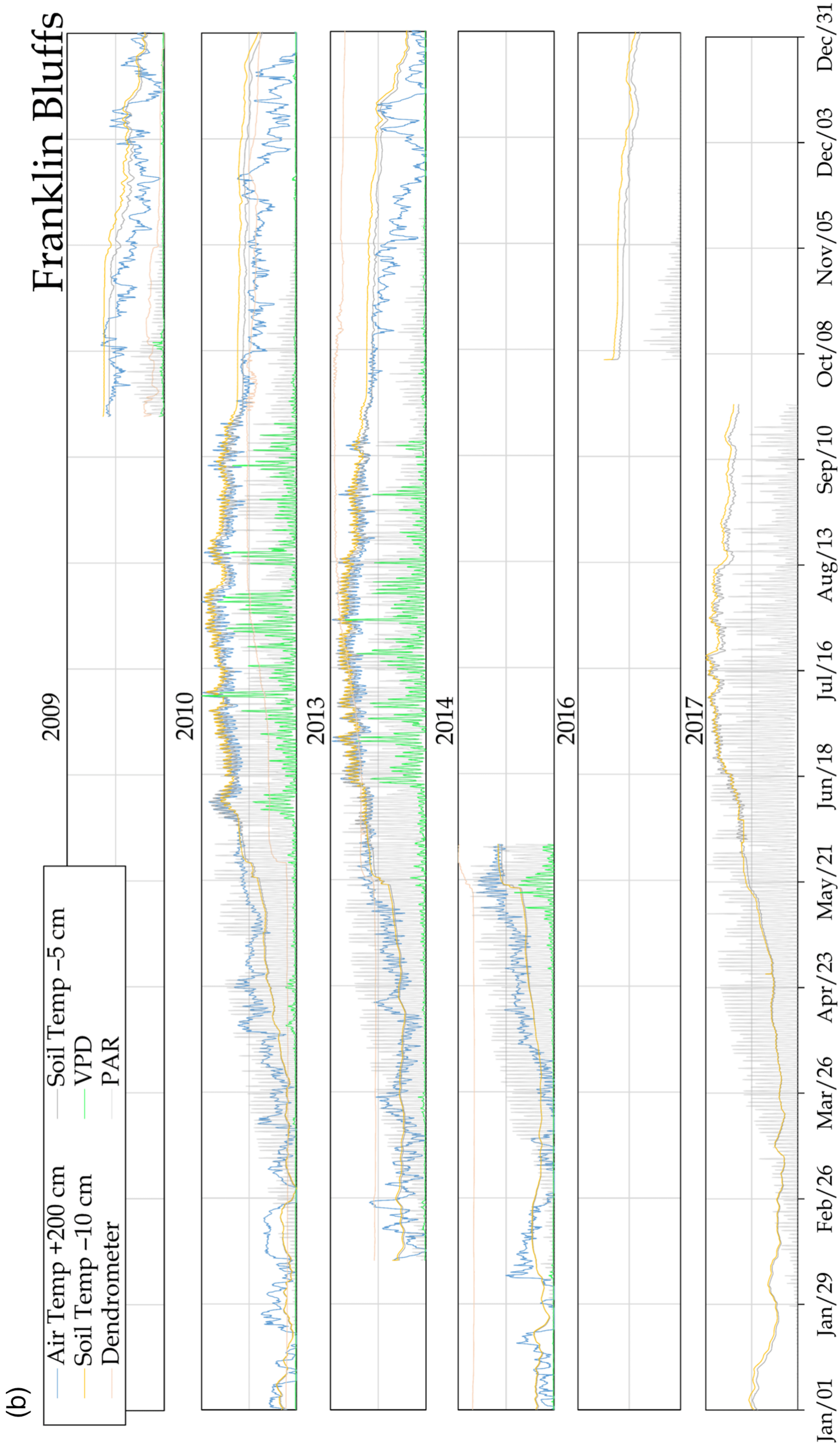


FIGURE 3 (Continued)

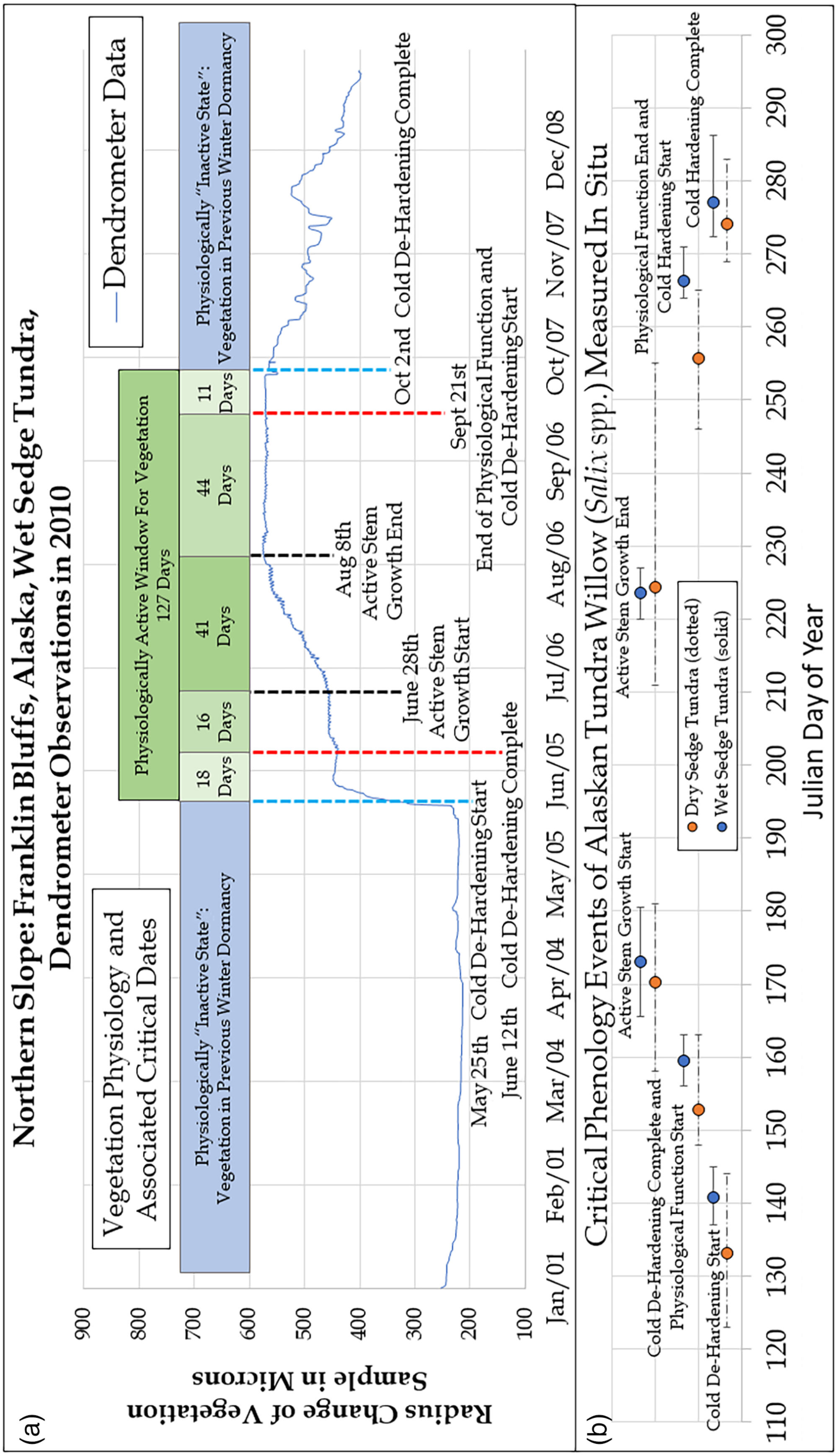


FIGURE 4 Legend on next page.

thawed), transitional (AM frozen and PM thawed), and inverse transitional (AM thawed and PM frozen). The frozen retrieval indicates a frozen condition in both the AM and PM overpass observations while the thawed retrieval indicates that there is a thawed condition present for both the AM and PM overpass observations. The other two states (transitional and inverse transitional) indicate that the overpass conditions did not agree; since the desired data were to determine whether the study sites were in a transitional state or not, these two states were binned together as a singular transitional state.

