SATELLITE ANALYSIS OF INTERANNUAL VARIABILITY IN THE SNOW-FREE SEASON AND ITS RELATION TO VEGETATION ACTIVITY IN NORTHERN LAND AREAS

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ABSTRACT

This study investigated variability and trends in the annual snow cover cycle in regions covering high latitude and high elevation land areas in the Northern Hemisphere. The annual snow cover cycle was examined with respect to the week of the last observed snow cover in spring (WLS), the week of the first observed snow cover autumn (WFS), and the duration of the snow-free period (DSF). The analysis employed a corrected version of a 29-year time-series (1972-2000) of weekly, visible-band satellite observations of Northern Hemisphere snow cover from NOAA. Substantial interannual variability was observed in WLS, WFS, and DSF (standard deviations of 0.8-1.1, 0.7-0.9, and 1.0-1.4 weeks, respectively), which is directly related to interannual variability in snow cover area in the regions and periods of snow cover transition. Over the nearly 3-decade study period, WLS in all study regions shifted earlier by 3-5 days/decade as determined by linear regression analysis. DSF increased by about 5-6 days/decade, primarily as a result of earlier snow cover disappearance in spring. No strong evidence of any systematic trend in WFS was observed. In addition to altering the surface energy balance through the snow-albedo feedback effect, the observed variability and trends in the annual snow cover cycle are potentially significant factors for terrestrial ecosystem functioning, including annual primary production and net ecosystem CO_2 fluxes.

INTRODUCTION

Satellite and surface observations have revealed that the spatial extent of annual snow cover in Northern Hemisphere (NH) land areas has decreased significantly over recent decades, most strongly in the spring season (Brown, 2000; Easterling et al., 2000; Robinson et al., 1995; Groisman et al., 1994). Such changes in terrestrial snow cover affect the Earth's geophysical systems by altering the surface energy and hydrological budgets (Groisman and Davies, 2001; Groisman et al., 1994; Pielke et al., 2000). These changes also have strong relevance to terrestrial ecosystems, including biogeochemical processes, even beyond the geographical limits of snow cover regions (Groisman and Davies, 2001).

Detection and monitoring of the annual timing of snow cover disappearance and onset and the duration of the snow-free period can provide useful indicators of climatic change (Foster, 1989; Ye, 2001), and potentially, of ecosystem change (Walker et al., 2001; Running et al., 1999). This study investigates variability and trends in the annual snow cover cycle in NH high elevation and high latitude land areas (mostly above 45° N). The temporal features of the snow cover cycle are quantified by analysis of a 29-year time series (1972-2000) of weekly, visible-band, satellite-derived observations of NH snow cover.

DATA AND METHODS

Satellite Snow Cover

The study used digital charts of weekly Northern Hemisphere snow cover distribution that were originally produced by NOAA (National Oceanic and Atmospheric Administration). A corrected version of the data set was obtained from D. Robinson (2001, personal communication) of the Rutgers University Climate Lab. The steps involved in production of the NOAA snow cover charts are described by Wiesnet et al. (1987) and Robinson et al. (1993) and are summarized as follows. Analogue snow cover charts were produced by manual interpretation of visible-band imagery from geostationary and polar-orbiting meteorological satellites. NOAA digitized the analogue charts by applying an 89 x 89 grid overlay. The spatial resolution of the grid cells varies from approximately 16,000 km^2 to 42,000 km^2. A binary classification system was used in which a grid cell with 50% or more snow cover was assigned a value of 1, otherwise the grid cell was considered snow-free and a value of 0 was assigned. The accuracy of the data product since 1972 is considered suitable for broad scale (continental and hemispheric) climate studies (Robinson et al., 1995; Wiesnet et al., 1987).

The data analysis was restricted to grid cells in which snow cover was observed at least once during both spring and autumn portions of the calendar year (defined as weeks 1-30 and 31-52, respectively) in each of the 29 years of the study. To avoid cases of missing data in the annual time series, all other grid cells were masked.

Quantifying the Snow Cover Cycle

The sequential day numbers corresponding to the observation periods of the weekly snow cover data files varied among years. To permit direct comparisons of snow cover timing among years, each weekly data file was assigned a sequential week number (1-52). Each data file was assigned the week number of the week that it overlapped by 4 or more days. This technique introduces an increment of temporal uncertainty of 0-3 days. An individual year consisted of 52 weeks, except for leap years, which had 53 weeks. The 53rd week was neglected.

