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Spaceborne Microwave Remote Sensing of Seasonal Freeze-Thaw Processes in the Terrestrial High Latitudes: Relationships with Land-Atmosphere CO₂ exchange

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ABSTRACT

Landscape transitions between seasonally frozen and thawed conditions occur each year over roughly 50 million square kilometers of Earth's Northern Hemisphere. These relatively abrupt transitions represent the closest analog to a biospheric and hydrologic on/off switch existing in nature, affecting surface meteorological conditions, ecological trace gas dynamics, energy exchange and hydrologic activity profoundly. We utilize time series satellite-borne microwave remote sensing measurements from the Special Sensor Microwave Imager (SSM/I) to examine spatial and temporal variability in seasonal freeze/thaw cycles for the pan-Arctic basin and Alaska. Regional measurements of spring thaw timing are derived using daily brightness temperature measurements from the 19 GHz, horizontally polarized channel, separately for overpasses with 6 AM and 6 PM equatorial crossing times. Spatial and temporal patterns in regional freeze/thaw dynamics show distinct differences between North America and Eurasia, and boreal forest and Arctic tundra biomes. Annual anomalies in the timing of thawing in spring also correspond closely to seasonal atmospheric CO₂ concentration anomalies derived from NOAA CMDL arctic and subarctic monitoring stations. Classification differences between AM and PM overpass data average approximately 5 days for the region, though both appear to be effective surrogates for monitoring annual growing seasons at high latitudes.

Keywords: Remote sensing, boreal, arctic, growing season, net primary production, freeze/thaw, SSM/I, carbon cycle.

1. INTRODUCTION

Each spring approximately 50 million km² of Earth's terrestrial northern hemisphere undergoes a seasonal transition from predominantly frozen to non-frozen (i.e. thawed) conditions¹. These relatively abrupt seasonal transitions represent the closest analog to a biospheric and hydrologic on/off switch existing in nature, affecting surface meteorological conditions, ecological trace gas dynamics, energy exchange and hydrologic activity profoundly. Boreal and arctic regions form a complex land cover mosaic where vegetation structure, condition and distribution are strongly regulated by environmental factors such as soil moisture and nutrient availability, permafrost, growing season length and disturbance. In these seasonally frozen environments, the growing season is determined primarily by the length of the non-frozen period. Variations in both the timing of spring thaw and the resulting growing season length have been found to have a major impact on terrestrial carbon exchange and atmospheric CO₂ source/sink strength in boreal regions^{2,3}. The timing of spring thaw in particular, can influence boreal carbon uptake dramatically through temperature and moisture controls to net photosynthesis and respiration processes^{4,5}. With boreal evergreen forests accumulating approximately 1% of annual net primary productivity (NPP) each day immediately following seasonal thawing, variability in the timing of spring thaw can trigger total interannual variability in carbon uptake on the order of 30%^{2,6}. Temporal variations in the onset of frozen conditions in the fall are also significant but generally have less

impact on annual productivity due to the increased importance of other controls on vegetation photosynthetic activity such as photo-period length⁶.

Microwave remote sensing techniques have the capability to monitor large-scale changes in the relative abundance and phase (frozen or thawed) of water at the landscape surface. Satellite microwave remote sensing, unlike optical/near-infrared systems, is directly sensitive to the freeze-thaw state of the landscape, including vegetation, snow and surface soil layers, and provides an effective measure of growing season initiation for boreal and subalpine evergreen forests^{6, 7, 8}. Satellite remote sensing in visible and near-infrared wavelengths is sensitive to changes in photosynthetic biomass and provides a means for regional mapping and monitoring of seasonal phenology (i.e., bud-burst, canopy growth and senescence) and growing season length for deciduous vegetation⁹. Boreal regions, however, are composed predominantly of evergreen coniferous forests that do not exhibit large seasonal variations in photosynthetic biomass. The growing season for evergreen vegetation is limited primarily by the seasonal non-frozen period, which can be 1–2 months longer than the growing season for deciduous vegetation¹⁰. Air temperature measurements from regional surface weather station networks can provide a relative measure of growing season length for evergreen vegetation, but regional application of these data is limited by sparse station networks and inconsistent monitoring at high latitudes¹¹.

