AMSR-E Snow Water Equivalent Associated with AMSR-E Growing Season Soil Moisture, Vegetation Opacity and Air Temperature Over Six Arctic Study Sites (2003-2008)

K.A. LUUS,[1] C.R. DUGUAY[1], R.E.J. KELLY[1], J.C. LIN[1] AND Y. GEL[1]

ABSTRACT

Snow plays an important role in arctic hydrology, ecology and climatology. The objectives of this study were to explore ecological and remote sensing linkages between non-growing season snow water equivalent (SWE) and growing season air surface temperature; vegetation opacity to microwave transmittance; and surface soil moisture. The analysis was limited to six study sites in the arctic, located at 60°N, 65°N and 71°N along two transects (110°W and 180°E), and made use of new AMSR-E products developed by the Finnish Meteorological Institute (SWE) and the Numerical Terradynamic Simulation Group (growing season parameters). Moderate to high correlations of SWE and growing season parameter distributions were found using analysis of annual first quartile, median and third quartile values. Further analysis consisted of comparing time-adjusted associations between non-growing season and growing season values against a null case sinusoidal function. A greater degree of association was found to exist between growing and non-growing season values than of either against a baseline sinusoidal case. Significant ecological and remote sensing linkages therefore exist in AMSR-E retrievals of growing and non-growing season data. These findings may have important implications for interseasonal data assimilation and modeling efforts.

INTRODUCTION

The influence of temperature, soil moisture and vegetation on spatial distributions of snow water equivalent (SWE) has been separately studied at differing scales. Distributions of snow depend on large scale climate circulations (Morin *et al,* 2008). Anomalies of soil moisture and soil temperature can persist over periods of months to seasons (Liu *et al*., 1999), and anomalies in soil moisture can cause subsequent anomalies in SWE (Shinoda, 2001). Greater SWE tends to occur in regions with denser vegetation due to wind redistribution (Sturm *et al.,* 2001), and greater soil moisture upon snow melt is found in regions with greater end of season SWE (Serreze and Barry, 2005). Understanding the strength, directionality and time lag between snow accumulation and growing season processes is crucial for being able to assess and predict the impacts of a change in climate regimes (Williams *et al*., 2009). Assessing the degree of association of SWE with temperature, vegetation and soil moisture at a single resolution will enable a better comparison of which of these parameters is most closely associated with SWE. It is also important to understand whether brightness temperature derived parameters are very closely correlated over different seasons prior to using interseasonal products in data assimilation and modeling efforts.

[1] Interdisciplinary Centre on Climate Change, University of Waterloo, 200 University Ave W, Waterloo, ON, N2L 3G1, Canada, kaluus@uwaterloo.ca

The primary objective of this study was, therefore, to examine coarse resolution linkages (25km) at passive microwave observation scales between winter season SWE and growing season parameters (land surface air temperature, vegetation opacity to microwave transmittance, and soil moisture). SWE and land surface parameter data were provided by the Finnish Meteorological Institute (Pulliainen, 2006) and Numerical Terradynamic Simulation Group (Jones *et al*., 2010), respectively. Both data sets have been calculated from Level 2A Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) data at a 25km resolution (2003-2008), and have been validated against meteorological and/or field data.

The second objective of this study was to examine whether significant similarities could be detected between SWE and growing season retrievals occurring over different time periods. Soil dielectric and roughness properties, as well as vegetation cover influence SWE retrievals, but these influences are currently corrected only through simple parameterizations. The impacts of soil moisture and vegetation on passive microwave SWE retrievals are typically mitigated using frequency differencing (18.7 GHz and 36.5 GHz), and forest fraction cover, respectively. However, the extent to which long-term memory, ecological linkages, and background reflectance influence measurements is not well understood in regions where extensive field studies have not been conducted. All investigations were conducted over six study sites, located along 140°E and 110°W longitude transects at 60°N, 65°N and 71°N.

Data sets

GlobSnow SWE estimates (in mm) are calculated using AMSR-E 18.7 and 36.5 GHz data as well as meteorological data (grain size and snow depth) (Pulliainen *et al.*, 1999). Single fixed parameters are used to estimate snowpack, soil and forest characteristics for the entire time period (2003-2008). GlobSnow SWE has been successfully validated for many northern pan-Arctic regions against in situ data (Luojos *et al.*, 2009). Growing season variables (vegetation opacity, surface soil moisture and land air surface temperature) were calculated from AMSR-E brightness temperature observations by the Numerical Terradynamic Simulation Group (NTSG). These products are available only during the snow-off period, so the GlobSnow and NTSG data products do not have a temporal overlap.