The temporal features of snow cover were quantified for each non-masked grid cell with respect to two key variables: the week number of the last week with snow cover in spring (WLS) and the week number of the first week with snow cover in autumn (WFS). The spring and autumn periods were defined as weeks 1-30 (January-July) and weeks 31-52 (August-December), respectively. The duration of the annual snow-free period (DSF) at each grid cell is was calculated as,

$$DSF_n = WFS_n - WLS_n - 1 \quad (1)$$

where n refers to the year and $1972 \leq n \leq 2000$.

Study Regions

Interannual variablity in WLS, WFS, and DSF were analyzed separately. For each analysis, non-masked grid cells were categorized into three groups according to the mean (1972-2000) of the grid cell values of WLS, WFS or DSF, indicated here as $\overline{WLS}$, $\overline{WFS}$, and $\overline{DSF}$ (units of decimal weeks). The ranges of $\overline{WLS}$, $\overline{WFS}$, and $\overline{DSF}$ selected for the categorization are given in Table 1. This procedure produced three circum-hemispheric regions for each analysis (Fig. 1). The grid cells in each region exhibit similar temporal features with respect to snow cover transitions.

Validation

No practical means exists for directly validating WLS, WFS, and DSF using *in situ* data (e.g., snow depth measurements at sites) at the broad spatial scale appropriate for the data set. As an alternative approach to validation, the relationship between the snow cover cycle and SCA was examined. Assuming the SCA estimates derived from the NOAA-NESDIS snow cover charts are reliable for broad-scale climate studies (Wiesnet et al.,

Table 1. Regions Used in Analysis of Snow Cover Area (SCA), Timing and Snow-Free Duration and Associated Parameters and Statistics

Analysis/Region	Region Definition (Grid Cell Means, 1972-2000)	Time Periods Used to Calculate SCA	Snow Cover Area			Snow Cover Timing & Snow-Free Duration (Area-Weighted)		
			Mean (1972-2000)	Std. Dev.	Coeff. of Variation	Mean (1972-2000)	Std. Dev.	Coeff. of Variation
Week of Last Observed Snow Cover in Spring (WLS)	week #	week #s	10^6 km^2			week #		
WLS-R1	22.0-26.0	23-26 (~June)	3.5	1.4	0.39	23.8	1.1	
WLS-R2	17.5-22.0	18-22 (~May)	4.5	1.1	0.25	19.9	1.0	
WLS-R3	13.5-17.5	14-17 (~April)	4.7	1.1	0.24	15.5	0.8	
Week of First Observed Snow Cover in Autumn (WFS)								
WFS-R1	36.0-39.0	36-39 (~September)	1.0	0.4	0.36	38.0	0.9	
WFS-R2	39.0-43.5	40-43 (~October)	6.4	1.4	0.21	41.3	0.7	
WFS-R3	43.5-47.5	44-47 (~November)	7.7	1.5	0.19	45.0	0.7	
Duration of Snow-Free Period (DSF)	weeks					weeks		
DSF-R1	8.0-18.0	1-52	6.9	0.2	0.03	14.3	1.4	0.10
DSF-R2	18.0-28.0	1-52	7.2	0.3	0.04	23.1	1.2	0.05
DSF-R3	28.0-37.0	1-52	3.1	0.1	0.04	30.9	1.0	0.03