Coarse resolution (~25km) spaceborne scatterometers such as the NASA Scatterometer (NSCAT) and the SeaWinds and ERS scatterometers have demonstrated utility for monitoring and quantifying freeze-thaw transitions at regional scales with daily temporal precision in northern latitudes^{6, 7, 8, 12, 13, 14}. Surface brightness temperature measurements acquired by spaceborne passive microwave radiometry offer the capability for retrospective investigation of variability in terrestrial freeze-thaw state and associated linkages to biophysical processes for the high latitudes. Brightness temperature measurements obtained from the Special Sensor Microwave/Imager (SSM/I) have been applied in terrestrial cryosphere studies including snow cover extent mapping and frozen soils analyses^{15, 16}. Daily mean SSM/I brightness temperatures have also been applied to analyze trends and variability in seasonal thaw events over the terrestrial high latitudes from 1988–2001¹⁷. In this paper, we utilize SSM/I brightness temperature measurements to examine variability in the timing of springtime thaw as observed in early morning and in early evening, separately across the pan-boreal high latitudes for the time period 1988–2002. We apply these data to monitor annual variability in springtime thaw, examining the multi-year time series afforded by the retrospective data set, and compare these results to surface biophysical measurements and annual anomalies in seasonal atmospheric CO₂ concentrations derived from arctic and sub-arctic monitoring stations.

2. METHODS

Microwave remote sensing signatures of natural terrain are controlled by the dielectric properties and structure of landscape constituents¹⁸. Operating at much longer wavelengths than optical sensors, they allow observations day and night throughout the year, regardless of cloud cover, solar zenith angle, and reduced solar illumination that are particularly problematic for optical-infrared remote sensing of high latitudes. Microwave radiometers are passive sensor systems that observe the target's natural emission (emissivity). While continuous coverage of surface state conditions is possible, actual coverage is defined by sensor design and orbital configuration.

The ability of microwave remote sensing instruments to observe freezing and thawing of the landscape has its origin in the distinct changes of surface dielectric properties that occur as water transitions between solid and liquid phases. A material's permittivity describes how that material responds in the presence of an electromagnetic field¹⁹. As an electromagnetic field interacts with a dielectric material, the resulting displacement of charged particles from their equilibrium positions gives rise to induced dipoles that respond to the applied field. A material's permittivity is a complex quantity (*i.e.*, having both real and imaginary numerical components) expressed as

$$\varepsilon = \varepsilon' - j\varepsilon'' \quad (1)$$

and is often normalized to the permittivity of a vacuum (ϵ_0) and referred to as the relative permittivity, or the *complex dielectric constant*:

$$\epsilon_r = \epsilon' / \epsilon_0 - j\epsilon'' / \epsilon_0 = \epsilon_r' - j\epsilon_r'' \quad (2)$$

The real component of the dielectric constant is related to a material's ability to store electric field energy. The imaginary component of the dielectric constant is related to the attenuation of energy within the material. At microwave wavelengths, the dominant phenomenon contributing to ϵ_r'' is the polarization of molecules arising from their orientation with the applied field. Consisting of highly polar molecules, liquid water exhibits a dielectric constant that dominates the microwave dielectric response of natural landscapes. As liquid water freezes, the molecules become bound in a crystalline lattice, impeding the free rotation of the polar molecules and reducing the dielectric constant substantially.

A material's radiometric brightness temperature, T_B , is characterized by its emissivity, e , as $T_B = e \cdot T$, where T is its physical temperature (K). Emissivity is a unitless variable ranging from 0 for a perfectly non-emitting material, to 1 for a perfect emitter (blackbody)²⁰. Emissivity is a function of the material's dielectric constant, and is directly sensitive to the phase (solid/liquid) of water within the media. As water changes from a solid to a liquid phase, its dielectric constant increases dramatically, and significant increases in e and T_B result. Defining freeze-thaw as the predominant state (solid or liquid) of water within the landscape, we utilize the temporal change in T_B associated with the primary landscape springtime thaw event to monitor the timing of thaw across the study domain.

