Changes in North American snow packs for 1979–2004 detected from the snow water equivalent data of SMMR and SSM/I passive microwave and related climatic factors

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Abstract Changes to the North American (NA) snow packs for 1979–2004 were detected from snow water equivalent (SWE) retrieved from SMMR and SSM/I passive microwave data using the non-parametric Kendall's test. In NA, about 30% decreasing trends in SWE for 1979–2004 are statistically significant, or about three times more than significant increasing trends of SWE. Significant decreasing trends in SWE are more extensive in Canada than in the USA. The overall mean trend magnitudes are about –0.4 to –0.5 mm/year, which translates to an overall reduction of snow depth of about 5–6 cm in 26 years. From detected increasing (decreasing) trends of gridded temperature (precipitation) based on the North American Regional Reanalysis (NARR) and the University of Delaware data set for NA, and their respective correlations with SWE data, it seems that the extensive decreasing trends in SWE detected mainly in Canada are caused more by increasing temperatures than by decreasing precipitation.

Key words snow water equivalent; SMMR and SSM/I passive microwave data; North America; Kendall's non-parametric trend test; surface temperature; precipitation; climate anomalies

1 INTRODUCTION

This study on detecting changes in snow packs of North America (NA) is based on snow water equivalent (SWE) data retrieved from the brightness temperature (T_B) in K (Kelvin) of passive microwave remote sensing platforms, such as the Scanning Multichannel Microwave Radiometer (SMMR) from 25 October 1978 to 20 August 1987, and the Special Sensor Microwave Imager (SSM/I) since 7 September 1987. The SMMR sensor flew on NASA's Nimbus 7 while SSM/I are mounted on the Defense Meteorological Satellite Program (DMSP) satellites of the USA. Since May 2002, T_B retrieved from the Advanced Microwave Scanning Radiometer-EOS (AMSR-E) sensor aboard the Aqua satellite has also been used to estimate SWE. The frequencies (resolution) of SSM/I are 6.6 GHz (150 km), 19 GHz, 22 GHz, 37 GHz (25 km) to 85 GHz (12.5 km), while that of AMSR-E are 6.9 GHz (50 km) to 89 GHz (5 km). These T_B values are either horizontally (H) or vertically (V) polarized. Because of limitations of passive microwave data, retrieval of SWE from such data based on equations (1) and (2) applied for NA is expected to have varying accuracy, depending on the vegetation types, snowpack characteristics, frozen and unfrozen water, topography, mountains *versus* flat plains, possible effect of wet snow, lake ice, ice lenses, depth hoar and deep snowpacks. The traditional T_B difference between 19 and 37 GHz has been shown to be inappropriate for lake-rich environments in the Arctic, and retrieving tundra SWE can be challenging. In view of these limitations, this trend analysis of SWE data derived from such data should be more reliable in regions dominated by grassland (e.g. Canadian Prairies) than in the Canadian Arctic with many frozen lakes, in forested or mountainous regions, and snowpacks that consist of depth hoar and wind slabs. Even though such SWE data are subject to uncertainties, it is the only data available to analyse SWE trends at the continental scale. Also, by using a non-parametric approach, we have overcome some of the limitations of the aforementioned uncertainties. The observed Northern Hemisphere snow cover since the 1920s had remained quite steady until around the 1980s, after which a significant decrease in snow cover has been observed (Lemke *et al.*, 2007). With about 26 years of continuous SWE data from SMMR (late 1978 to 1987) and SSM/I (summer of 1987 until 2004), it is now feasible to perform a trend analysis of SWE over NA for the winter and spring seasons to detect possible changes.

2 RESEARCH OBJECTIVES

With the above background information, this study has the following objectives: (1) to analyse monthly monotonic trends for the October–April SWE over NA for the 1979–2004 period; (2) to compute trend magnitudes, trend homogeneity, and the spatial distributions of trends and variability in SWE across NA from 1979 to 2004; (3) to perform principal component analysis (PCA) on SWE, and to correlate PCAs of SWE with climate anomalies; and (4) to relate SWE to major climate variables, and from the results, identify possible cause(s) for the detected changes of the snowpacks of NA from 1979 to 2004.

