Observed Inconsistencies between Snow Extent and Snow Depth Variability at Regional/Continental Scales

YAN GE AND GAVIN GONG

Department of Earth and Environmental Engineering, Columbia University, New York, New York

(Manuscript received 20 December 2006, in final form 12 July 2007)

ABSTRACT

Snow extent and snow depth are two related characteristics of a snowpack, but they do not need to be mutually consistent. Differences between these two variables at local scales are readily apparent. However, at larger scales, which interact with atmospheric circulation and climate, snow extent is the primary variable considered, owing largely to the scarcity of snow depth data. In this study, three regional-/continental-scale gridded snow depth/snow water equivalent (SWE) datasets, derived from station observations or passive microwave satellite sensors, are utilized to quantitatively evaluate the relationship between snow extent and snow depth/SWE over North America. Various statistical methods are used to ensure the robustness of the results, including correlations, composites, and singular value decomposition analyses.

Results indicate that continental-scale snow depth variations are substantial in their own right and that depth and extent anomalies are largely unrelated over broad high-latitude regions north of the snow line. Snow extent and snow depth vary more consistently in the vicinity of the snow line, especially in autumn and spring, during which precipitation and ablation can affect both variables. It is also found that deeper (shallower) winter snow translates into larger (smaller) snow-covered areas in the following spring/summer season, and also a longer (shorter) snow season, but only in specific regions. These results suggest a possible influence of snow depth on spring and summer climate. Overall, the observed lack of mutual consistency between these two snowpack variables at continental/regional scales suggests that snow depth variations may be of sufficiently large magnitude, spatial scope, and temporal duration to interact with regional–hemispheric climate, in a manner unrelated to the more extensively studied snow extent variations.

1. Introduction

Snow–atmosphere interactions have long been a topic of speculation and study. Substantial relationships are expected because snow can influence the energy budget at various spatial and temporal scales. Snow extent and snow depth are two related but distinct snowpack characteristics that can potentially affect climate. However, historical research on the influence of snow on climate has primarily focused on snow extent, owing largely to the scarcity of snow depth data. This omission is a major shortcoming of our current understanding of snow–climate linkages, and serves as motivation for this investigation into the similarities and differences between large-scale snow extent and snow depth variability.

Research on the understanding of snow's interaction with local, regional, and hemispheric climate has grown dramatically since 1966, when continuous records of visible satellite-based snow extent observations over the Northern Hemisphere first became available. Numerous studies have identified a statistical relationship between snow extent and surface temperature over various spatial and temporal scales (e.g., Dewey 1977; Walsh et al. 1982; Namias 1985; Baker et al. 1992; Leathers et al. 1995; Serreze et al. 1998). Observational studies have also shown that large continental-scale snow extent anomalies lead to important variations in climate and general circulation via changes to the energy budget in the lower atmosphere (Foster et al. 1983; Karl et al. 1993; Leathers and Robinson 1993; Groisman et al. 1994; Cohen and Entekhabi 1999, 2001; Saito and Cohen 2003; Saunders et al. 2003). Modeling studies have addressed the causal relationship between snow extent and climate variations. For example, snow extent can be an important forcing mechanism for the Northern Hemisphere general circulation and helps ex-

---

Corresponding author address: Yan Ge, Department of Earth and Environmental Engineering, Columbia University, 918 S. W. Mudd Hall, 500 West 120th Street, New York, NY 10027.
E-mail: yg2124@columbia.edu

DOI: 10.1175/2007JCLI1829.1

plain interannual climate variations throughout the Northern Hemisphere (Cohen and Rind 1991; Cohen and Entekhabi 2001; Gong et al. 2002, 2003, 2004; Marshall et al. 2003; Kumar and Yang 2003). Conversely, other observational studies demonstrate snow cover responses to atmospheric anomalies. Walsh et al. (1982), Serreze et al. (1998), and Robok et al. (2003) found that the fluctuation of snow cover could be viewed as the consequence of temperature anomalies and variable large-scale circulations, such as the Pacific–North American (PNA) and the east Pacific (EP) teleconnection patterns.

These studies typically focused on the presence or absence of snow cover but did not consider the depth of the snowpack. In reality, snow cover at a point is not a yes/no binary variable, but rather a continuous variable in which snow depth varies spatially and temporally. Clearly, snow depth can vary between different regions within a snow-covered domain and can vary at a given location throughout the course of its snow season. Such snow depth variations can interact with the overlying climate through a variety of thermodynamic mechanisms (Cohen 1994), such as surface albedo, terrestrial radiation, thermal conduction, and ablation, and potentially alter the surface energy balance and surface temperatures when snow cover is continually present.