RESULTS

We evaluated critical phenological events (phenophases) for the two Arctic sites, determining initiation and termination dates of seasonal transitions associated with each in situ sensor. We provide the 2010 phenophase dates as an example and the entire compiled climatology of available in situ data for several years. The number of days between critical events is also examined in relation to the implications of changing lengths of active stem growth in vegetation, thawed active layer, and soil moisture availability. The number of days between events, such as when soil layers are isothermal, hinges on the duration in which microbial activity is thermally permitted, therefore allowing the production and emission of carbon from the soil. We also compare these in situ events with the AMSR-based land freeze/thaw state classification products for the two tundra site locations.

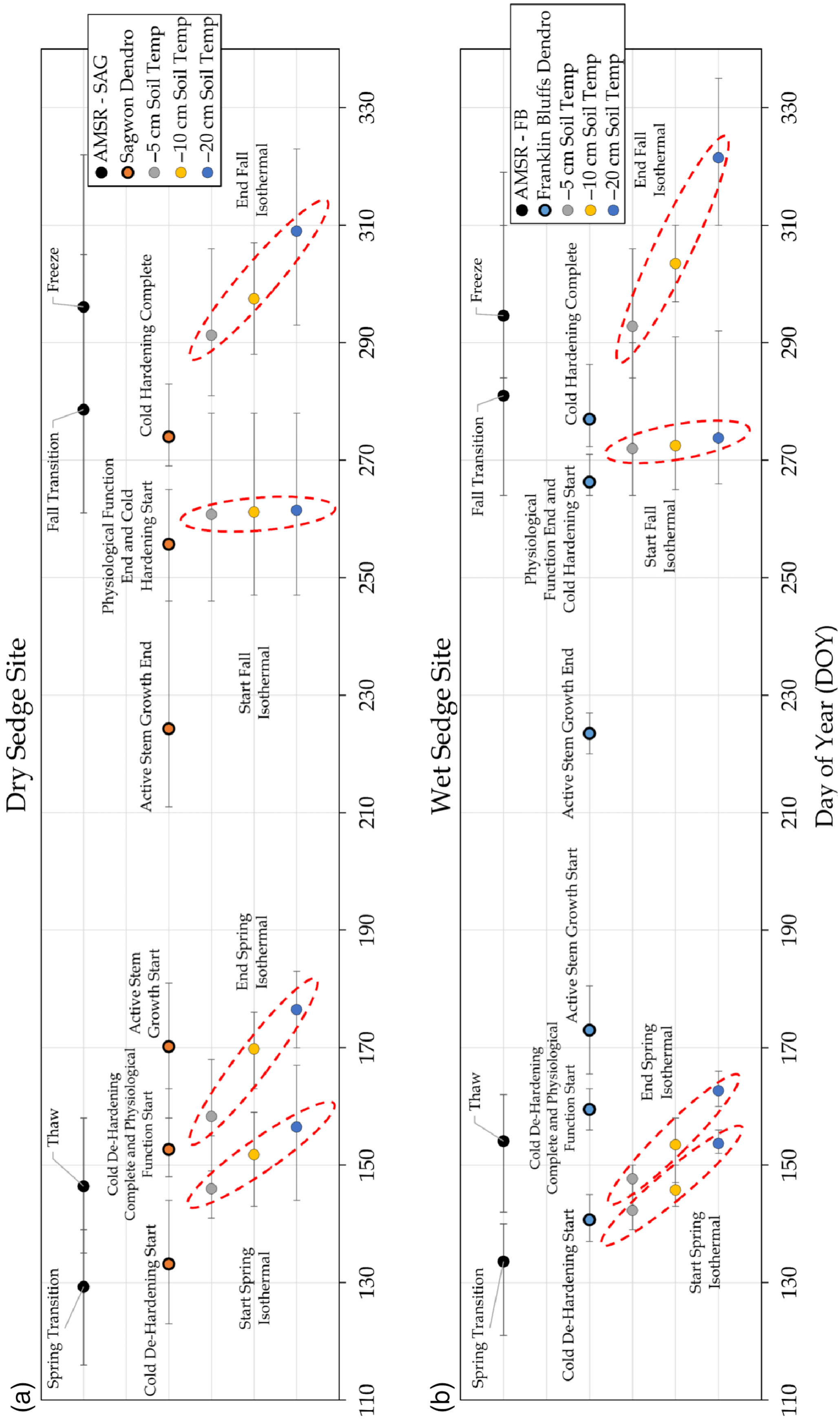
Dendrometry measurements of stem growth

Stem growth of small willows (*Salix* spp.) from the Franklin Bluffs site (Figure 4) is shown for 2010. Vegetation dendrometry began with multiple dendrometers; however, some sensors stopped functioning over the course of the study. We examined data from sensors that functioned throughout the duration of our study at each site. Figure 4a shows the readings of one dendrometer for the year 2010 with the data subdivided into individual phenophases. These vegetation phenophases are annotated with title by DOY. The transitional dates elucidate associated phenophase time windows and are plotted for the wet sedge tundra at the top of Figure 4a. For each year, in situ dendrometer data were available (Figure 3), and phenophase dates were recorded and compiled into a site average per phenophase. Figure 4b shows the results of the average time of phenophase occurrence as measured by the dendrometers. The comparison of the wet and dry sedge tundra sites shows relative timing differences between sites.

The willow vegetation at Sagwon initiates all critical phenological events (except one) before the willow vegetation located at Franklin Bluffs reflecting the difference in growth conditions between the two study sites. If looking at the events in order (from left to right in order of DOY), Franklin Bluffs climatological vegetation phenophases lag Sagwon's by up to 12 days. Across all critical phenophase events, Sagwon's events start and end earlier with the exception of the active stem growth end. The full range of data is provided in Figure 4a; however, the diurnal fluctuations are difficult to see unless the reader zooms in on the figure. The growth signal provided through the data is superimposed by a diurnally variable shrinking and swelling attributed to xylem sap flow and hydraulic saturation of the stem tissue. The min/max lines and markers show the high variability of phenophase occurrence throughout the observed in situ data collection period (Figure 3) with Sagwon (dry sedge tundra) being more variable than Franklin Bluffs (wet sedge tundra).