3 SWE RETRIEVED FROM SMMR AND SSM/I PASSIVE MICROWAVE DATA

On the basis of volumetric scattering, which is the dominant loss mechanism for microwave radiation greater than 15 GHz incident on a snowpack, it is possible to empirically relate the brightness temperature (T_B) of a certain frequency and polarization (H or V) to the SWE of snow packs. The NSIDC at the University of Colorado, Boulder, USA, provides such passive microwave T_B data at Equal-Area Scalable Earth, or EASE Grid format. The 1979–1987 SMMR SWE data of NSIDC were retrieved from equation (1) (Chang *et al.*, 1987):

$$\text{SWE (mm)} = 4.77(T_{B18H} - T_{B37H}) \quad (1)$$

where T_{B18H} and TB_{37H} are the horizontally polarized T_B at 18 GHz and 37 GHz, respectively. The 1987–2004 SSM/I SWE data of NSIDC were retrieved from equation (2) (Armstrong *et al.*, 2001):

$$\text{SWE (mm)} = 4.77(T_{B18H} - T_{B37H} - 5) \quad (2)$$

which is slightly different from equation (1), probably because of sensitivity differences between SMMR and SSM/I sensors in detecting shallow snow. Daily SWE is adjusted for the surface forest cover using the BU-MODIS (NSIDC, 2005) land cover data so that SWE (mm) = SWE/(1 – Forest%). Further, to ensure snow packs are detectable by passive microwave data, SWE less than 7.5 mm is considered unreliable and set to zero. Given that the SMMR and SSM/I data are at 25-km resolution, we can only analyse meso- to regional-scale variability of snowpack from these data. Furthermore, some studies found errors in the SWE record from passive microwave observations suggesting systematic biases related to grain size, not SWE, e.g. in northern Siberia, the approach of Chang *et al*. (1987), because thin snowpack and a strong thermal gradient promoted large crystals that enhanced scattering, grossly overestimated SWE. For NA, a 7-month (October to April) running mean (solid curve) and the monthly (dotted curve) SWE anomalies based on SMMR and SSM/I data of 1979–2004 generally show negative anomalies since the late 1980s (see Figure 2.20 of Barry & Gan, 2011).

4 NON-PARAMETRIC, MANN-KENDALL'S TEST AND TREND MAGNITUDE (*β*)

The non-parametric, Mann-Kendall test (Mann, 1945; Kendall, 1975) for testing trends in seasonal time series should be more robust than parametric methods because it can handle non-normality, censoring, and seasonality. To safeguard against non-representative results, only data sets with a few missing values were tested. Since Kendall's statistic, S_k, is not based on the magnitudes of individual SWE, it is expected to be more robust than say, the simple linear regression. However, we expect some degree of uncertainties in estimating SWE from two different satellite sensors. From the perspective of detecting trend of SWE data, S_k for season k will be first based on SWE estimated from equation (1) from 1979 to 1987. In changing to SWE of SSM/I based on equation (2) from 1987 to 2004, S_k could be affected in one step change, because after the transition, it will be based on SWE values estimated from equation (2) only. Albeit SWE estimated from equations (1) and (2) based on SMMR and SSM/I T_B data, respectively, may not be exactly the same, this non-parametric approach merely accounts for whether SWE has been increasing (or decreasing) from one time step to the next, so the effect of using SWE data estimated from two satellites on S_k should be minimal.