The simplified treatment of snow as a binary variable is a major restriction on our current understanding of snow–climate relationships. A common justification for this approach within the snow–climate interactions research community is that snow depth variations are thought to be minor and/or mutually consistent compared to snow extent variations, even if this assumption is rarely verified. A number of studies have considered the effect of snow depth on climate (e.g., Serreze et al. 1998; Davis et al. 1999; Ellis and Leathers 1999; Cohen and Entekhabi 2001; Ye 2001; McCabe and Dettinger 2002; Marshall et al. 2003; Gong et al. 2003, 2004). However, these studies typically merge snow extent and snow depth into an aggregate forcing without differentiating the two components.

A limited number of exploratory studies have attempted to explicitly distinguish climate responses to snow depth. Wagner (1973) and Baker et al. (1992) showed that deeper snow enhances snow-forced temperature suppression at local scales. Some modeling results have reported that snow depth may have a greater impact on the Indian monsoon than snow extent via alterations to the hydrological cycle and surface energy budget (Barnett et al. 1989; Yasunari et al. 1991). Watanabe and Nitta (1998) performed a model study over Siberia and reported that broad dipole snow-depth anomalies are reminiscent of the dominant mode of extratropical Northern Hemisphere climate variability. Observational evidence has also demonstrated the possible causal influence of climate teleconnection patterns on winter snow water equivalent (SWE) over various spatial and temporal domains (Ye 2001; Sobolowski and Frei 2006). While SWE and snow depth are not interchangeable, both characterize the amount of snow on the ground rather than just its presence or absence. These studies tend to be limited to small/local datasets, but the work nonetheless suggests that snow depth/SWE can have a nonnegligible and distinct contribution to the overlying atmospheric thermodynamics.

The impact of snow depth/SWE has historically been understudied due mostly to the lack of reliable observational data, but this shortcoming has been addressed in recent years, using point station data, passive microwave satellite sensors, and reanalysis techniques. For example, Brown (2000) and Dyer and Mote (2006) interpolated gridded daily snow depth time series from data provided by the National Oceanic and Atmospheric Administration (NOAA)/National Climatic Data Center (NCDC) and the Meteorological Service of Canada. Meanwhile, improved algorithms for remotely sensed snow depth/SWE have been developed. The National Snow and Ice Data Center (NSIDC) has compiled global-scale snow depth/SWE derived from passive microwave data (Armstrong and Brodzik 2001; Derksen et al. 2004; Chang et al. 2005). These products provide new opportunities to help improve our understanding of the relationship between snow extent, snow depth, and climate variability.

This study aims to quantitatively test the magnitude of interannual snow depth variations and its differing behavior from snow extent variability by utilizing available snow datasets. The various datasets and methods used are presented in section 2. Section 3 discusses the results of observational analyses, and conclusions are provided in section 4. Our focus is on regional/continental scales at which the potential for regional and remote snow depth–climate linkages is the greatest, but the distinction between snow depth and snow extent may not be clear. At local scales this difference is readily apparent since, during conditions of uninterrupted snow cover, snow depth at a point can vary substantially due to snowfall events, metamorphosis, and ablation. If such differences are maintained across broad spatial scales, it is conceivable that snow depth anomalies (independent of snow extent anomalies) may be able to influence the surface energy balance and temperature over a broad land surface region and, in turn, affect atmospheric flow regimes, circulation patterns, and hemispheric climate. Hence, this study is an important first step for effectively understanding the role of snow depth in climate variability.

2. Approach

a. Datasets

Three regional/continental-scale gridded datasets of snow depth or SWE are utilized to qualitatively evaluate the relationship between snow extent and snow depth/SWE over North America. The datasets are all characterized by broad spatial coverage and multidecadal temporal duration but are derived from different sources (i.e., station observations versus satellite remote sensing). These datasets are all relatively new but represent a mix of widely used (Brown 2000), underutilized (Derksen et al. 2004), and newly released (Dyer and Mote 2006) data. Because these data collection methods are still evolving, it is prudent to evaluate a spectrum of high-quality datasets from different sources.