In general, landscapes of the terrestrial cryosphere consist of a soil substrate that may be covered by some combination of vegetation and seasonal or permanent snow. The composite remote sensing signature represents a sampling of the aggregate landscape dielectric and structural characteristics, with sensor wavelength having a strong influence on the sensitivity of the remotely sensed signature to the various landscape constituents. First-order contributions to the landscape brightness temperature are (1) emission by the underlying surface that is attenuated by upward propagation through the vegetation canopy, (2) vegetation volume emission propagating in the upward direction, and (3) vegetation volume emission propagating in the downward direction that is reflected back through the vegetation volume by the underlying surface. These first-order relationships between the landscape physical characteristics and the observed brightness temperature T_{Bp} at polarization p (vertical or horizontal) can be expressed as²⁰:

$$T_{Bp} = T_s e_p \exp(-\tau_c) + T_c (1 - \omega) [1 - \exp(-\tau_c)] + T_c (1 - \omega) [1 - \exp(-\tau_c)] r_p \exp(-\tau_c) \quad (3)$$

where T_c and T_s are the physical temperatures (K) of the vegetation canopy and the underlying surface, respectively, τ_c is the vegetation opacity along the slant path defined by the radiometer look angle and canopy height, ω is the single-scattering albedo of the vegetation medium, and r_p is the soil reflectivity. The surface reflectivity is related to its emissivity by $r_p = (1 - e_p)$.

The brightness temperature response to freeze/thaw dynamics is affected by surface roughness, topography, and vegetation and snow cover. For bare surface or sparsely vegetated conditions, the surface terms dominate the received signal, with brightness temperature being influenced primarily by contributions from the soil surface and snow cover. Because of the high dielectric constant of liquid water, microwave penetration of the vegetation decreases as biomass moisture levels increase. In general, opacity increases with increasing frequency, vegetation density, and dielectric constant.

The Special Sensor Microwave/Imager (SSM/I) is a multifrequency, linearly polarized passive microwave radiometer operating with a constant incidence angle of 53.1 degrees and has flown on the Defense Meteorological Satellite Program (DMSP) platform series. Coverage is global and began in August 1987. We utilized the 19 GHz, horizontally polarized channel, which has a 70×45 km footprint resolution. Data for this study were acquired as globally gridded brightness temperatures derived from orbital (swath) data²¹. The SSM/I sensors have 6 AM and 6 PM equatorial crossing times for the ascending or descending orbital nodes, with the crossing time and corresponding node depending on the platform in the DMSP series. Brightness temperature data corresponding to orbital passes with 6

AM and 6 PM equatorial crossing times were mapped separately to a 25 km resolution polar EASE-grid projection for each 24-hour period and used for temporal classification of primary thaw events. The data gridding scheme maximizes the radiometric integrity of the original brightness temperature values, maintains high spatial and temporal precision, and involves no averaging of original swath data. Daily SSM/I data, spanning January 1988 through autumn 2002, were assembled onto the 25 km EASE-grid grid covering the study domain, which consists of the pan-Arctic basin and Alaska. The daily composite data allow examination of annual thaw cycles from 1988–2002 for AM and PM observations separately.

Common approaches employing satellite microwave remote sensing to classifying landscape freeze/thaw state involve temporal change detection schemes applied to time-series remote sensing observations. The general approach of these techniques is to identify landscape freeze/thaw transition sequences by exploiting the dynamic remote sensing temporal response to differences in the aggregate landscape dielectric constant that occur as the landscape transitions between predominantly frozen and non-frozen conditions. These techniques assume that the large changes in dielectric constant occurring between frozen and non-frozen conditions dominate the corresponding temporal dynamics, rather than other potential sources of temporal variability such as changes in canopy structure and biomass or large precipitation events. This assumption is generally valid during periods of seasonal freeze/thaw transitions for most areas of the cryosphere.

Temporal edge detection techniques classify freeze/thaw transitions by identifying predominant step-edges in time series remote sensing data that correspond to freeze/thaw transition events. As freeze/thaw events induce large temporal changes in landscape dielectric properties that tend to dominate the seasonal time-series response of the microwave radiometric signatures for the terrestrial cryosphere, edge detection approaches are suitable for identification of these events using time-series microwave remote sensing data. We employ a step-edge detection scheme to identify the predominant springtime thaw transition event on an annual basis. In boreal regions this event has been found to be generally coincident with the arrival of maximum surface wetness in spring associated with rising air temperatures, seasonal snowmelt, soil active layer thawing and growing season onset^{17, 22}. The technique is based on the application of an optimal edge detector for determining edge transitions in noisy signals²³. The time of the primary springtime thaw event is determined from the convolution applied to T_B :