Vegetation opacity is dimensionless with a range of 0-1 that is greater with less vegetation, and is influenced by water content, geometry and spatial distribution of stems and leaves (Njoku and Chan, 2006). Vegetation opacity was calculated separately using 6.9, 10.7 and 18.7 GHz inputs, and these products are analyzed separately. Comparisons with MODIS LAI, NDVI and EVI yielded correlations of up to 0.9 (Jones and Kimball, 2010).

Soil moisture was primarily calculated from 6.9 GHz AMSR-E data, and is expressed as a dimensionless value ranging between 0-1. Observations affected by radio frequency interference at 6.9 GHz were replaced with values calculated from 10.7 GHz AMSR-E. Soil moisture was found to be correlated with precipitation at meteorological stations in the Northern Hemisphere ($0.2<r<0.8$) (Jones and Kimball, 2010).

Land air surface temperature (in Kelvin) was retrieved from AMSR-E and AIRS. Minimum air temperature is calculated according to morning retrievals, and maximum air temperature is calculated according to evening retrievals. Air temperatures from meteorological stations were used for calibration (270 stations) and validation (273 stations) of resulting products, with these stations being assigned randomly. Comparisons indicated root mean squared error values of 3.5 K when comparing AMSR-E derived temperature with meteorological data. Larger errors were observed in regions with sparse vegetation, higher elevations and higher fractional water content.

Study sites

Six study sites situated along two north-south transects (60°N, 65°N and 71°N) were selected for this study. One transect runs along 110°W in Canada, and the other runs along 140°E in Russia. These study sites are denoted as Canadian Low, Mid and High Arctic; and as Russian Low Mid and High Arctic according to position along the transect. Transects were selected to include a variety of elevation and phytomass characteristics from Walker *et al*. (2005) [Figure 1]. Elevation and phytomass tend to decrease with an increase in latitude, with the exception of the Canadian mid-latitude site which has the lowest phytomass [Table 1].

Table 1. Site locations, elevation and range of vegetation characteristics from Walker *et al.* (2005),

	Can High	Can Mid	Can Low	Rus High	Rus Mid	Rus Low
Latitue	71N	65N	60N	71N	65N	60N
Longitude	110W	110W	110W	140E	140E	140E
NDVI	0.15-0.26	<0.03	0.39-0.50	0.39-0.50	0.39-0.50	0.57-0.62
Phytomass (g/m^2)	101-250	<50	501-1000	501-1000	501-1000	1501-2000
Elevation (m)	100-333	334-667	334-667	<100	668-1000	668-1000

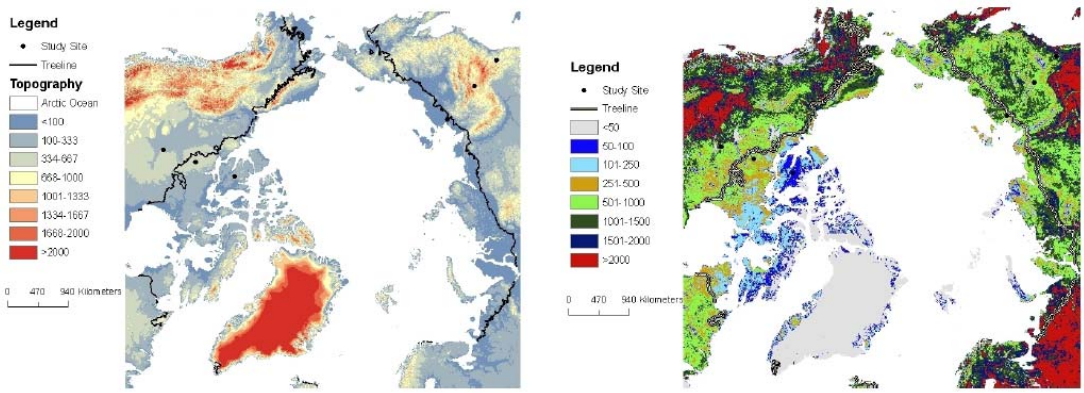

Figure 1. Elevation (left, in m) and phytomass class (at right, in g/m2) according to the Circumpolar Arctic Vegetation Map (Walker *et al*., 2005).