First, Dyer and Mote (2006) describe a new and comprehensive set of daily 1° × 1° gridded snow depth data for North America from 1900 through 2000. Daily observations from about 7000 measurement stations in the United States and Canada were converted to 1° × 1° grids using a modified version of the Shepard (1968) interpolation procedure for irregularly spaced data. We performed an independent quality review of this dataset by analyzing spatial station distributions and corresponding snow depth fields at different times and visually identifying years with erroneous snow depth fields. It is found that the quality of interpolated gridpoint values is most reliable after 1956 when additional stations throughout Canada became available, as indicated in Figs. 1a and 1b. The decades prior to 1956 are characterized by sparse and uneven station coverage (not shown).

Monthly North American snow extent time series are derived by summing the area of snow-covered land over all grid cells. Snow-covered area in each grid cell is computed by multiplying monthly snow frequency (monthly snow duration/number of days in month) by the land area of the grid point, following Brown (2000). The resulting North American snow extent time series for January is shown in Fig. 2a, alongside the well-established Brown (2000) station dataset described below (adjusted to represent all of North America excluding Greenland) and also NOAA visible satellite imagery (Robinson 1999). The basic features of snow extent across North America are well captured, that is, a gradual upward trend peaking in the late 1970s or early 1980s, followed by a general decrease to minimum values in the late 1980s and early 1990s (Frei et al. 1999; Brown 2000; Cohen and Entekhabi 2001; Frei et al. 2003). Suspect data quality in the early years of the Dyer and Mote (2006) dataset is apparent in the noticeably reduced snow extent values prior to 1956, and especially prior to 1925, although even after 1956 snow extent appears to be slightly underestimated.

Monthly snow depth time series are computed as the area-weighted average snow depth over the snow-covered extent. Figure 2b shows the January average snow depth time series computed from Dyer and Mote (2006) and Brown (2000). Note that the Dyer and Mote (2006) gridcell domain covers all of North America; thus, the monthly average snow depth time series values are expected to be higher than for Brown (2000), whose gridcell domain only includes regions south of about 55°N (see below). Therefore, January average snow depth time series over the region south of 55°N from the Dyer and Mote (2006) dataset is also shown in Fig. 2b. Suspect high-latitude data quality in the early years of the Dyer and Mote (2006) dataset is very apparent in the roughly twofold increase in average snow depth over North America between the first and second half of the twentieth century and the similarity between average values with and without high-latitude regions. The data quality issue is less obvious (but still noticeable) in Fig. 2a since this snow extent is less sensitive to interpolation errors than snow depth; that is, erroneous interpolated snow depths are still recorded as being snow covered. After the 1950s, differences still exist between these two datasets, due in part to the arbitrary 55°N boundary applied for the Dyer and Mote (2006) dataset. Nevertheless, they exhibit similar overall trends: average snow depth increases until the 1970s and then drops in the 1980s and 1990s. The Dyer and Mote (2006) dataset is the principal data used in this study due to its extensive spatial coverage (all of North America, excluding Greenland) and temporal duration (45 yr).

Second, a gridded snow depth dataset spanning North America is available for the 1915–97 period (Brown 2000), following the NOAA 190.5-km polar stereographic projection. Gridpoint values are interpolated from 349 stations located in the United States and southern Canada, so the spatial domain of this dataset covers the area south of approximately 55°N latitude (Fig. 1c). Monthly mean values are provided, from November to April, each snow season. Furthermore, Brown (2000) employed the satellite-observed 1972–92 North American snow extent mean and standard deviation to convert the gridded midlatitude snow depth data into a time series of snow cover extent over all of North America for the temporal interval from 1915 to 1997. The result is one of the most widely recognized long-term North American snow extent time series, de-