$$CNV(t) = \int_{-\infty}^{\infty} f'(x)T_B(t-x)dx \quad (4)$$

where $f'(x)$ is the first derivative of a normal (Gaussian) distribution. The occurrence of the primary springtime thaw event is given by the time when $CNV(t)$ is a maximum. The variance of the normal distribution may be selected to identify step edges with varying dominance, *i.e.* selection of a large variance identifies more predominant step edges, while narrower variances allow identification and discrimination of less pronounced events. As the winter-spring transition progresses, the landscape may thaw and re-freeze repeatedly. This technique accounts for the occurrence of weak edges, or less pronounced freeze/thaw events, as well as larger seasonal events indicated by strong edges, and can distinguish the frequencies and relative magnitudes of these events. This approach has been applied to daily SSM/I time series brightness temperature measurements to map primary springtime thaw events annually across the pan-Arctic basin and Alaska¹⁷. For this investigation we map the spring thaw events separately for morning and evening data acquisitions for each 25-km grid cell within the pan-Arctic basin and Alaska study region. Previously, thaw classification algorithm performance has been compared with surface station temperature measurements at sites within North America and Eurasia where biophysical data were collected, validating algorithm performance¹⁷.

The thaw classification algorithm was applied to each annual time series of SSM/I brightness temperatures from 1988 through 2002, producing yearly maps of the timing of primary spring thaw events across the pan-Arctic basin and Alaska for both early morning and early evening data acquisitions. A linear trend analysis was applied on a grid-cell-by-grid-cell basis to quantify the statistical significance of temporal trends in spring thaw timing over the 15-year period. We used a NOAA AVHRR based global land cover classification to define major biomes within the study region^{24, 25} (Figure 1). Non-vegetated areas were masked from the analysis to isolate relationships between seasonal thawing, vegetation growing season dynamics, and associated impacts on seasonal atmospheric CO₂ patterns. Mean

primary thaw dates were determined for each of the 15 years for the entire pan-boreal study domain, as well as for major biomes defined from the regional land cover map, and North American and Eurasian portions of the study region.

We compared SSM/I-derived measurements of pan-arctic spring thaw timing to seasonal atmospheric CO₂ concentration records from NOAA CMDL arctic and subarctic monitoring stations to assess the role of spring thaw timing in regulating high latitude CO₂ seasonal patterns. Mean monthly CO₂ records were extracted for Point Barrow (71°N), Ocean Station (66°N), Cold Bay (55°N), Alert (82°N) and Mould Bay (76°N) stations²⁶. Previous studies have shown that the seasonal atmospheric CO₂ cycle at high northern latitudes is dominated largely by northern terrestrial ecosystems, with minimal impacts from ocean exchange, fossil fuel emissions and tropical biomass burning^{27, 28, 29}. The average of the five stations' mean monthly records were normalized as the difference between monthly and mean annual CO₂ concentrations for each year. We extracted a set of variables from the normalized station records describing the shape of the yearly seasonal CO₂ pattern including timing of springtime 0 ppm crossings and the period between the springtime and autumn 0 ppm crossings. These variables were used as surrogates for the timing of growing season initiation and length, respectively^{17, 27, 30}. These seasonal shape parameters were derived from individual station records, averaged on a yearly basis across all high latitude stations and compared with pan-arctic averages of SSM/I spring thaw results. Annual anomalies of SSM/I and CMDL station results were calculated relative to long-term means or linear least-squares regression results where significant secular trends were observed. Significance was assessed based on a 90% probability level. Relationships between annual anomalies in spring thaw timing and seasonal CO₂ patterns were then evaluated accordingly.

3. RESULTS

Figure 2 shows a graph of the mean thaw day as computed for 1988 to 2002 across the pan-Arctic study domain for AM and PM acquisitions. Areas of bare land were masked from this computation using a land cover map (Figure 1). Maximum annual variability in the mean thaw day for the period was 17 and 14 days for early morning (AM) and early evening (PM) acquisitions, respectively. Linear regression analyses of regionally averaged data provide a measure of the rate of change in annual thaw day across the study domain. The early morning (AM) data acquisitions show a 2.3 day advance toward an earlier thaw day across the 15 year record, while the early evening (PM) acquisitions show a 2.3 day retreat in mean thaw day, although neither of these trends is statistically significant ($P < 0.10$).