5 DISCUSSION OF RESULTS

In terms of SWE, about 30% of detected decreasing trends in SWE for 1979–2004 are statistically significant at α/2 = 0.05, which is about three times the detected increasing trends in SWE (see Table 1). Significant decreasing trends in SWE are more extensive in Canada than in the USA, where such decreasing trends are mainly found along the American Rockies (Fig. 1(a)). Scattered increasing trends are found mainly near Hudson Bay in Canada, but not near the Great Lakes where large increases in lake-effect snowfall since 1951 had been reported. Apparently in Canada statistically significant decreasing trends are mainly detected east of the Canadian Rocky Mountains. We did not detect much change to SWE along the coastal areas of NA likely because SWE data retrieved from passive microwave data suffer from mixing signals emitted from relatively dense vegetation along the coastal areas. Albeit few significant trends have been detected, we believe SWE along the western coastal areas of NA had also undergone decreasing trends. The SWE data along the American and Canadian Rockies could be affected by terrain features of mountainous areas, but the net effects may be more or less averaged out by the relatively coarse resolution of such data. This could be partly why significant trends are detected in these areas, but not along the western coastal areas generally covered with dense forest covers. A vigorous approach to compute the trend magnitude β_k (mm/year) used is:

$$\beta_k = median \frac{\left(X_{jk} - X_{ik}\right)}{\left(j-i\right)} \tag{3}$$

where k =1, 2, q where $1 < I < j < n$. β_k estimated using equation (3) are about –0.4 to –0.5 mm/year, which are of smaller range than that of simple regressions, while the mean (median) of negative trends alone is about –1.5 (–1.2) mm/year (Table 2). This means that from 1979 to 2004, the overall SWE of NA has decreased by about 10 to 13 mm or possibly more, and in terms of snow depth could range from about 4 to 5 cm (depending on the average snow density which typically ranges between 200 and 250 g/cm^3). Based on the negative trends, apparently the decrease in SWE mainly occurred in the area extending from the western part of the Canadian high Arctic to north of the five Great Lakes; the decrease in SWE amounts to 25–30 mm.

Table 1 Results of Kendall's test on statistically significant increasing (+ to +****) and decreasing (– to –****) trends of monthly SWE for 1979–2004 at different significance levels.

Mon	+ α/2 <.95	+* α/2 >.95	+** α/2 <.975	+*** α/2 <.99	+**** α/2 <.995	– α/2 ≥.05	–* α/2 <.05	–** α/2 <.025	–*** α/2 <.01	–**** α/2 <.005	Total pixels analysed	SWE >7.5mm
Jan	4374	393	327	151	165	5148	1015	1007	566	695	13841	12091
Feb	4387	473	481	296	562	4090	985	1226	743	1598	14841	12147
Mar	5886	470	469	287	401	4303	1076	1197	650	967	15706	11982
Apr	7613	439	395	186	234	3368	806	928	494	1069	15532	9645

Table 2 Means and medians of trend magnitudes (β in mm/year) for NA SWE between 1979 and 2004.

Month	Overall mean of negative and positive trends	Mean of negative trends only (mm/year)	Median of negative trends only
January	–0.441	–1.216	–1.0
February	–0.541	–1.779	–1.5
March	–0.482	–1.506	–1.28
April	–0.376	–1.371	–1.18

6 INFLUENCE OF CLIMATIC ANOMALIES ON SWE

The possible effects of the Pacific Decadal Oscillation (PDO), Pacific/North American (PNA) teleconnection pattern, and the El Nino-Southern Oscillation (ENSO) on SWE are examined using the PDO, PNA, Southern Oscillation Index (SOI) and Nino3 indices (Tables 3 to 4) since these