Mean growing season soil moisture is highest at the Russian Mid Arctic site (0.20), and lower at the other five sites (≈0.12) [Table 2]. Growing season air temperature ranges from 265K at the Canadian High Arctic site to 278K at the Low Arctic sites. Vegetation microwave opacity is inversely related to vegetation cover, with values between 0.5-0.6 at high arctic sites, and 0.1-0.4 at low to mid arctic sites. When comparing vegetation opacity at different frequencies, low frequency (6.9GHz) observations yield the greatest difference between high and low arctic sites. However, these variations are minimal. Overall, there is little difference between vegetation opacity at 6.9, 10.7 and 18.7 GHz. GlobSnow SWE is highest at the Canadian and Russian mid-latitude sites (40mm), followed by high (40mm) and low (36mm) latitude sites in Russia, and finally Canadian low and high latitude sites (26mm). From a temporal standpoint, many variables appear to have an approximately sinusoidal annual cycle, whereby air temperature and SWE both peak in mid-season, vegetation opacity has a trough in mid-season, and soil moisture varies greatly [Figure 2].

Table 2. Mean AMSR-E derived values for each study site (2003-8).

	Can High	Can Mid	Can Low	Rus High	Rus Mid	Rus Low
Soil Moisture	0.1224	0.1102	0.1219	0.0979	0.2006	0.1219
Air Temp (K)	265.9941	272.6846	278.2213	272.2953	271.7593	278.3019
Veg (6.9 GHz)	0.6602	0.3666	0.2473	0.5652	0.1533	0.1543
Veg (10.7 GHz)	0.5920	0.3378	0.2391	0.5711	0.1368	0.1487
Veg (18.7 GHz)	0.5166	0.3303	0.2686	0.5436	0.1798	0.1919
GlobSnow SWE	25.6186	40.3622	26.3067	29.8721	39.7475	36.2467