In the first phenophase, cold de-hardening start, the average occurrence date difference between the wet and dry tundra sites is ~8 days. This phenophase is when the vegetation is emerging from winter dormancy. During the second phenophase, cold de-hardening and physiological function start, the average occurrence date is quite similar with a smaller day difference of ~7 days between them. This activity event marks when cells are rehydrated and physiological function may potentially begin. Phenophase 3, active stem growth start, occurred with an even smaller difference of ~3 days. This is the point when the vegetation has a surplus of carbon and nutrients available and begins adding cells to the stem diameter, resulting in measurable growth. Phenophase 4, active stem growth end, is observed to vary the least with a difference of <1 day. This event denotes when the cellular addition to the aboveground stem ceases. The

FIGURE 4 (a) Dendrometer observations in 2010 at the Franklin Bluffs (wet sedge tundra) site. Phenophase occurrence is marked along with the date of observed occurrence. Window durations between marked phenophases are also provided by day of year (DOY). (b) A comparison of dendrometer-based phenophases for Sagwon and Franklin Bluffs. Mean occurrence dates over the available in situ data are plotted showing the inter-site differences between the studies tundra ecosystems. Minimum and maximum (respectively, meaning earliest and latest) DOY occurrence dates for each phenophase are shown with horizontal limits extending from each event



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fifth phenophase, physiological function end/cold hardening start, has the largest difference between wet and dry sedge tundra vegetation with an observed difference of ~11 days. It is at this point when the vegetation begins preparing for the imminent cold season and produces its sugary sap (biological anti-freeze) while also removing water from the cells to prevent frost-induced cell lysing (cell rupture). The difference in this phenophases activity date may be due to the higher latitude vegetation's ability to physiologically function longer than vegetation at lower latitudes. The sixth phenophase, cold hardening completion, varies only by ~3 days between sites due to vegetation being required to complete this physiological activity in order to survive the rapid decrease in atmospheric temperature as the region enters the cold season. This is when the vegetation has achieved sufficient cold season protective measures and has returned to its winter dormancy state.

Soil temperature profile

The active soil layer thermal regime was monitored at depths −5, −10, and −20 cm from the soil surface using custom-built NTC thermistor assemblies that were potted and sealed for protection. The time series temperature data were applied to determine initiation and termination of isothermal conditions associated with the springtime thaw and the autumn freeze-up shoulder seasons at each depth. The thermal soil threshold for a change in state (in both spring and fall) is when the soil layer arrives or departs 0°C. This analysis supports understanding of the soil thaw and freeze transitions and their associated relationship with vegetation growth over the years in which thermal soil data were available.

The thermal soil phenophase dates related to vegetation physiology (Figure 4b) are shown in Figure 5 for both tundra sites. Red dotted ellipses denote the grouped critical thermal phenophases for the upper active layer across the measured profile. The slanted ellipses, owing themselves to a step-wise progression through the soil profile, are clearly evident in the thawing stages (first, second, and fourth phenophase groupings for both sites) while the vertical ellipses, owing themselves to a more rapid progression of a phenophase through the soil profile, are more evident in the initiation of the fall isothermal period (third phenophase grouping). Notice also the drastic stepwise progression of the end of the fall isothermal period (fourth phenophase grouping) for both sites, more notably Franklin Bluffs. The number of days between the first and the second phenophases for each soil depth is the length of the time of the spring zero curtain in days for that respective soil layer. This is also true in between the third and fourth phenophase groupings for the fall zero curtain. Figure 5 beautifully presents characterization of relational chronology, phenology, and the quantitative timing of soil and vegetation processes in the Alaskan tundra over the in situ study sites, as well as dictating and differentiating which phenophases occur rapidly or gradually across the tundra soil profile.

Soil moisture profile measurements

Soil moisture measurements collected using the Stevens Soil Hydra Probes at −5, −10, and −20 cm are presented in Figure 6. Similar to how the thermal soil phenophases were derived and presented, the critical soil moisture phenophase events are plotted by depth and site, along with annotations for window length in days between each event per depth. The intermittent soil moisture events were determined at the initiation or cessation of soil sensor readings (meaning departing or returning to zero) while the consistent soil moisture event dates were manually identified. The phenophases (the start and end of intermittent and consistent soil moisture) are labeled in Figure 6a for the −5 cm layer but apply to all layers (−5, −10, and −20 cm) in both sub-figures.

Wet sedge tundra experiences longer window times between soil moisture phenophases than dry sedge tundra in five out of the seven comparable phenophase windows. Consistent liquid soil water exists at the wet sedge site at the surface for 115 days while surface soil water is consistently available for ~109 days at the dry. The number of consistent soil water availability days decreases with depth in the dry sedge (from ~109 to ~107) while the wet sedge shows the opposite with an increase in days with depth (from ~115 to ~118).

FIGURE 5 Mean phenological event dates for vegetation and upper active soil layers thermal minimum and maximum (respectively meaning earliest and latest) for the two study sites: the dry site (Sagwon, a) and the wet site (Franklin Bluffs, b). The observed date occurrence is represented with horizontal error limits extending from each critical date. Also plotted in the same manner is the AMSR land surface state product. The abscissa is in day of year (DOY), and the ordinate is unitless; view these figures as a vertically expanded one-dimensional timeline. Red dotted ellipsis shows the critical thermal phenophases grouped across soil depths. Using this figure, relational and quantitative timing between soil layer critical events, vegetation critical events, and remote sensing estimations can be observed and determined

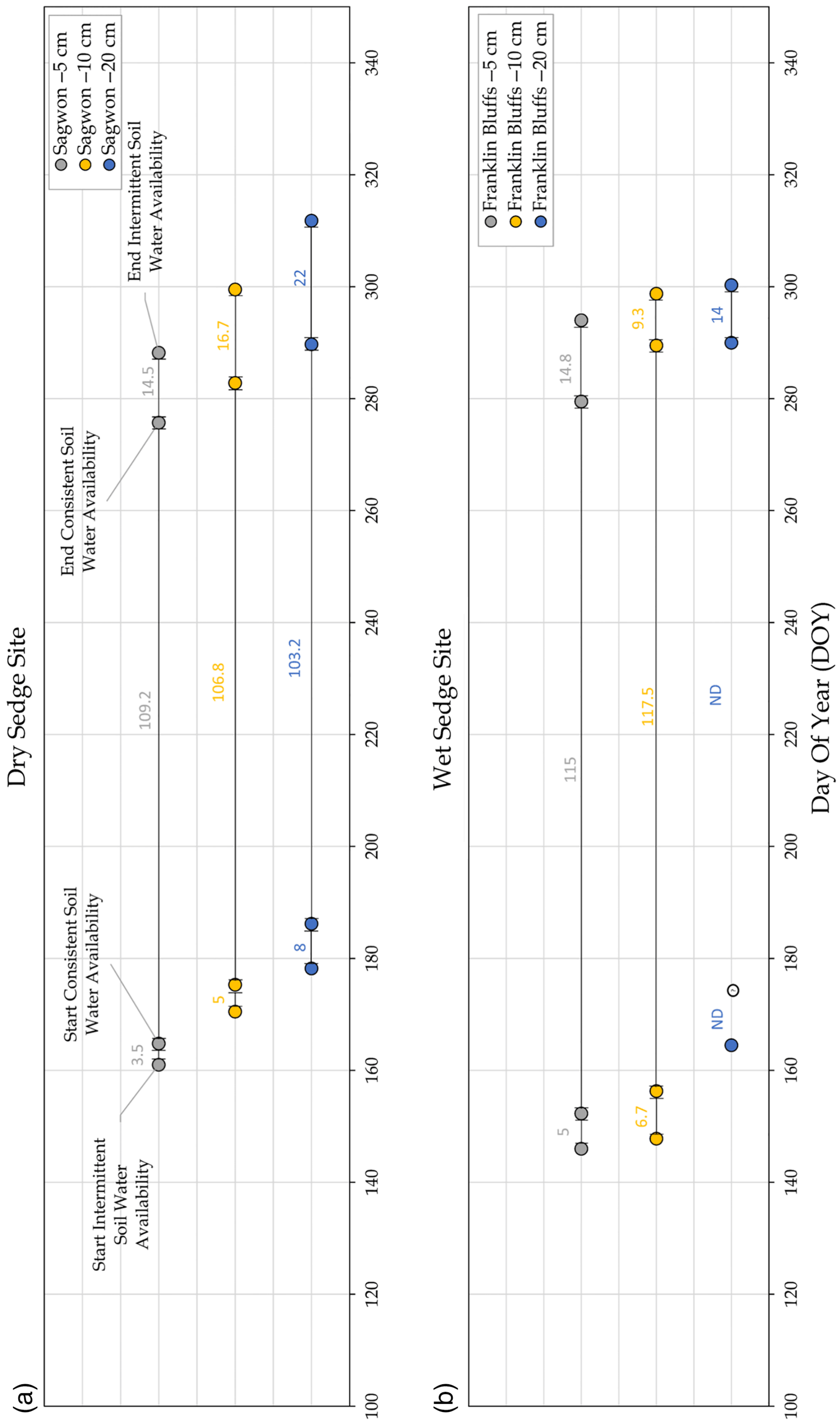


FIGURE 6 Legend on next page.