Maps of the average (1988-2002) timing of primary spring thaw events for the study domain as derived from SSM/I AM and PM overpass data are presented in Figure 3 and summarized by region and major biome type in Table 1. Masked areas representing barren land, open water, and permanent ice and snow are shown in gray. The average timing of the primary seasonal thaw event extends over a 12 week period, from March through May, with lower latitudes and elevations showing generally earlier thawing relative to higher latitudes and elevations. A map of the average differences between AM and PM overpass derived thaw dates is presented in Figure 4. Spatial patterns in the timing of seasonal thawing and differences between AM and PM overpass derived thaw dates reflect the distribution of major biomes (Figure 1). Tundra-dominated regions have shorter growing seasons and show a general delay in the timing of seasonal thawing of more than 2 weeks relative to boreal forest and grassland regions. North America also shows a general pattern of earlier seasonal thawing of approximately 6 days relative to Eurasia and the entire pan-arctic domain.

Table 1: Mean primary thaw day (year-day) for the terrestrial pan-Arctic basin and Alaska, and for North American and Eurasian portions of the study domain. Mean thaw day is shown for dominant biomes and for early morning (AM) and early evening (PM) data acquisitions.

	Pan-Arctic			North America			Eurasia		
	AM	PM	AM-PM	AM	PM	AM-PM	AM	PM	AM-PM
Tundra	128.8	121.8	7.0	125.8	118.0	7.8	131.0	124.6	6.4
Forest	110.9	105.2	5.7	103.7	93.8	9.9	114.5	110.9	3.6
Grassland	103.2	105.0	-1.8	101.4	101.7	-0.3	104	106.5	-2.5
All Vegetated Land	117.4	112.0	5.4	113.8	106.0	7.8	119.3	115.3	4.0

A map of the differences between SSM/I AM and PM overpass-derived spring thaw calculations is presented in Figure 4 and summarized in Table 1. These results show that for most of the domain, including arctic tundra and boreal forest regions, timing of the primary spring thaw event occurs approximately 5 days earlier in the year for PM overpass data than for AM overpass data. This indicates regions where initial seasonal thawing occurs after the AM overpass data acquisition, under increasing incident solar radiation loading during the day, while remaining in a predominantly non-frozen state into the evening. Grassland regions, however, show a general pattern of earlier arrival of seasonal thawing for AM overpass data by approximately 2 days relative to PM overpass data. These differences may reflect atmospheric aerosol and vegetation cover effects on surface radiation and associated freeze/thaw diurnal patterns, though the specific mechanisms driving these patterns are currently unknown.

SSM/I-derived measures of the average primary thaw day for the region correspond strongly with the timing of annual growing seasons inferred from seasonal patterns of atmospheric CO₂ concentrations (see Figure 5). The timing of the spring 0-ppm crossing is a surrogate measure of the initiation of the growing season indicated by the seasonal drawdown of atmospheric CO₂ concentrations by photosynthesis and terrestrial net primary production with the arrival of warmer temperatures and seasonal thawing in spring. Spring thaw annual anomalies correspond directly to spring CO₂ zero crossing time anomalies, with somewhat better correspondence for PM overpass ($r = 0.671$, $P = 0.006$) data than for AM overpass ($r = 0.523$, $P = 0.045$) data. Years with relatively early spring thaw events show generally earlier growing seasons and associated seasonal declines in atmospheric CO₂ concentrations, while years with delayed thaw events show the opposite effect on growing season timing and spring CO₂ patterns. The improved correspondence for the PM overpass results indicate that the timing of these observations may better capture conditions where photosynthesis and NPP initially occur under mid-day non-frozen periods, while earlier AM overpass conditions may still be predominantly frozen and biologically inactive. Spring thaw date anomalies derived from PM overpass data are also inversely proportional to growing season length as defined by the period between spring and fall 0-ppm crossings of the atmospheric CO₂ concentration curve (e.g., Figure 5, lower graph). Years with relatively early seasonal thawing are associated with longer growing seasons, while years with relative delays in seasonal thawing have shorter growing seasons. These relationships are not significant ($r = -0.423$; $P = 0.116$), however, because of the June 1991 eruption of Mt. Pinatubo, which resulted in a short-term global cooling, but relatively large terrestrial CO₂ sink anomaly for 1992³¹. With the exclusion of the 1992 outlier, annual anomalies in the average timing of the primary spring thaw event correspond significantly ($r = -0.651$, $P = 0.011$) to atmospheric CO₂ derived growing season length anomalies. Annual variability in growing season initiation is primarily driven by timing of seasonal thawing and snowmelt in spring, while termination of the growing season in fall is primarily governed by photoperiod length at high latitudes⁶. Thus early spring thawing promotes an earlier and longer time interval of net photosynthetic carbon uptake and greater NPP, resulting in generally earlier and larger seasonal decreases in atmospheric CO₂, while years with delayed spring thaw cycles promote the opposite response.