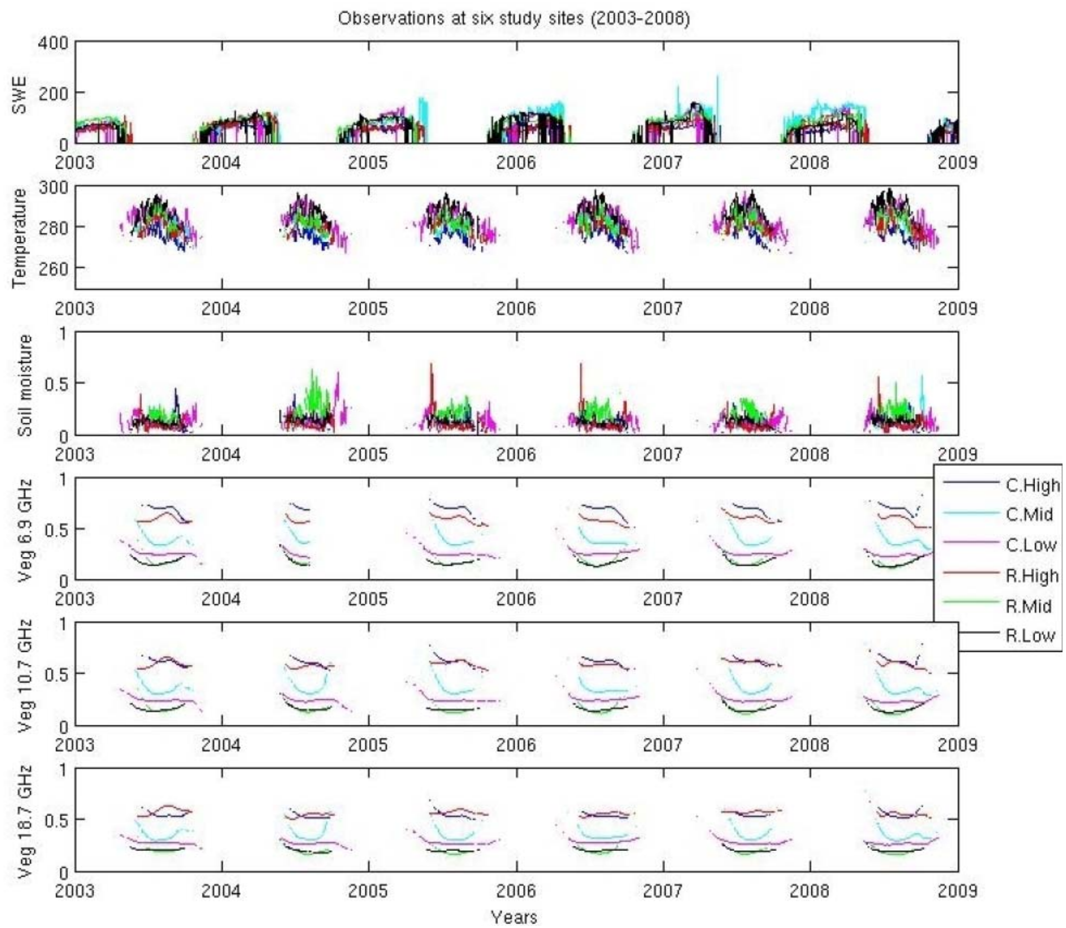

Figure 2. Snow water equivalent (mm), surface air temperature (K), surface soil moisture (0-1) and vegetation opacity (0-1) (6.9, 10.7 and 18.7 GHz) over six study sites (2003-2008)

METHODOLOGY

All statistical comparisons focused on assessing similarity of the non-growing season (SWE) dataset against growing season data sets (soil moisture; land surface air temperature; and vegetation opacity at 6.9, 10.7 and 18.7 GHz). Similarity of distributions was assessed using correlation analysis of first quartile, median, and third quartile values for each of the six years, resulting in a comparison of eighteen values per site per growing season dataset. As the GlobSnow and NTSG datasets are collected during different time periods (non-growing/snow-on season, and growing/snow-off season), comparisons of snow and growing season parameter values over time first required removing the time lag between datasets. The advantage of this approach is that it removes the influence of many temporal linkages (i.e., high soil moisture immediately after snowmelt of a high SWE snowpack). Time lag was removed by aligning observations of GlobSnow SWE with the observations of growing season parameters for every year, such that both datasets begin with the first recorded value for each year. The arrays for each year were set to finish with the last observation for that year, whether from GlobSnow or NTSG. The amount of similarity between datasets due to a commonality of shape was estimated by running a regression of each dataset separately against two null case sinusoidal functions [Figure 3] which replicate annual cycles: cos(2πJulianDay/365) + sin(2πJulianDay/365). The extent to which similarity between datasets exists because of coincidental similarities in shape, versus the extent of similarity occurring due to true similarity of values, can therefore be assessed.

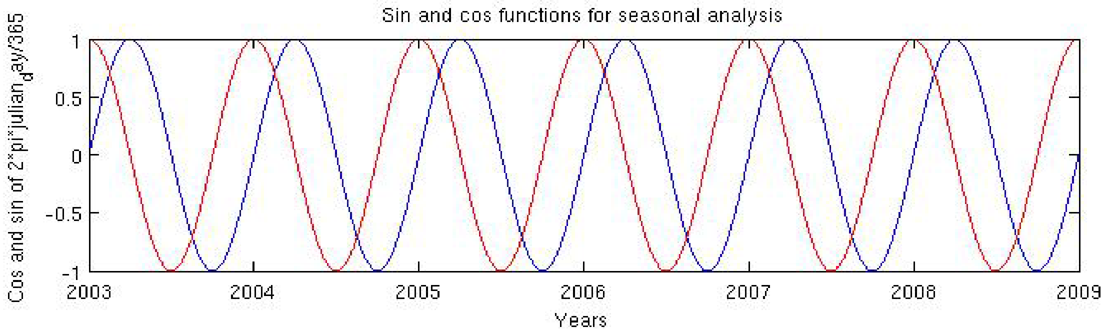

Figure 3. Similarity of datasets due to a common annual sinusoidal shape assessed using regression against two sinusoidal functions.

RESULTS

Similarity of distributions

Correlation analysis of mean annual median, first and third quartile values indicated that SWE has a moderate to high association with soil moisture and air temperature [Table 3] over each of the six study sites ($0.5<R<0.9$). Annual median, first and third quartiles of vegetation opacity have a significant, moderate correlation with SWE ($0.3<R<0.8$).

Table 3. Results from correlation of annual first quartile, median, and third quartile values for GlobSnow SWE and AMSR-E derived land surface parameters (R). All values have significant p-values (α<0.01).