Critical phenophase timeline for tundra ecosystems

Figure 7 represents characterization of dry and wet sedge Alaskan tundra ecosystems through a linear time plot with phenophases placed in chronological order. In addition, the slightly transparent light green and light blue lines represent air temperature at 2 m and the onsite VPD (vapor pressure deficit) calculated from meteorological measurements. These figures (Figure 7a,b) robustly offer a comprehensive chronological visualization serving as a "road map" of sorts for both wet and dry sedge tundra phenology related to vegetation, soil (both thermal and hydrological), and atmospheric growth conditions. For example, an interesting finding this figure shows is that the vegetation cold de-hardening phase began, for both wet and dry tundra willows, prior to air temperatures warming to zero degrees. This suggests that the willow shrubs were prepping for the warm season while the environment still had sub-freezing atmospheric temperatures. Another example is that by the time vegetation cold de-hardening is complete at the dry tundra site, only the −5 cm soil layer has thawed. Comparatively, at the wet tundra site, when vegetation has completed warm season processes prep, the −5, −10, and −20 cm soil layers have all thawed. A third example is that willow shrubs take, at both tundra sites, 8 days to complete winter prep processes (suggesting that the physiological activity that must occur does not depend on continuously available soil moisture since all soil layers show that continuous soil moisture has ended).

Interannual variability of wet and dry sedge tundra soil and vegetation measured in situ

Interannual variability is determined as IAV = LOS − EOS, where IAV = interannual variability, or observed event occurrence range, of the respective parameter captured over the available in situ data, LOS = latest observed start date, and EOS = earliest observed start date. All dates are reported in DOY. Interannual variability is reported in Table 1. Of the 30 cumulative in situ vegetation and soil phenophases observed and monitored over Alaskan tundra, one phenophase was not comparable between sites (as shown in Figure 6, i.e., initiation of soil water availability at the −20 cm layer for wet tundra). This was the only phenophase to not have at least one representative occurrence date. In addition, one phenophase had the same start date range between the wet and dry tundra sites (−10 cm soil start intermittent water availability), resulting in a start date occurrence range difference of zero between the sites.

Of the remaining 28 comparable phenophases between Sagwon (dry sedge tundra) and Franklin Bluffs (wet sedge tundra), dry sedge tundra shows a more variable start date range for 24 of the 28 phenophases. The wet sedge tundra controlled a wider phenophase start date range for the four remaining phenophases; these included the cessation of both consistent and intermittent soil water availability for the −5 and −10 cm soil layers. These results show the dry sedge tundra ecosystem as having higher interannual variability for the initiation of the majority of phenophases for both vegetation and soil processes when compared to wet sedge tundra ecosystem. It is also accurate to state the inverse that the wet sedge tundra ecosystem exhibits a more precise interannual variability for vegetation and soil phenophase initiation when compared to the dry sedge tundra. Furthermore, since wet sedge has a narrower start date window for all of its thermally related soil phenophases, this shows that the freeze/thaw cycle consistently occurs in a more decisive window of time than its dryer tundra counterpart ecosystem. The comparatively more particular thermal phenophase occurrence behavior is suggested to be from the higher volume of water present at the wet sedge tundra site, creating a thermal inertia stabilization effect making the thermal phenophase start dates occur with lower variability and not being as susceptible to atmospheric temperature fluctuations.

Comparison of in situ variables with remote sensing datasets

We employ our in situ data to assessment of the AMSR-based freeze/thaw dataset of the land surface state to examine the associated relationships with the time windows for which the soil layers are frozen, isothermal, or

FIGURE 6 Critical hydrological phenophases of the upper soil layers by depth for the two Alaskan tundra sites. Phenophases for soil moisture/soil water availability are labeled and titled in (a). They are listed chronologically placed left to right as follows: start intermittent soil moisture availability, start consistent soil moisture availability, end consistent soil moisture availability, and end intermittent soil moisture availability. In (b), there is no data for the −20 cm soil layer phenophase of start consistent soil water availability. No data were available for this phenophase over the available in situ datasets. This also prevents the calculation of a window length between phenophases 1 and 2 as well 2 and 3, annotated on the figure with ND (no data)