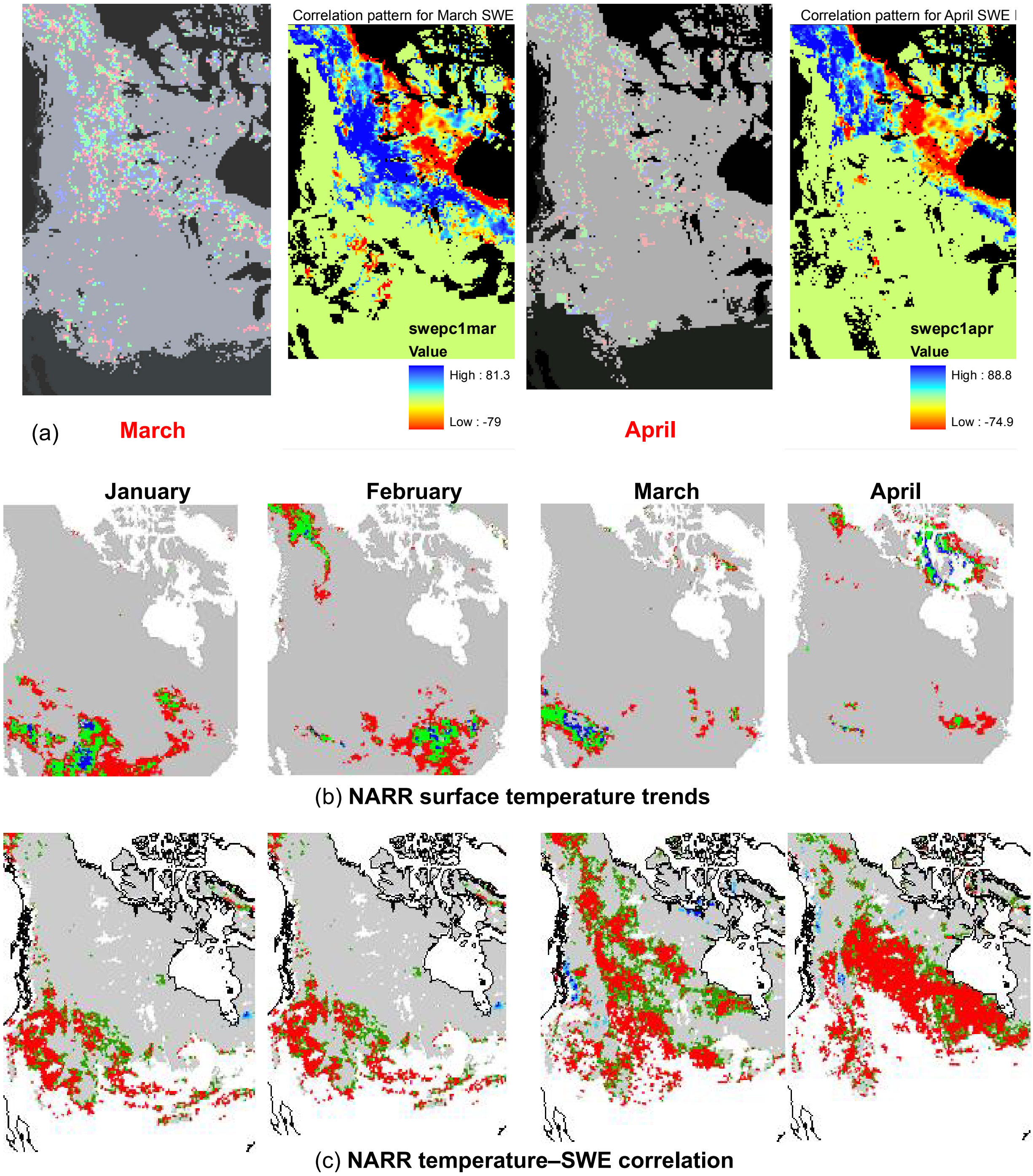

Fig. 1 (a) The spatial distributions of both decreasing [March and April] trends in SWE, the snow cover extent (grey colour) in NA for detected trends that are statistically significant at $\alpha/2 = 0.05$ (red), $\alpha/2 = 0.025$ (green) and $\alpha/2 = 0.01$ (blue), respectively. The PC1 patterns are also presented. (b) Monthly NARR surface temperature trends based on a 2-tailed significance level of 5% (red), 2.5% (green) and 1% (blue); and (c) NARR surface temperature–SWE correlation, where colour shadings are for 5% significance level (green for negative and light blue for positive correlations) and 1% significance level (red for negative and dark blue for positive correlations). (Note: printed in grayscale.)