	Can High	Can Mid	Can Low	Rus High	Rus Mid	Rus Low
Soil Moisture	0.6170	0.5140	0.7113	0.8454	0.7047	0.6150
Air Temp (K)	0.6449	0.6596	0.8685	0.7745	0.7490	0.6721
Veg (6.9 GHz)	0.3359	0.3313	0.6627	0.4169	0.7743	0.5756
Veg (10.7 GHz)	0.2870	0.4511	0.6581	0.3414	0.7264	0.6087
Veg (18.7 GHz)	0.4223	0.4442	0.7337	0.2849	0.6220	0.3957

Soil moisture distributions are most similar to SWE at the Russian High Arctic, followed by the Canadian Mid Arctic and Russian Mid Arctic. Soil moisture distributions at these sites have larger maxima in their time series than at other sites [Figure 2]. Vegetation opacity is most closely associated with SWE at the Canadian Low arctic site, Russian Mid arctic site and Russian Low arctic site. Each of these sites has a low mean vegetation opacity [Table 2], and show a clearer linear or sinusoidal shape over time [Figure 2]. SWE is moderately associated with air temperature over all study sites ($0.5<R<0.8$), and varies little in terms of shape and mean annual value across study sites. In conclusion, distributions of SWE and growing season values are most similar at the Canadian Low arctic, Russian Mid arctic and Russian Low arctic sites, which have relatively higher phytomass (lower vegetation opacity) and larger peaks in soil moisture.

Similarity of time-adjusted datasets

The similarity in the SWE and growing season parameter datasets without the influence of temporally based processes was assessed using regression of these datasets with a six month lag, such that early winter SWE is compared to early spring growing season parameters of the same year [Table 4].

Table 4. Degree of association (R^2) of time adjusted SWE against growing season parameters. All values shown are significant ($\alpha<0.01$).

	Can High	Can Mid	Can Low	Rus High	Rus Mid	Rus Low
Soil Moisture	0.6795	0.7605	0.7976	0.6819	0.8901	0.8916
Air Temp (K)	0.9891	0.9757	0.9714	0.9638	0.9847	0.9871
Veg (6.9 GHz)	0.9872	0.9381	0.9245	0.9775	0.9304	0.9465
Veg (10.7 GHz)	0.9824	0.9451	0.9360	0.9721	0.9313	0.9532
Veg (18.7 GHz)	0.9876	0.9565	0.9533	0.9752	0.9712	0.9783

Soil moisture had a moderate to high degree of association with SWE, which was lowest at the high arctic sites (0.7), followed by the Canadian Low and Mid arctic sites (0.8), and then the Russian Low and Mid arctic sites (0.9). The degree of association of SWE and soil moisture is therefore higher at sites with greater soil moisture. Air temperature and vegetation opacity both had very high degrees of association with SWE over all six sites ($R^2>0.9$). Despite the lack of temporal correspondence, it appears that AMSR-E derived values of growing and non-growing season parameters over time are very similar.

Although the high degree of association of these variables seems to indicate either ecological or remote sensing linkages, it is important to fully account for the portion of similarity that is due simply to datasets having a similar shape over time. As the datasets tested all display an annual sinusoidal pattern, the degree of association of each variable against a sinusoidal fit was examined.

Seasonal dependence

Table 5. Degree of association (R^2) of each value against sinusoidal functions. One non-significant value ($\alpha<0.01$) is indicated with an asterisk.

	Can High	Can Mid	Can Low	Rus High	Rus Mid	Rus Low
Soil Moisture	0.1169	0.0443	0.0165	0.0727	0.2362	0.2363
Air Temp (K)	0.5757	0.3849	0.1055	0.3216	0.6390	0.4023
Veg (6.9 GHz)	0.6450	0.2284	0.1490	0.3916	0.0907	0.0018*
Veg (10.7 GHz)	0.5673	0.1206	0.1169	0.3736	0.0697	0.0160
Veg (18.7 GHz)	0.4626	0.0617	0.0590	0.3214	0.2265	0.1979
GlobSnow SWE	0.6805	0.6003	0.5500	0.6494	0.7320	0.6882

At the site level, seasonal analysis shows the degree of association of each variable against annual sinusoidal functions: $\cos(2\pi JulianDay/365)+\sin(2\pi JulianDay/365)$ [Table 5]. Analysis indicated that SWE had the highest degree of association with the seasonal function, followed by air temperature, vegetation opacity and then soil moisture. Stronger seasonal patterns in SWE were found for study sites with higher mean annual SWE [Table 2]. Conversely, soil moisture and vegetation opacity show lower R^2, and therefore do not fit well against a sinusoidal function. Vegetation opacity had a stronger association with seasonal functions at higher latitude sites with a lower frequency (6.9 GHz) and vice versa. The sinusoidal functions showed little to no degree of association with low frequency vegetation opacity at low latitude sites, most likely due to large variations in the vegetation opacity signal between seasons [Figure 2]. Soil moisture has a low fit with a seasonal function at all sites. Poor fit is likely due to the large peaks in soil moisture associated with precipitation events, as seen in Figure 2.