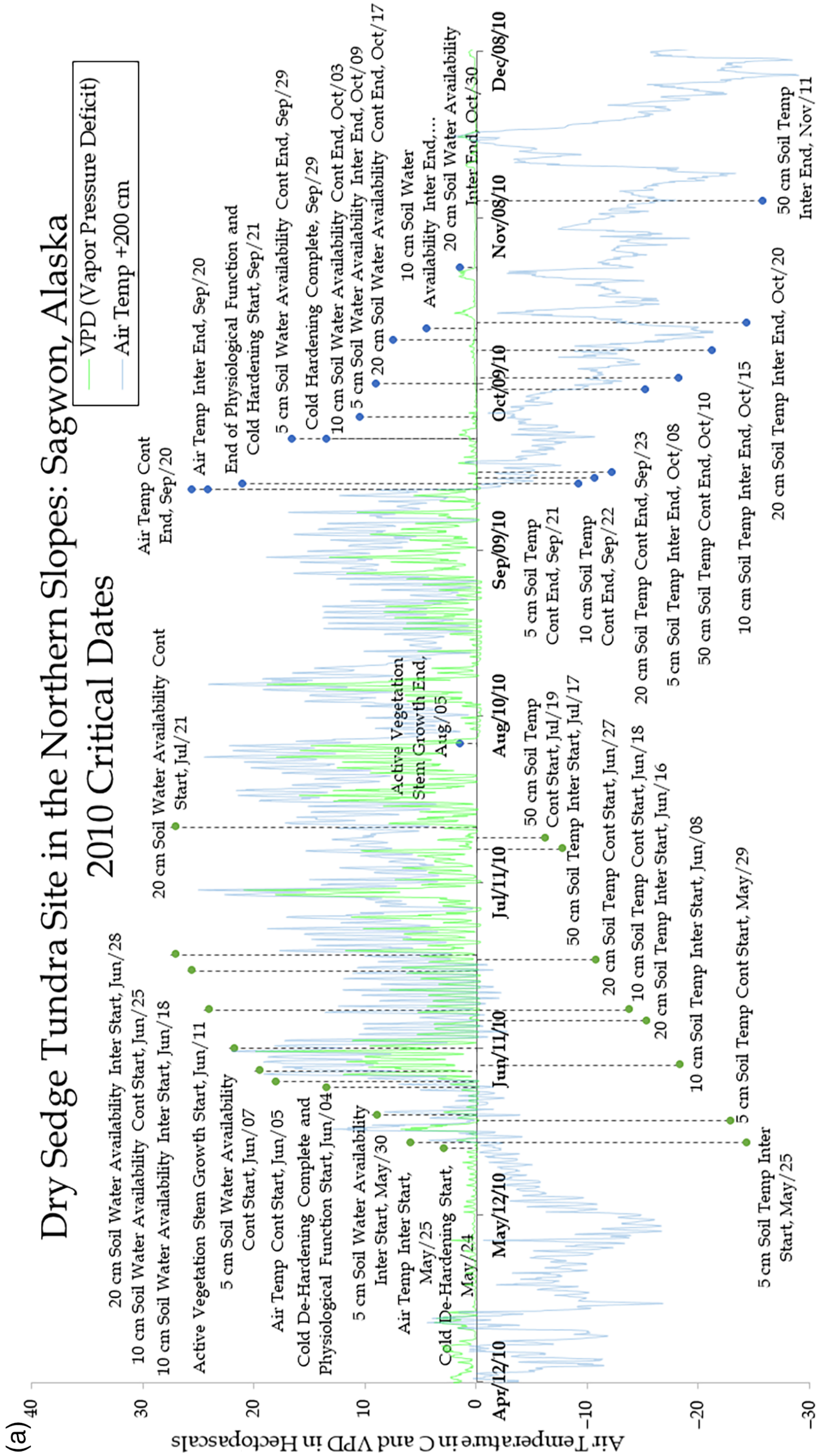


FIGURE 7 Legend on next page.

thawed. The estimated dates for land surface state changes through the AMSR products were retrieved for both sites (Figure 8) and compared to the in situ phenological dates derived from the upper active soil layer (−5 cm depth) thermal and hydrological measurements. Overall, the derived phenophase dates compared show that the AMSR land surface state product is more precise over wet sedge tundra than it is over dry sedge tundra. This result suggests that the AMSR product is more sensitive to, and reliable for, wet sedge tundra land cover.

Tables 2 and 3 show the compilation of phenophases compartmentalized into four sub-tables representing the four land state changes: spring transition (A), thaw (B), fall transition (C), and freeze-up (D). These satellite-based observations were compared to the four phenophases for thermal and hydrological soil measurements. However, since there were six vegetation phenophases, phenophases 1, 2, 5, and 6 were used. The sub-tables are denominated according to the difference in days between the satellite observation and the in situ measurement for each year. Underlined values and values in italics result in the AMSR product leading the in situ date by more than 10 days (underlined values) or by 10 days or less (italics). A match is represented by the value without type enhancement. Boldface and italic boldface values represent the same temporal scale; however, they represent a slight lag and a large lag, respectively, in satellite sensor phenophase dates opposed to a lead. “ND” indicates no date. When viewing the sub-tables for both the wet and dry sedge tundra, it is clear that the AMSR product preemptively estimates changes in both ecosystems during the spring transition while the product lags wet and dry ecosystem changes during the fall transition and freeze-up.

DISCUSSION

The present study aimed to assess plant phenology events related to vegetation growth, hydrological status, and soil condition in the Alaskan tundra. This was achieved by monitoring and characterizing the in situ phenological variability and trends of the vegetation and active soil layers. We also provide a validity assessment of synergistic spaceborne passive microwave remote sensing information derived from AMSR data by using in situ data from two contrasting tundra sites which allowed the identification of critical phenological event dates for soil temperature, soil moisture, and vegetation activity.

Abiotic thermal and soil humidity observations were used in conjunction with observed radial stem changes in willows where radial stem variation served as a proxy for the vegetation growth activity. Plant and vegetation growth may occur only when plant water status is suitable, when the thermal regime allows cambial cell division, and when a surplus of carbohydrates and minerals exists in the cells. The stem dendrometers used in this study allow the identification of active stem growth phases.

Structural biomass growth of woody plant tissue requires that various factors coincide in plants: (1) surplus of carbohydrate production (which in turn requires the function of the leaf photosynthetic apparatus, stomatal control, water, and mineral transport, i.e., sap flow), (2) root uptake of liquid water from the soil, (3) favorable thermal conditions of the aboveground plant tissues for cambial cell division and cell enlargement (i.e., well above the freezing point), and (4) full hydration of the cambial tissue, that is, the absence of significant water stress caused either by excessive water loss by transpiration or by impeded root water uptake. All these conditions must be met if cell growth is to occur in woody stems. Thus, the occurrence and duration of stem radial growth indicates the envelope of time during which tundra vegetation may thrive. The small willows at the tundra sites were chosen as proxy for the vegetation growth envelope because they allow consistent monitoring of cell enlargement. They are also representative of other vascular plants in the tundra since rooting depth for all species is limited by the shallow active layer. All vascular species experience the same hydrologic and thermal challenges in such a small active soil layer. Changes in water transport and saturation of the woody stem axis tissue are reflected by diurnal and reversible shrinking and detailed analysis of the diurnal amplitude of radial shrinking during the day is a further proxy of the occurrence of plant drought stress (Zweifel et al., 2006).

FIGURE 7 Timeline visualization of the observed thermal and hydrological soil phenophases combined with the dendrometric willow vegetation measurements for (a) the dry sedge tundra site for the year 2010 and (b) the wet sedge tundra site over the same year for comparison. The *x*-axis is time, and the *y*-axis is both air temperature in degrees Celsius and vapor pressure deficit (VPD) in hectopascals. Air temperature at 2 m (in light blue) and VPD (in light green) are added for auxiliary backdrop data. The *y*-axis only corresponds to the line data (air temp and VPD). Dot marker lines (vertical black dotted lines) show when the activity occurred on the *x*-axis and are located at different heights for label placement space and clarity; the dot markers are not to be read with the *y*-axis. The dot markers are colored green and blue, binning them as either a spring (thaw) phenophase or a fall (freeze-up) phenophase. “Inter” is the abbreviation for “intermittent” conditions (i.e., parameter is not yet consistently present), and “Cont” is the abbreviation for “continuous” conditions (i.e., parameter is consistently present)