climate anomalies have been shown to be teleconnected to the precipitation and streamflow of western Canada (e.g. Gobena & Gan, 2006). To reduce the dimensionality and capture any dominant signals in the SWE data, a PCA was conducted. Pearson correlation coefficients (ρ_p) of

Table 3 Pearson's Correlations (ρ_p) between PC1 to PC4 with the corresponding monthly PDO, one-season lag, seasonal PDO of OND, NDJ, DJF, and JFM.

ρ_p	Monthly PDO				OND		NDJ	DJF		JFM
Mon	Oct	Feb	Mar	Apr	Mar	Apr	Mar	Mar	Apr	Apr
PC1	–0.13	**0.44***	**0.43**	0.36	0.26	0.30	0.29	0.36	**0.39**	**0.44**
PC2	**0.38**	0.34	0.15	0.09	0.14	0.02	0.10	0.17	0.05	0.12
PC3	–0.06	–0.21	–0.36	0.36	**–0.57**	0.31	**–0.56**	**–0.52**	0.30	0.30
PC4	–0.14	–0.32	0.17	0.25	–0.04	**0.45**	–0.04	–0.01	**0.43**	0.34

Numbers in bold mean statistically significant at $\alpha/2 = 0.05$.

Table 4 Spearman's rank correlation (ρ_s) between PC1, PC2, and PC3 and the corresponding monthly PDO, one-season lag, seasonal PDO of OND, NDJ, DJF, and JFM.

ρ_s	Monthly PDO				OND		NDJ	DJF		JFM
Mon	Jan	Feb	Mar	Apr	Mar	Apr	Mar	Mar	Apr	Apr
PC1	–0.25	0.28	0.21	0.34	0.02	0.26	0.03	0.15	0.23	0.26
PC2	–0.25	0.25	0.13	0.10	0.17	0.09	0.21	0.18	0.08	0.09
PC3	–0.30	–0.24	–0.35	0.32	$-0.53^{\#}$	0.32	–0.54	–0.39	0.26	0.27

Table 3 show several statistically significant ρ_p between monthly PC1, PC2, PC3 and PC4 of NA's SWE and monthly or seasonal (OND to JFM) PDO. No significant ρ_p was found between PDO-JAS and SWE of October to December, which means that winter to early spring SWE are more affected by PDO than the autumn SWE. Table 3 shows more statistically significant ρ_p than statistically significant Spearman's statistics ρ_s (Table 4). Apparently, PDO exerts some influence on the overall snowpack SWE of NA during March, and possibly April. The climate of western NA have been related to interdecadal oscillations of PDO, with warm PDO being associated with warm, dry conditions and cool PDO being related to cool, wet conditions in western NA (Gobena & Gan, 2006). The PDO regime has also been shown to modulate winter temperature responses over most of western Canada during El Nino and La Nina events. By exerting an influence on the moisture and temperature regimes of NA, PDO is expected to affect its snowpack. Compared to PDO, the effect of PNA is relatively modest with significant ρ_s and ρ_p in February (PC2) and March (PC3 and PC4), while Nino3 and SOI exhibit less influence over the snow of NA. ENSO is teleconnected to the precipitation of western NA. The PC1 relationship is located mainly in the north (south) central to western regions of USA (Canada), while the PC3 relationship stretches from the mid-west to eastern USA and Atlantic Canada. The first four PCs of monthly SWE are also compared with these climate anomalies. The influence of PDO is mostly represented by PC1 for November, and February to April. Except for October and January, PC1 is mainly positive until about 1988 and is mainly negative thereafter, and it likely describes SWE variations of low-frequency. It seems PDO is more correlated to PC1 until 1988, after which PDO's influence became fuzzy. To better understand the spatial relationships between climate anomalies and SWE, some selected cases of correlation fields between PC1, PDO, PNA, and monthly SWE of individual pixels for February to April are examined. They show a wide range of negative and positive relationships that are mainly centred along northern Canada, above the Great Lakes on the east, to Alaska of USA on the west, and in the mid-west near the American Rockies. PDO and PNA had affected the snow packs of southern Canada and the USA since selected cases exhibit either statistically significant ρ_p or ρ_s (Tables 3 and 4).