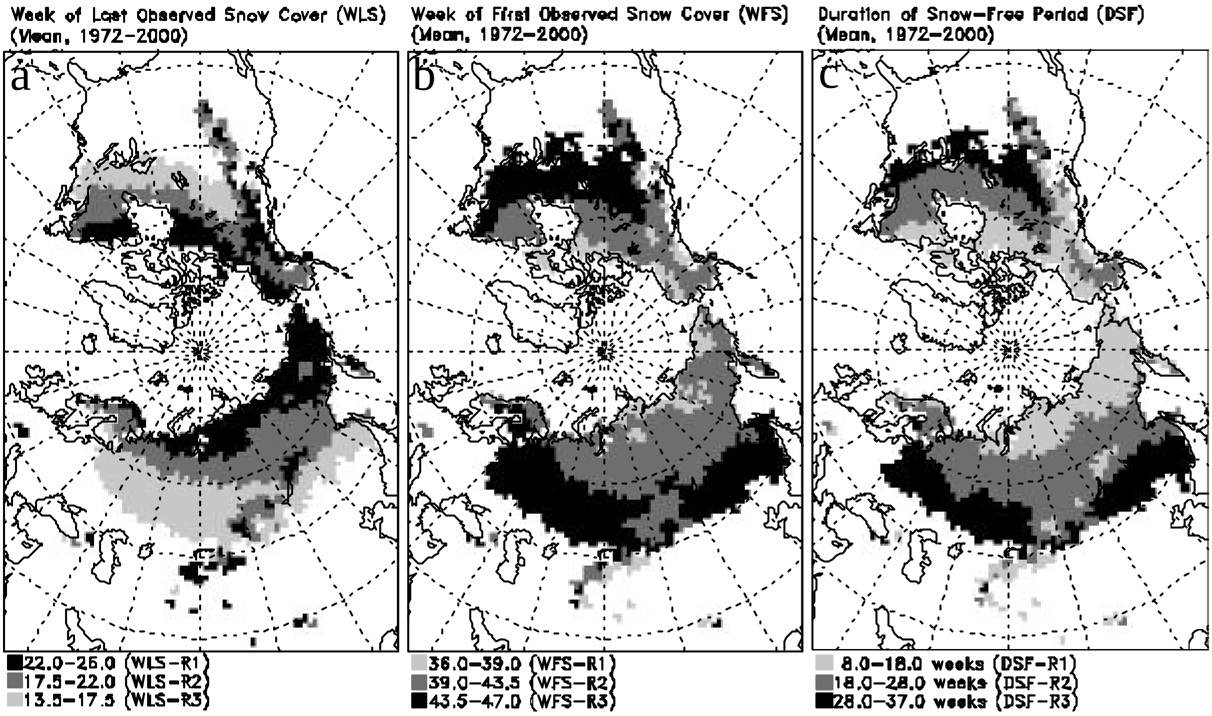

Figure 1. Distribution of study regions for the analysis of a) week last observed snow cover in spring (WLS), b) week of first observed snow cover in autumn, and c) duration of the snow-free period (DSF). Refer to Table 1 and the text for criteria employed to delineate the study regions.

1987), a strong correlation between interannual fluctuations in SCA and WLS, WFS, and DSF strengthens confidence in the data for the snow cover cycle analysis.

Yearly values of SCA (Table 1) were calculated for each of the nine study regions (Fig. 1) with respect to the time periods specified in Table 1. The mean SCA during the target time period was calculated for each grid cell. SCA values for the study regions were computed as the sum of the snow cover area values for grid cells within each region.

RESULTS AND DISCUSSION

Relation between the Snow Cover Cycle and Snow Cover Area

The time series of annual anomalies in SCA and WFS, WLS, and DSF are shown in Figure 2 for six of the nine study regions. Both SCA and the snow cover cycle variables exhibit substantial interannual variability. Coefficients of variation of 19-39% for SCA in spring and autumn periods correspond to standard deviations in WFS and WLS of 0.7-1.1 weeks (Table 1). These values are consistent with the expectation that a shift of about 1 week in snow cover disappearance or onset (about 25% of a monthly period) would be associated with an increase or decrease of close to 25% in the average monthly SCA.

Coefficients of determination (R^2) values for the correlation between SCA and the snow cover cycle variables are given in Table 2 for all study regions, and scatter plots for the R2 regions only are shown in Figure 3. In all of the analyses except WFS-R1, the snow cover cycle anomalies correspond closely to the SCA anomalies (Table 2, Fig. 2). While a strong correlation between SCA and the snow cover cycle is intuitive and expected, such a relationship has not previously been reported in quantitative terms using observational data. These results suggest that WLS, WFS and DSF are effective indicators of interannual variability in the snow cover cycle for the circum-hemispheric regions considered in this study.