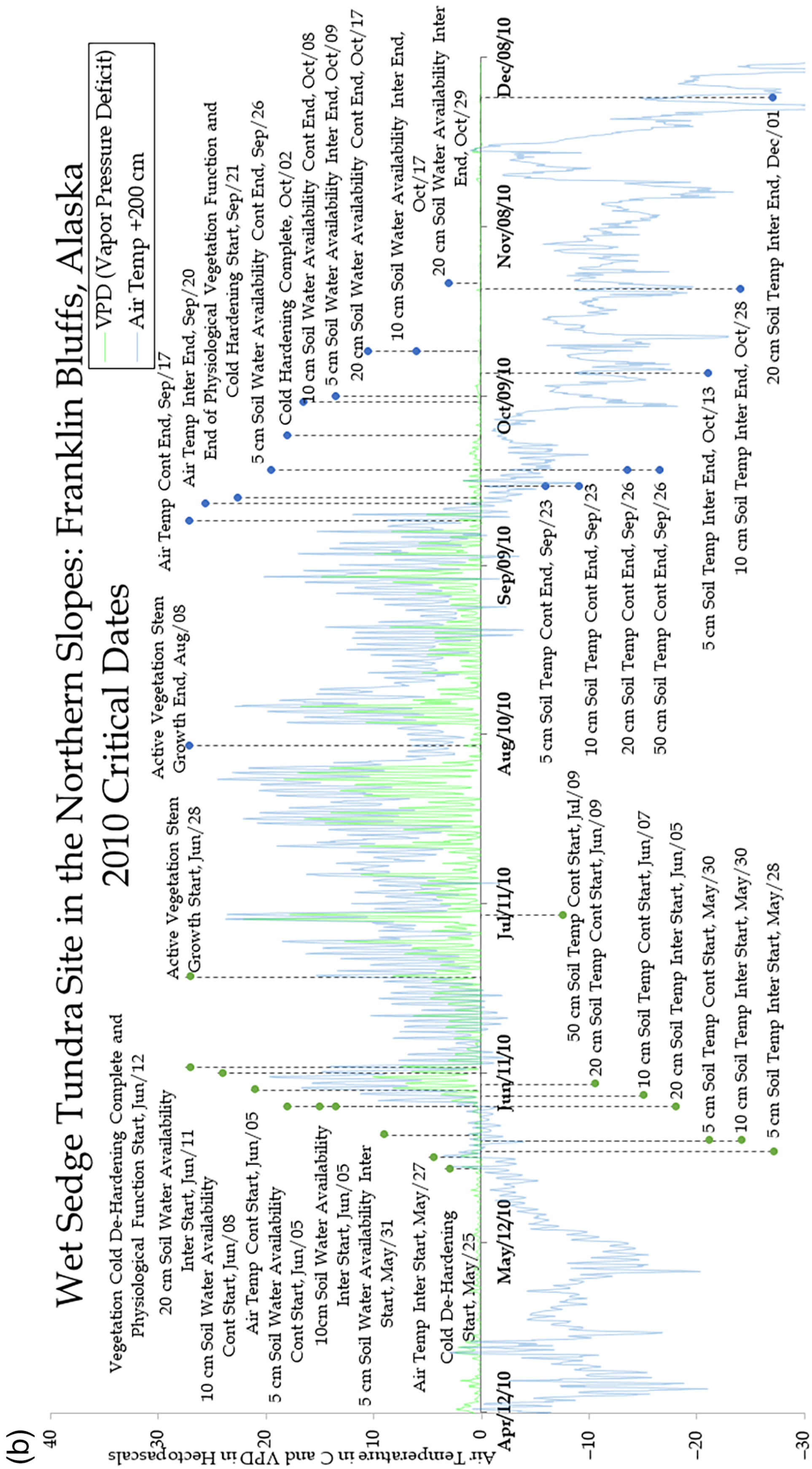


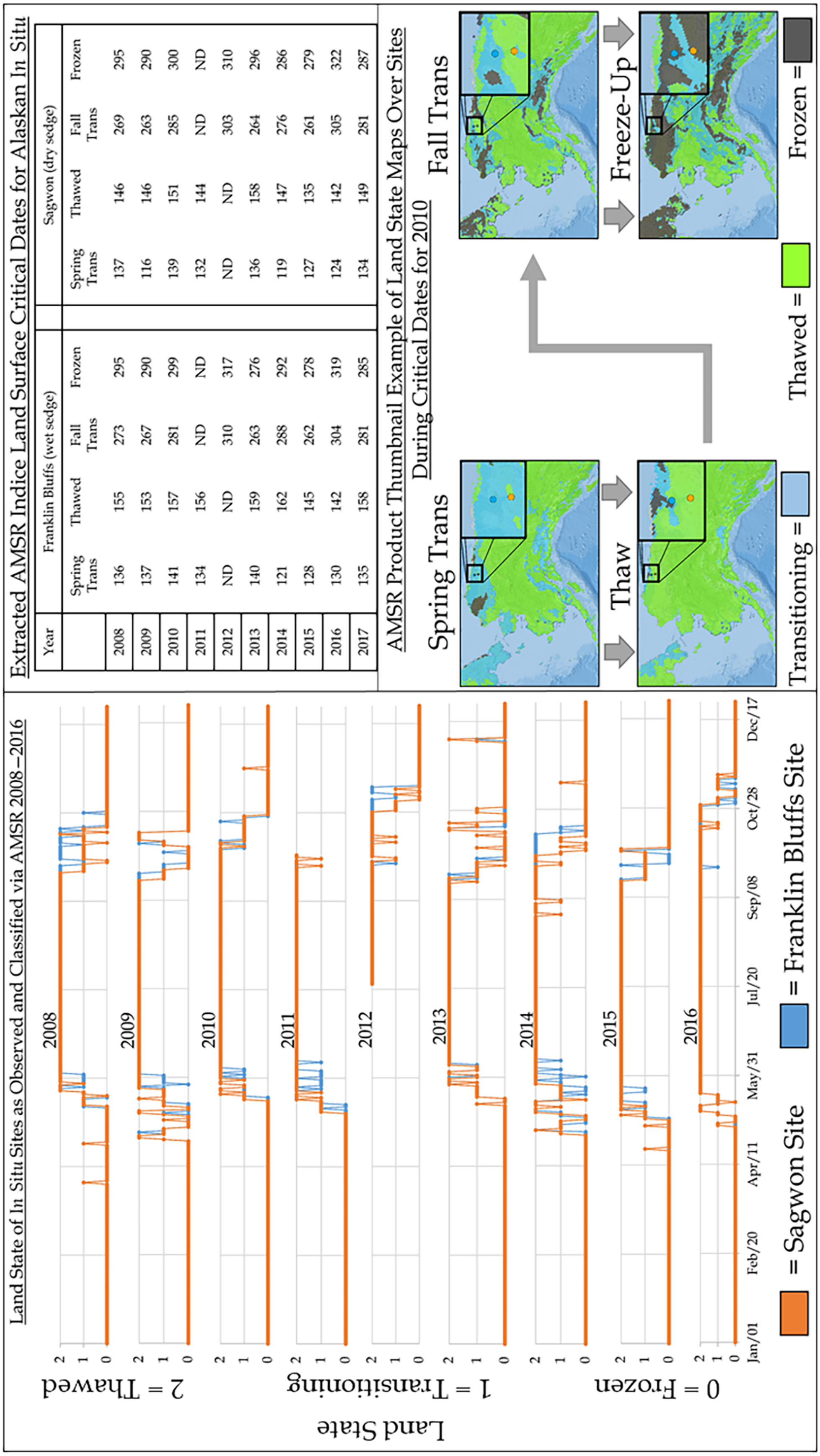
FIGURE 7 (Continued)

TABLE 1 Observed phenophases' interannual start date variability is reported in day of year (DOY)

		Phenophase variability (DOY start date)	
Soil layer depth by phenophase type	**Respective phenophases**	**Sagwon (dry)**	**Franklin Bluffs (wet)**
Vegetation	Cold de-hardening start	21 (133.2)	8 (140.7)
	Physiological function start	15 (152.7)	7 (159.5)
	Active stem growth start	23 (170.2)	12 (173.0)
	Active stem growth end	44 (224.3)	7 (223.5)
	Physiological function end	19 (255.7)	7 (267.5)
	Cold hardening complete	14 (274.0)	11 (280.5)
Soil temperature			
5 cm	Start spring isothermal	14 (146.0)	9 (142.3)
	End spring isothermal	19 (158.3)	5 (147.7)
	Start fall isothermal	32 (260.8)	26 (272.0)
	End fall isothermal	25 (291.3)	22 (292.8)
10 cm	Start spring isothermal	16 (151.8)	7 (145.8)
	End spring isothermal	13 (169.8)	11 (153.5)
	Start fall isothermal	31 (261.2)	26 (272.5)
	End fall isothermal	19 (297.5)	13 (303.5)
20 cm	Start spring isothermal	33 (156.5)	4 (153.7)
	End spring isothermal	13 (176.5)	6 (162.7)
	Start fall isothermal	31 (261.5)	26 (273.8)
	End fall isothermal	30 (309.0)	25 (321.5)
Soil moisture			
5 cm	Start intermittent soil water availability	21 (161.0)	11 (146.0)
	Start consistent soil water availability	15 (164.8)	6 (152.3)
	End consistent soil water availability	33 (275.7)	39 (279.5)
	End intermittent soil water availability	18 (288.2)	29 (294.0)
10 cm	Start intermittent soil water availability	14 (170.5)	14 (147.8)
	Start consistent soil water availability	13 (175.3)	6 (156.3)
	End consistent soil water availability	17 (282.8)	40 (289.5)
	End intermittent soil water availability	17 (299.5)	30 (298.8)
20 cm	Start intermittent soil water availability	14 (178.2)	5 (164.5)
	Start consistent soil water availability	26 (186.2)	ND
	End consistent soil water availability	19 (289.7)	0 (290.0)
	End intermittent soil water availability	17 (311.8)	13 (300.3)