7 SWE–TEMPERATURE AND SWE–PRECIPITATION RELATIONSHIPS

Higher air temperatures in the last three decades in NA could be a major contributor to the fairly wide spread reduction in its SWE. Similarly, possible changes to precipitation could be partly responsible. In lower latitude regions, not much change in the annual precipitation had been observed but less snowfall and more rainfall had been observed in some places. To find possible climatic factors leading to a general reduction in the snow packs of NA, the next step is to correlate changes of SWE to gridded precipitation and air temperature data to explore the possible relationships between temperature, precipitation and SWE. Trend analysis of both the gridded 2-m air temperature data of the University of Delaware (Willmott & Robeson, 1995) and that of the North American Regional Reanalysis (NARR) (Mesinger *et al*., 2006) showed little agreement between areas of detected increasing temperature trends and that of decreasing SWE trends that are statistically significant based on passive microwave data. However, extensive areas of significant negative correlations between SWE and temperature exist both across the USA and Canada except in January, and the distribution of these areas of negative correlation closely follow the areas of the decreasing trends detected from the SWE data (Fig. 1(a)–(c)). Unlike SWE trends, only scattered significant precipitation trends are detected, which implies that extensive decreasing SWE trends detected were more likely caused by warming than by decreasing precipitation. Albeit climatic anomalies could contribute to part of the detected changes, it seems that extensive decreasing trends in SWE detected in Canada and parts of USA were caused more by increasing temperatures than by decreasing precipitation. The global-scale decline of snow and ice cover since 1980 (Lemke *et al*., 2007), likely support our conclusion that warmer temperature, which we believe to be driven by a general warming of the atmosphere in response to rising greenhouse gases, caused the decline in SWE detected in NA. Relative to the 1906–1970 surface temperature of NA, Forster *et al*. (2007) found both observed and 58 cases of GCMs' modelled results showing drastic increase in NA's surface temperature in recent decades.

8 SUMMARY AND CONCLUSIONS

On the basis of the non-parametric Kendall's test applied to the SWE data of SMMR and SSM/I for NA, decreasing trends have been detected. About 30% of the detected decreasing trends in SWE for 1979–2004 are statistically significant at $\alpha/2 = 0.05$, which is about three times more than detected increasing trends in SWE that are statistically significant. Significant decreasing trends in SWE are more extensive in Canada than in the USA, where such decreasing trends are mainly found along the American Rockies. Because of uncertainties associated with SWE data retrieved from passive microwave data, results obtained for mountainous or forested areas of NA, the tundra in Arctic Canada with many frozen lakes or snowpacks that consist of depth hoar and wind slabs should be treated with caution. The overall mean trend magnitudes are about –0.4 to –0.5 mm/year, which means an overall reduction of snow depth of about 5 to 6 cm (assuming a snow density of about 200 to 250 g/cm^3). The PC1 of NA's SWE is found to be significantly correlated to the PDO, marginally correlated to the PNA pattern and to ENSO. The PDO for February to April was significantly correlated to the SWE of Canada, and the SWE PC1 scores and PDO indices show quite similar variation, such that the PC1 score and PDO are positive until about 1988, after which the values are mostly negative. From the detected significant increasing trends of gridded temperature data of NARR and the University of Delaware for NA, and their respective correlations with SWE data, it seems that the extensive decreasing trends in SWE detected in NA are more attributed to increasing temperatures than to decreasing precipitation.

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