4. CONCLUSIONS

The results of this study identify strong linkages between the timing of spring thaw as derived from temporal classification of satellite microwave remote sensing daily time series observations of landscape brightness temperatures and boreal-arctic growing season dynamics and associated seasonal patterns of atmospheric CO₂ concentrations. Spatial and annual variability in the timing of seasonal thawing is substantial for the region with significant impacts to atmospheric CO₂ concentrations and the terrestrial carbon cycle. Years with relatively early seasonal thawing appear to promote both earlier and longer growing seasons and associated seasonal uptake of atmospheric CO₂, while years with delayed seasonal thawing promote the opposite response. Significant differences in the timing of seasonal thawing were observed between SSM/I AM and PM overpass results. Timing of the primary spring thaw event determined from early evening acquisitions generally precedes that determined from early morning data acquisitions for arctic tundra and boreal forest landscapes, while grasslands show the opposite pattern. While both AM and PM overpass results correspond to growing season dynamics inferred from seasonal atmospheric CO₂ anomalies, the PM overpass data appear to better reflect annual anomalies in both the timing and length of the seasonal growing seasons. These findings underscore the importance of characterizing freeze/thaw patterns from consistent temporal observations, and the utility of high-repeat satellite microwave remote sensing for biospheric monitoring of boreal and arctic regions.

Existing surface biophysical monitoring networks provide detailed information on freeze/thaw patterns and associated carbon cycle dynamics, but generally over limited spatial extents, especially at high latitudes. The SSM/I and other active and passive satellite microwave sensors are sensitive to landscape freeze-thaw state transitions associated with the onset of the growing season at high latitudes. The relative independence of these data from atmospheric aerosol contamination and solar illumination provide the potential for spatially explicit, daily monitoring of this important biophysical variable at high latitudes where global change is projected to occur first and may already be occurring, with the greatest magnitude and with significant feedbacks to global climate and carbon, water and energy cycles. While current satellite microwave sensors have the potential to resolve pan-arctic growing season dynamics with better temporal (i.e., daily) accuracy than other existing satellite and surface biophysical monitoring networks, their ability to accurately resolve these patterns at finer (<25km) spatial scales is less certain, particularly for topographically complex landscapes. However, new satellite platforms are currently under development that will allow improved spectral and spatial characterization of this important biophysical variable³².

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Figure 1: Map of the study area, including the pan-Arctic basin and Alaska, showing major land cover classes. A NOAA AVHRR-based global land cover classification was used to define major biomes within the study region. Major biomes represented include boreal forest, arctic tundra (indicated as Shrublands), grassland, agricultural (indicated as Croplands), and barren (including open water, barren land, and permanent ice and snow) categories. Areas outside the study region are shown in gray.

Figure 2: Mean primary thaw day (day of year) for the pan-Boreal study domain, showing thaw day derived separately from early morning (AM) and early evening (PM) satellite data acquisitions. Trends observed over the 15-year time series were not statistically significant.

Figure 3: Maps of mean primary thaw day (day of year) for the pan-Boreal study domain, derived separately from early morning (AM) and early evening (PM) satellite data acquisitions. Each 25 km x 25 km grid cell represents mean thaw day for the respective grid cell over the 15 year record (1988-2002). Barren areas identified by the land cover map in Figure 1 are shown masked in gray.

Figure 4: Difference in primary thaw dates determined from SSM/I AM and PM data acquisitions for the pan-boreal study region. Positive values correspond to grid cells that exhibit PM thaw earlier than AM thaw; negative values correspond to regions with earlier AM thaw.

Figure 5: Correspondence between annual anomalies of SSM/I AM and PM overpass derived primary thaw events and growing season initiation (top) and growing season length (bottom) inferred from seasonal patterns in mean monthly atmospheric CO₂ concentrations from NOAA CMDL arctic and subarctic monitoring stations.