Note: Compiled table consists of 30 start dates for vegetation, soil temperature, and soil moisture phenophase activity (soil phenophases are shown according to soil layer/depth). Un-parenthesized values represent the variability range (in days) of respective phenophase occurrence with the mean occurrence date in terms of day being parenthesized. For example, the first respective phenophase of vegetation (cold de-hardening start) for Franklin Bluffs reads "8 (140.7)." This represents there is an observed 8-day range across the available in situ dataset for this phenophase, and on average, it occurs on day 140.7. ND stands for "no data."

At the dry tundra site, vegetation physiological activity begins on average ~7 days earlier and ends ~11 days earlier than at the wet sedge site. The mean active stem growth window lasts ~54 days for the dry sedge tundra and ~51 days for the wet tundra. The average duration of the vegetation cold de-hardening phase in spring varies by ~1 day with the dry sedge tundra taking longer. As for the duration of the fall cold hardening process, the sites vary by ~8 days with the dry sedge tundra vegetation taking longer to complete its winter dormancy preparation process. In the case of both vegetation processes, although the dry sedge tundra takes more days to



Year	Franklin Bluffs (wet sedge) Spring Trans	Franklin Bluffs Thawed	Franklin Bluffs Fall Trans	Franklin Bluffs Frozen	Sagwon (dry sedge) Spring Trans	Sagwon Thawed	Sagwon Fall Trans	Sagwon Frozen
2008	136	155	273	295	137	146	269	295
2009	137	153	267	290	116	146	263	290
2010	141	157	281	299	139	151	285	300
2011	134	156	ND	ND	132	144	ND	ND
2012	ND	ND	310	317	ND	ND	303	310
2013	140	159	263	276	136	158	264	296
2014	121	162	288	292	119	147	276	286
2015	128	145	262	278	127	135	261	279
2016	130	142	304	319	124	142	305	322
2017	135	158	281	285	134	149	281	287

FIGURE 8 Legend on next page.

complete the necessary biological activities, the process begins and ends earlier in autumn at the dry sedge tundra site.

This shows that there is a smaller inter-site difference for entering the spring phase of de-hardening than entering cold hardening and dormancy (Figure 4). The active vegetation stem growth window for both tundra sites is well within the window for the continuously thawed soil at −5 cm, a depth where most of the plant roots for water and mineral uptake exist. Active stem growth in the wet sedge tundra occurs within the bounds of all the soil depths monitored, not only the −5 cm depth. The dry sedge tundra site has an active stem growth period contained within the bounds of the −5 and −10 cm thawed soil layers. At −20 cm soil depth, the spring isothermal condition ends 6.3 days after the initiation of active stem growth. This shows that the willow's cambial activity does not depend on fully thawed soil conditions at −20 cm or below. Consequently, it can be concluded that woody plants of the tundra do not require a full upper active layer thaw for growth and may have survived more thermally unfavorable years with much less active layer thaw than presently observed. In turn, consistent deeper active layer thaw under a warming climate will present a competitive advantage for willows over the accompanying herb layer. Since willows already grow steadily over vast Arctic regions, they will be able to expand climatic growth boundaries more easily than other herbaceous plants that require more stringent growth parameters. This effect can be currently observed along thermally favorable sites in the southern tundra (Zimmermann et al., 2014).

Regarding thermal conditions, wet sedge tundra shows a longer continuous summer thaw period than the dry sedge tundra site by ~26 days across the active layer (~22 days at the surface −5 cm soil depth). It is likely that this is because the larger thermal inertia of the significantly wetter soils found at the wet sedge (Franklin Bluffs) site compared with the dry sedge (Sagwon) site, which, responds more quickly to air temperature swings. Dry sedge tundra had longer spring and fall soil isothermal conditions than wet sedge by ~9 and 5 days across the measured active layer, although the difference varies by depth. The isothermal condition that occurs during soil state transitions is an important aspect in cold soils and the duration of this phase change determines the soil microbial activity for both organic carbon decomposition and methanogenesis. This length of time during phase change, typically measured in days, in both thawing and freezing soils, is called zero curtain. The longer soils are thawed, the longer soil microbes are actively breaking down organic material, and therefore, the longer high-latitude soils are emitting carbon. Conversely, the longer soils are thawed, vegetation may actively carry out photosynthesis, and therefore sequester carbon from the atmosphere. It is through these two annual cycles that active layer state (freeze/thaw) is critically tied to the carbon cycle/fluxes in the Arctic.

Active stem growth and soil moisture data show that for both sites the active stem growth window is well within the consistent liquid soil water availability period at −5 cm soil depth. The start of the dry tundra active stem growth precedes the onset of the spring isothermal date by <1 day at −10 cm and by ~8 days at −20 cm soil depth. The start of active stem growth and intermittent water availability is currently less than 1 day apart, thereby suggesting that active stem growth requires little or no water availability at −20 cm soil depth and vegetation stem growth mainly depends on liquid soil water availability for wet and dry sedge tundra in the upper 5 cm of the soil layer. This further points out the ecophysiological importance of the upper active soil layers in cold soils in relation to vegetation activity.

In exploring the potential of the remote sensing freeze/thaw state dataset, comparative analysis was performed using our in situ observations with the intent of determining ecologically relevant phases in the tundra environment. We compared the AMSR products from the NSIDC with various ecosystem parameters measured in situ including the upper soil temperature and moisture regimes, as well as vegetation physiology. Overall, we support the use of the AMSR MEaSUREs product utilized

FIGURE 8 Compiled charts (left) show the surface land state for the tundra sites of interest derived from the advanced microwave scanning radiometer (AMSR). The charts on the left provide a time series of the land state as estimated by the product over each year. The *x*-axis is time, and the *y*-axis determines land state in one of three possible categories: 0 indicates frozen, 1 indicates transitioning, and 2 indicates thawed. The sub-table (top right) shows remotely sensed land surface state change date derived from the AMSR products shown by day of year (DOY). "ND" represents "no data" due to the gap in acquisition time in-between AMSR-E and AMSR-2. When the remote sensing freeze/thaw products are mapped to be viewed spatiotemporally, they appear as shown in the thumbnail images provided in the lower right. The thumbnail images are shown at the point of state transition to show the state of the landscape during transition. Note, such maps exist for each day of the year over the years studied. These thumbnails are shown to provide a sense of the data. The data are in the geographic coordinate system GCS_NAD_1983_CORS96 and are rendered in the Alaskan Albers projection. Each pixel in this dataset represents 6 km^2, and the subset zoom image for each thumbnail represents an area of ~200 km^2