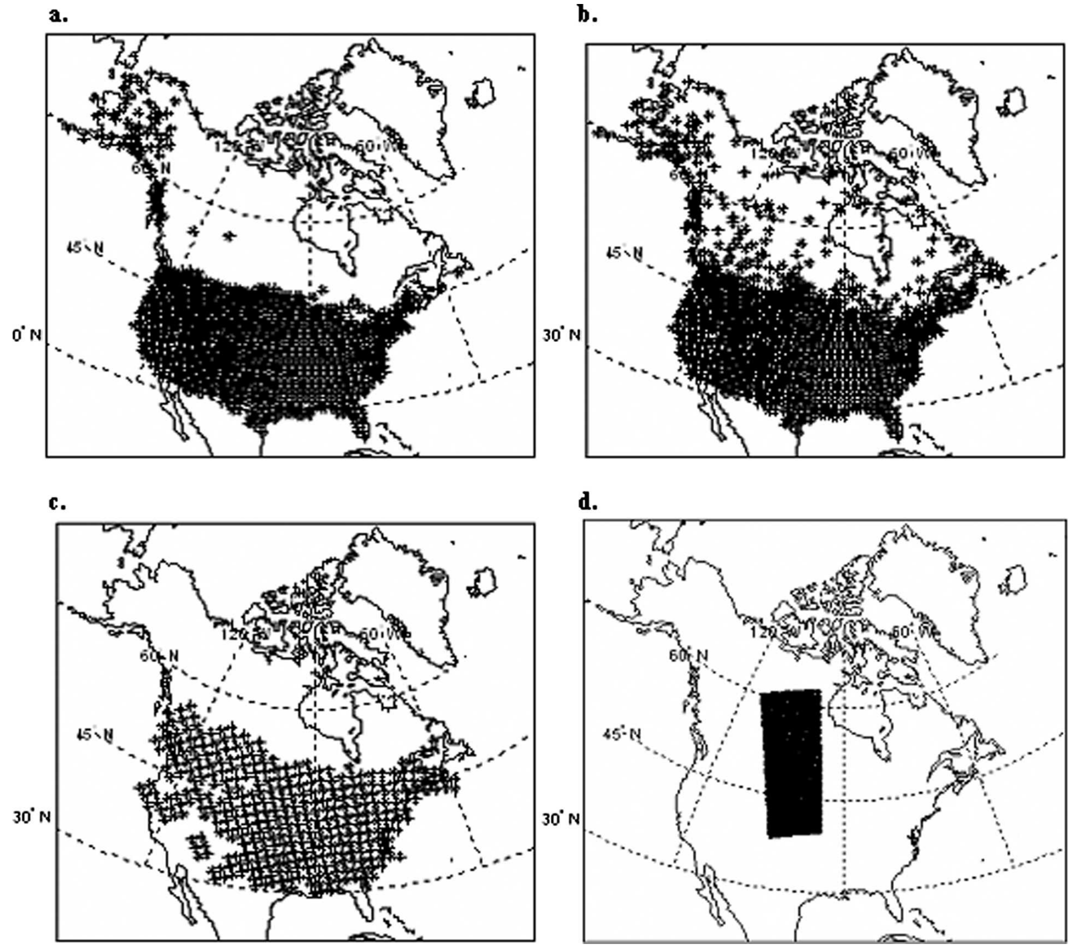
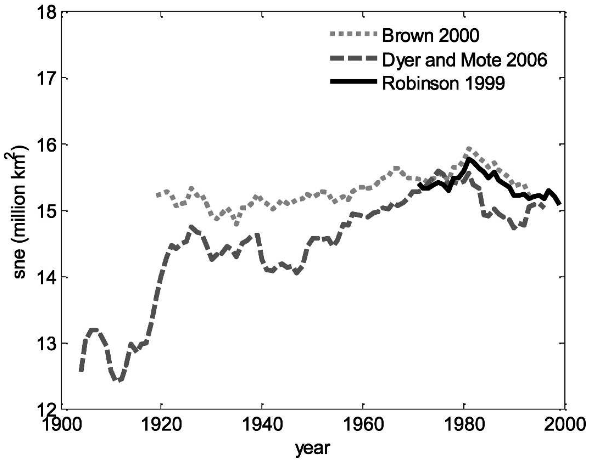


Fig. 1. Gridcell locations for the regional/continental-scale gridded datasets of snow depth and snow water equivalent used in this study: Daily 1° × 1° gridded dataset covering all of North America interpolated from station snow depth observations from 1956 through 2000 (Dyer and Mote 2006); grid cells with at least one station (a) in January 1950 and (b) in January 1956 are shown. (c) Gridded snow depth dataset spanning North America interpolated from 349 stations located in the United States and southern Canada for the 1915–97 period (Brown 2000). (d) SWE maps for the Canadian prairies derived using passive microwave data from the NASA SMMR and SSM/I instruments from 1978 to 1997 (Derksen et al. 2004).

rived without high-latitude snow depth data and used extensively in snow–climate studies (e.g., Ye 2001; Marshall et al. 2003; Sobolowski and Frei 2006), due to its high quality and 83-yr duration. Hence this well-known dataset serves as a good reference for validating the Dyer and Mote (2006) dataset in this research (Fig. 2). The trade-off with the Brown (2000) dataset is that the grids only cover part of North America so that snow depth information is lacking in high-latitude regions. Therefore, for our assessment of snow depth versus snow extent, Brown (2000) will only be used for its long-term North American snow extent time series. High-latitude snow depth data is obtained exclusively from the Dyer and Mote (2006) dataset.