DISCUSSION

The distributions of SWE and growing season parameter (surface soil moisture; surface air temperature; and vegetation opacity at 6.9, 10.7 and 18.7 GHz) annual first quartiles, medians and third quartiles are highly correlated. SWE distributions are more highly correlated with growing season distributions over lower arctic sites containing greater phytomass and higher soil moisture, likely because the values of each parameter at these sites show a greater difference between first quartile, median and third quartile values. Similarity of distributions indicates either similarity in snow and growing season values at each site, or that all products still contain the same fundamental distributions as the AMSR-E brightness temperature observations from which they are all derived.

There is a greater degree of association between SWE and the growing season variables than between SWE and the null case sinusoidal functions. Therefore, significant similarity exists between AMSR-E derived observations of arctic non-growing season SWE and arctic growing season variables. Similarities may be due in part to the propensity for regions that receive greater snowfall tend to have greater vegetation biomass and soil moisture. Previous studies have found greater (lesser) soil moisture anomalies to persist through land-surface heat and moisture fluxes, and result in a greater (lesser) snow mass anomaly (Shinoda, 2001; Koster *et al.,* 2001). Furthermore, static properties such as the distance from catchment divide, soil texture, and soil depth have an important influence on both soil moisture and snow accumulation (Williams *et al.*, 2009). Similarity of SWE and soil moisture is therefore due to a combination of dynamic (system memory) and static characteristics. The spatial variability of soil moisture upon snowmelt also influences soil moisture for the rest of the season (Williams *et al.,* 2009), further explaining the strength of these interseasonal linkages. Distributions of higher vegetation biomass as expressed by increased NDVI estimates over central Siberia are also known to be associated with thicker snowpacks and later snowmelt (Grippa *et al.*, 2005). Shifts in the spatial distributions of snow and soil moisture can also directly influence distributions of vegetation (Williams *et al.*, 2009). The similarity of these AMSR-E derived datasets over both Canadian and Russian study sites is therefore in line with previous findings.

The high degree of association of validated parameters measured over different time periods could also indicate that arctic sites have similar brightness temperature values over time over six month periods. Similarities between datasets due to remote sensing can hinder the accuracy of data assimilation efforts, and similarities between interseasonal parameters due to environmental linkages may need to be considered in hydrologic and climatologic models. Further validation against field data is also required to determine which portion of similarities observed in these datasets are due to interseasonal hydrometeorological linkages, and which portion is due to remote sensing linkages arising from the acquisition of all datasets from AMSR-E brightness temperature observations.

Sub-nivean ground characteristics such as soil roughness, freeze-thaw state and vegetation density are known to influence SWE retrievals (Kelly *et al.,* 2003). Close associations between SWE and growing season parameter retrievals in the High Arctic may indicate a need for further work to focus on the impacts of winter season changes in ground characteristics on SWE retrievals. It may be worthwhile for efforts to improve northern SWE estimates (i.e., Derksen *et al.,* 2010) to consider whether the influence of ground characteristics should be more completely accounted for.

CONCLUSIONS

Understanding the associations between winter SWE and preceding growing season variables in the Arctic is important for our understanding of the arctic hydroclimatic system. Field-scale associations between greater SWE, greater soil moisture and greater biomass (lower vegetation opacity) are observed in passive microwave retrievals at a coarse (25km) resolution over six study sites. Statistical distributions of snow water equivalent are likewise very similar to distributions of growing season parameters (air temperature, soil moisture, vegetation opacity). Although there is a moderate degree of association between each variable and an annual sinusoidal function, variations in SWE are more closely associated with growing season variables. The similarity in distributions and of time adjusted fit indicate that it is likely that a system memory process exists in these systems, such that winter season SWE is influenced by antecedent soil moisture and vegetation opacity of the previous season. A possibility also exists that SWE in low phytomass arctic regions needs to be further calibrated to remove the influence of ground characteristics. Further work is ongoing in an attempt to explore the nature of these linkages with respect to the hydrometeorological controls on the Arctic system.

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