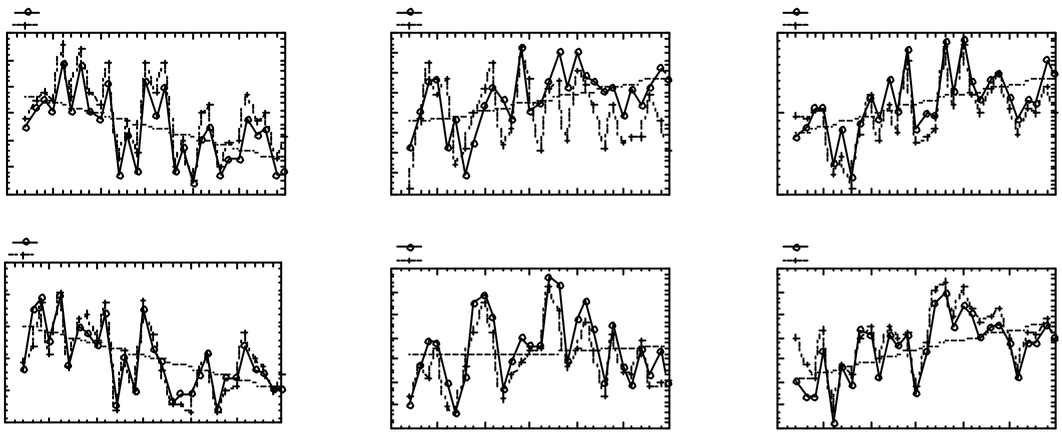

Figure 2. Time series plots of snow cover area (SCA) and snow cover cycle variables (WLS, WFS, DSF) for the following study regions: a) WLS-R1, b) WLS-R2, c) WFS-R1, d) WFS-R2, e) DSF-R1, f) DSF-R2.

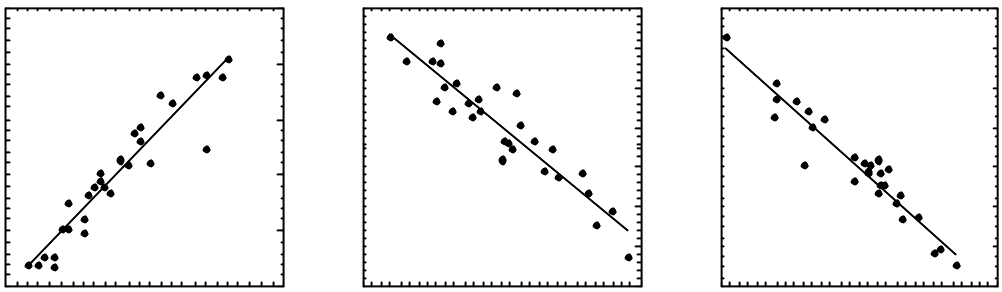

Figure 3. Scatter plots of SCA versus a) WFS, b) WFS, and c) DSF for the R2 study regions. Best fit lines from least-squares linear regression line are shown.

Table 2. Coefficients of Determination (R^2) Values From Correlation of Snow Cover Cycle Variables with Snow Cover Area (SCA)

Analysis/Region	R^2
Week of Last Observed Snow Cover in Spring (WLS)	
WLS-R1	0.80
WLS-R2	0.90
WLS-R3	0.96
Week of First Observed Snow Cover in Autumn (WFS)	
WFS-R1	0.25
WFS-R2	0.87
WFS-R3	0.65
Duration of Snow-Free Period (DSF)	
DSF-R1	0.87
DSF-R2	0.91
DSF-R3	0.81

Table 3. Trends (Least-Squares Linear Regression Coefficients) for Snow Cover Cycle Variables (1972-2000)

Analysis/Region	**Trend (days/decade)**
Week of Last Observed Snow Cover in Spring (WLS)	
WLS-R1	-5.1**
WLS-R2	-5.0**
WLS-R3	-3.2**
Week of First Observed Snow Cover in Autumn (WFS)	
WFS-R1	3.6*
WFS-R2	0.4
WFS-R3	0.4
Duration of Snow-Free Period (DSF)	
DSF-R1	6.4**
DSF-R2	5.3**
DSF-R3	3.1

*95% confidence level
**99% confidence level

Trends in the Snow Cover Cycle

Despite substantial year-to-year fluctuations, statistically significant trends were detected (Fig. 2, Table 3). The trend analysis indicates a shift toward earlier snowmelt of about 3-5 days/decade and an increase in the duration of the snow-free period of about 3-6 days/decade.

There was no strong evidence for any systematic trend in snow cover onset in autumn. A significant positive trend was detected in WFS for the analysis of WFS-R1 (Table 3), however the small spatial sample size and relatively weak correlation with SCA renders this region suspect. These results are consistent with other studies that report declining trends in continental and NH snow cover extent in spring, but not in autumn (Brown, 2000; Robinson et al., 1995).