TABLE 2 Compiled phenophase dates for the dry sedge tundra (Sagwon) over all years available for both the in situ data and remote sensing data

Year	Day of year	Temperature	Moisture	Vegetation
(A) Spring trans				
2008	137	ND	<u>154</u>	ND
2009	116	ND	ND	ND
2010	139	*145*	<u>150</u>	*144*
2011	132	ND	ND	ND
2012	ND	ND	ND	ND
2013	136	ND	ND	ND
2014	119	<u>155</u>	<u>168</u>	*123*
2015	127	<u>143</u>	<u>158</u>	*131*
2016	124	<u>141</u>	<u>165</u>	*132*
2017	134	<u>146</u>	<u>171</u>	*136*
(B) Thaw				
2008	146	*154*	<u>158</u>	*154*
2009	146	ND	ND	ND
2010	151	**149**	*158*	*155*
2011	144	ND	ND	ND
2012	ND	ND	ND	ND
2013	158	ND	ND	ND
2014	147	<u>168</u>	<u>170</u>	*148*
2015	135	<u>156</u>	<u>162</u>	<u>163</u>
2016	142	<u>165</u>	<u>168</u>	*148*
2017	149	*158*	<u>173</u>	**148**
(C) Fall trans				
2008	269	***258***	*274*	***257***
2009	263	ND	ND	ND
2010	285	***264***	***272***	***264***
2011	ND	ND	ND	ND
2012	303	ND	ND	ND
2013	264	ND	<u>292</u>	ND
2014	276	***246***	276	***246***
2015	261	**254**	**259**	ND
2016	305	***278***	***281***	ND
2017	281	***265***	ND	ND
(D) Frozen				
2008	295	**291**	**285**	***275***
2009	290	ND	ND	ND
2010	300	***281***	***282***	***272***
2011	ND	ND	ND	ND
2012	310	ND	ND	ND
2013	296	ND	ND	ND
2014	286	<u>306</u>	*294*	***271***
2015	279	*281*	*281*	**269**
2016	322	***292***	***288***	***283***
2017	287	ND	ND	ND

Note: The differences in type style show the difference between the remote sensing data date and each in situ date separately. Underlined values and values in italics result in the AMSR product leading the in situ date by more than 10 days (underlined values) or by 10 days or less (italics). A match is represented by the value without type enhancement. Boldface and italic boldface values represent the same temporal scale; however, they represent a slight lag and a large lag, respectively, in satellite sensor phenophase dates opposed to a lead. "ND" indicates no date.

TABLE 3 Compiled phenophase dates for the dry sedge tundra (Franklin Bluffs) over all years available for both the in situ data and remote sensing data

Year	Day of year	Temperature	Moisture	Vegetation
(A) Spring trans				
2008	136	ND	ND	ND
2009	137	ND	ND	ND
2010	141	*148*	*151*	*145*
2011	134	ND	ND	ND
2012	ND	ND	ND	ND
2013	140	*143*	*148*	140
2014	121	<u>139</u>	<u>140</u>	<u>137</u>
2015	128	ND	ND	ND
2016	130	ND	ND	ND
2017	135	*142*	*145*	ND
(B) Thaw				
2008	155	ND	ND	ND
2009	153	ND	ND	ND
2010	157	**150**	**156**	*163*
2011	156	ND	ND	ND
2012	ND	ND	ND	ND
2013	159	***148***	**151**	**156**
2014	162	ND	ND	ND
2015	145	ND	ND	ND
2016	142	ND	ND	ND
2017	158	***145***	**150**	ND
(C) Fall trans				

(Continues)

TABLE 3 (Continued)

Year	Day of year	Temperature	Moisture	Vegetation
2008	273	ND	ND	ND
2009	267	**264**	*275*	**264**
2010	281	***266***	***269***	***264***
2011	ND	ND	ND	ND
2012	310	ND	ND	ND
2013	263	*268*	*267*	*271*
2014	288	ND	ND	ND
2015	262	ND	ND	ND
2016	304	***290***	*306*	ND
2017	281	ND	ND	ND
(D) Frozen				
2008	295	ND	ND	ND
2009	290	*295*	*298*	***270***
2010	299	***286***	***282***	***275***
2011	ND	ND	ND	ND
2012	317	ND	ND	ND
2013	276	*284*	*285*	*286*
2014	292	ND	ND	ND
2015	278	ND	ND	ND
2016	319	***306***	**311**	ND
2017	285	ND	ND	ND

Note: The differences in type style show the difference between the remote sensing data date and each in situ date separately. Underlined values and values in italics result in the AMSR product leading the in situ date by more than 10 days (underlined values) or by 10 days or less (italics). A match is represented by the value without type enhancement. Boldface and italic boldface values represent the same temporal scale; however, they represent a slight lag and a large lag, respectively, in satellite sensor phenophase dates opposed to a lead. "ND" indicates no date.

in this study but the following findings should be considered during future assessments of Arctic tundra conditions. The spaceborne AMSR surface land state products were determined to be more precise over the wet sedge tundra site when compared to the dry sedge tundra site. It was also determined that the AMSR product estimates ecosystem spring transitional changes earlier than they occur in both wet and dry sedge tundra when studied in situ. Furthermore, this was not found to be the same case for the fall transitional changes as the AMSR product was shown to lag ecosystem changes in both tundra subtypes. The pre-emptive spring thaw, as observed from the AMSR product utilized in this study, could be applied to create a predictive algorithm for tundra ecosystems. For example, when the satellite senses a thawed state, users would know that a true surface ground thaw is only a few days away. Conversely, in the fall, users could use the AMSR product used here to firmly say that the soil surface is frozen (since the sensor lags behind the ground state when measured in situ). Moreover, this information could be used to more accurately feed regional, or even global, climate/carbon models that use space borne remote sensing data as inputs to determine freeze/thaw status of high-latitude soils.

CLOSING REMARKS

This analysis shows that Alaskan dry sedge tundra has more variability in soil thermal and vegetation phenophase occurrence dates than wet sedge tundra. We showed that soil isothermal conditions across the active layer column are established rapidly in the fall (<2 days) but not in the spring (~11 days). This demonstrates that heat and energy fluxes are slower moving downward through the active layer in the spring during thaw than they are in fall during freeze-up, thereby dictating zero curtain length (Figure 5).

Springtime isothermal conditions occur and end layer-by-layer in response to rising atmospheric temperatures while in the autumn freeze-up begins isothermally across the entire active soil layer simultaneously buts ends consecutively layer-by-layer; this was observed at both the wet and dry sedge tundra sites. Furthermore, we show that dry sedge tundra is phenologically more variable than wet sedge tundra. Wet sedge tundra had a more consistently occurring freeze/thaw cycle during the observed years.

The Arctic regions are currently undergoing intense climatic changes. Thus, current phenological sequences cannot be assumed rigidly set in neither time or duration, nor at its extreme—the order of occurrence. This may result in significant future changes with severe ecophysiological functional and structural repercussions for the tundra ecosystems (Zimmermann et al., 2014). Therefore, continual monitoring and assessment of chronological–phenological sequences in the tundra ecosystem will allow the identification of ecological shifts as they are occurring in order to illuminate anticipated, yet currently unknown, ecological repercussions. Our future research will examine in situ measurements over cold soils (focusing on zero curtain) and additional high northern latitude sites located in the boreal forests of Alaska and Alberta, Canada.

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CONFLICT OF INTEREST

The authors declare no conflict of interests.

DATA AVAILABILITY STATEMENT

Data (Brown, 2021) are available from Zenodo: https://doi.org/10.5281/zenodo.5787115.

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