For both WLS and DSF, the strongest trends (Table 3) were observed for the two highest latitude study regions (R1 and R2), which are mostly above 55-60° N (Fig. 1). Trends in WLS and DSF for the lower latitude study regions (R3, mostly in the range from 45-60° N) were roughly 40-50% lower than those observed in the higher latitude study regions (Table 3).

Significance for Terrestrial Ecosystems

Snowmelt in high latitudes occurs close to or within the period of annual maximum solar irradiance and photoperiod, so even small shifts toward earlier snowmelt may have a potentially significant effect on both the surface energy balance (Pielke et al., 2000) and biotic activity (Huemmrich et al. 1999). The low albedo of the snow-free land surface increases the surface absorption of shortwave radiation, contributing to the warming of soil and air temperatures (Groisman and Davies, 2001). With the disappearance of snow cover, ground-layer vegetation can begin to capture the photosynthetically active radiation (PAR) required for photosynthesis, most of which is otherwise lost by reflection from the snow surface and essentially wasted from the perspective of vegetation capture of light and CO_2. An early snowmelt thus permits an early initiation of photosynthetic activity (Running et al., 1999).

At the hemispheric scale, the observed shift toward earlier spring snowmelt is consistent with results from time series analyses of independent indicators of the active growing season. A temporal shift in the springtime transition to net ecosystem uptake of CO_2 is indicative of a temporal shift in the initiation of photosynthetic activity. Keeling et al. (1996) reported that the timing of this transition as measured at Pt. Barrow and Mauna Loa shifted earlier by about 3.5 days per decade between 1975 and 1994. Time series analysis of satellite-derived normalized difference vegetation index (NDVI) data for northern high latitude land areas showed that the timing of vegetation "green-up" in spring shifted earlier by about 7 days per decade between 1981 and 1991 (Myneni et al., 1997). This analysis indicates that the snow cover disappearance (WLS) in spring shifted earlier by 3-5 days per decade between 1972 and 2000 (Table 2), which is close to the reported rates of change in CO_2 uptake and the NDVI green-up. The observed trend toward early snow cover disappearance is generally consistent with reported trends toward an earlier onset of spring in North America and Europe during recent decades as inferred from surface observations of plant phenology (Cayan et al., 2001; Menzel and Fabian, 1999).

SUMMARY AND CONCLUSIONS

The results from this study indicate that over the 29-year study period there were significant trends toward earlier snow cover disappearance in spring (3-5 days/decade) and a lengthening of the snow-free period (3-6 days/decade) cycle in NH land areas, mostly above 45° N. These shifts in the annual snow cover cycle are associated with the changes in continental and NH snow cover extent reported by other investigators for the spring season. The contention that the observed shifts in the snow cover cycle reflect real changes in high latitude climate is consistent with the warming trend in surface air temperature reported for recent decades in northern high latitude land areas during winter and spring seasons (Serreze et al., 2000; Easterling et al., 2000). The results support earlier suggestions that high latitude climate warming will lead to a lengthening of the snow-free period (Maxwell, 1992). The trend toward earlier snow cover disappearance is also consistent with the reported trend toward earlier spring uptake of atmospheric CO_2 by Northern Hemisphere terrestrial ecosystems (Keeling et al., 1996) and with satellite observations of the earlier green-up of vegetation in high northern latitude land areas (Myneni et al., 1997).

The observed changes in the annual snow cover cycle have strong implications for terrestrial ecosystem functioning. The alterations to air and soil temperatures and the hydrologic budget that accompany changes in the terrestrial snow regime may induce, over seasonal and annual time scales, significant changes in plant phenology, productivity and net ecosystem CO_2 exchange. Evidence of such changes in Northern Hemisphere land areas over recent decades has been noted in the preceding discussion.

An improved understanding of how an earlier and lengthened snow-free season affects the coupled snow-climate-vegetation-soil system constitutes a major research challenge (Groisman and Davies, 2001). Achieving this goal requires detailed consideration of the interactions among snow cover, the surface energy balance, the hydrologic budget, and biotic processes of vegetation and soils. Future progress will depend on a combination of of observational and modeling studies, together aimed at detection and monitoring of snow cover dynamics and determination of their ecosystem effects and feedbacks at regional, continental and global scales.

REFERENCES

Brown, R.D., 2000. Northern hemisphere snow cover variability and change, 1915-97. Journal of Climate**,** 13**,** pp. 2339-2355.

Cayan, D.R., Kammerdiener, S.A., Dettinger, M.D., Caprio, J.M., Peterson, D.H., 2001. Bulletin of the American Meteorological Society, 82, pp. 399-415.

Easterling, D.R., Karl, T.F., Gallo, K.P., Robinson, D.A., Trenberth, K.E., Dai A., 2000. Observed climate variability and change of relevance to the biosphere. Journal of Geophysical Research, 105, pp. 20,101-20,114.

Foster, J.L., 1989. The significance of the date of snow disappearance on the arctic tundra as a possible indicator of climate change. Arctic and Alpine Research**,** 21, pp. 60-70.

Groisman, P.Y., Davies, T.D., 2001. Snow cover and the climate system. In: Snow Ecology, edited by Jones, H.G., Pomeroy, J.W., Walker, D.A., and Hoham, R.W., Cambridge Univ. Press, New York, pp. 1-44.

Groisman, P.Y., Karl, T.R., Knight, R.W., Stenchikov, G.L., 1994. Changes of snow cover, temperature, and radiative heat balance over the Northern Hemisphere. Journal of Climate, **7,** pp. 1633-1656.

Huemmrich, K.F., Black, T.A., Jarvis, P.G., McCaughey, J.H., and Hall, F.G., 1999. High temporal resolution NDVI phenology from micrometeorological radiation sensors. Journal of Geophysical Research, 104, pp. 27,935-27,944.

Keeling, C.D., Chin, J.F.S., Whorf, T.P., 1996. Increased activity of northern vegetation inferred from CO2 measurements. Nature**,** 382, pp. 146-149.

Maxwell, B., 1992. Arctic climate: potential for change under global warming. In: Arctic Ecosystems in a Changing Climate, edited by Chapin III, F.S., Jefferies, R.L., Reynolds, J.F., Shaver, G.R., Svoboda, J., and Chu, E.W., Academic Press, San Diego, pp. 11-33.

Menzel, A., Fabian, P., 1999. Growing season extended in Europe. Nature, 397, p. 659.

Myneni, R.B., Keeling, C.D., Tucker, C.J., Asrar, G., Nemani, R.R., 1997. Increased plant growth in the northern high latitudes from 1981 to 1991. Nature, 386, pp. 698-702.

Pielke Sr., R.A., Liston, G.E., Robock, A., 2000. Insolation-weighted assessment of Northern Hemisphere snow-cover and sea-ice variability. Geophysical Research Letters, **27**, pp. 3061-3064.

Robinson, D.A., Dewey, K.F., Heim Jr., RR. 1993. Global Snow Cover Monitoring: An Update. Bull. Amer. Meteor. Soc., **7**4, pp. 1689-1696.

Robinson, D.A., Frei, A., Serreze, M.C., 1995. Recent variations and regional relationships in Northern Hemisphere snow cover. Annals of Glaciology, 21, pp. 71-76.

Running, S.W., Way, J.B., McDonald, K.C., Kimball S., Frolking S., Keyser A.R., and Zimmerman R. 1999. Radar remote sensing proposed for monitoring freeze-thaw transistions in boreal regions. EOS, Transactions, American Geophysical Union, 80, pp. 213-221.

Serreze, M.C., Walsh, J.E., Chapin III, F.S., Osterkamp, T., Dyurgerov, M., Romanovsky, V., Oechel, W.C., Morison, J., Zhang, T., Barry, R.G., 2000. Observational evidence of recent change in the northern high-latitude environment. Climatic Change, 46, pp. 159-207.

Walker, D.A., Billings, W.D., de Molenaar, J.G., 2001. Snow-vegetation interactions in tundra environments. In: Snow Ecology, edited by Jones, H.G., Pomeroy, J.W., Walker, D.A., and Hoham, R.W., Cambridge Univ. Press, New York, pp. 266-324.

Wiesnet, D.R., Ropelewski, C.F., Kukla, G.J., Robinson, D.A,. 1987. A discussion of the accuracy of NOAA satellite-derived global seasonal snow cover measurements. In: Large Scale Effects of Seasonal Snow Cover, edited by Goodison, B.E., Barry, R.E., and Dozier, J., IAHS Publication no. 166, pp. 291-304.

Ye, H., 2001. Increases in snow season length due to earlier first snow and later last snow dates over North Central and Northwest Asia during 1937-94. Geophysical Research Letters, 28, pp. 551-554.