Third, SWE maps for the North American prairies have been derived using passive microwave data from the National Aeronautics and Space Administration (NASA) Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) instruments (Derksen et al. 2004). This dataset covers the central North America region (38°–63°N) for three consecutive months (December, January, and February) from 1978 to 1997 (Fig. 1d). SWE is distinct from snow depth, but similarly reflects the amount of snow on the ground; hence, SWE can also be compared against spatial snow extent to assess their mutual consistency. Although this SWE dataset is of limited use owing to its modest spatial and temporal coverage, it nevertheless serves as an independent, high-quality alternative to the two station-derived snow depth datasets described above, for a broad swath of our North American study domain.

a. Snow Extent



b. Snow Depth

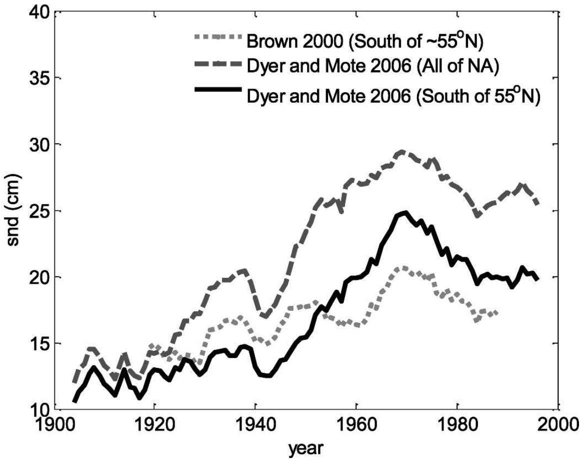


FIG. 2. January 9-yr running mean continental snow extent (sne) and snow depth (snd) time series from the Brown (2000), Dyer and Mote (2006), and Robinson (1999) datasets: (a) snow extent over North America excluding Greenland and (b) snow depth computed as the area-weighted average snow depth over the snow-covered extent. Brown (2000) only includes regions south of approximately 55°N latitude, while Dyer and Mote (2006) includes all of North America excluding Greenland.

b. Methodology

The mutual consistency between interannual snow depth and snow extent anomalies is assessed using a variety of statistical methods and data domains, in order to verify that the results are meaningful and not simply a statistical artifact of any single analysis method. We begin with a time series analysis between North American snow extent and the average snow depth over all North American snow-covered lands. Next, correlation and composite analyses are performed between North American snow extent and gridpoint snow depth within North America to evaluate the spatial patterns of any consistencies over the continent. One-parameter empirical orthogonal function (EOF) and two-parameter singular value decomposition (SVD) analyses are also performed for gridpoint snow frequency and snow depth variability to provide another means of evaluating spatial patterns and relationships between snow extent and snow depth. To investigate the relationship between snow depth and snow persistence, lagged correlations between gridpoint snow depth and subsequent North American snow extent are computed, and correlation and SVD analyses are performed between gridpoint snow depth and gridpoint snow season duration. A comprehensive evaluation using different statistical techniques, coupled with different datasets from various sources, helps to ensure the robustness of the results and conclusions.

3. Results

a. Snow extent versus average snow depth over North America

The monthly snow extent time series over North America during the 1956–97 period is provided directly by Brown (2000). The monthly snow depth time series is computed using the Dyer and Mote (2006) gridded dataset, as the area-weighted average snow depth over the North American snow-covered extent provided by Brown (2000). Figure 3a shows monthly box plots of snow extent and average snow depth over North America. It indicates that the annual cycle of the two snow variables follows different temporal patterns for both the mean and interannual variability. Monthly mean snow extent increases in the early snow season and reaches its maximum value in January as expected, but interannual variability of monthly snow extent is relatively small in January and February. In contrast, both the mean value and range of variability for monthly snow depth increases steadily through March. Autumn (winter) is characterized by relatively large (small) snow extent variability but relatively small (large) snow depth variability.

Another indication of different behavior of these two snow parameters is the monthly linear correlation between snow depth and snow extent time series, presented in Fig. 3b. For a sample size of 42 yr, a correlation coefficient of 0.30 (0.39) is statistically significant at the 5% (1%) level (Snedecor and Cochran 1989). The interannual snow depth and snow extent time series are weakly correlated in general, especially in winter. During autumn and spring, snow is of limited spatial extent and generally shallow so that snowfall events and inter-

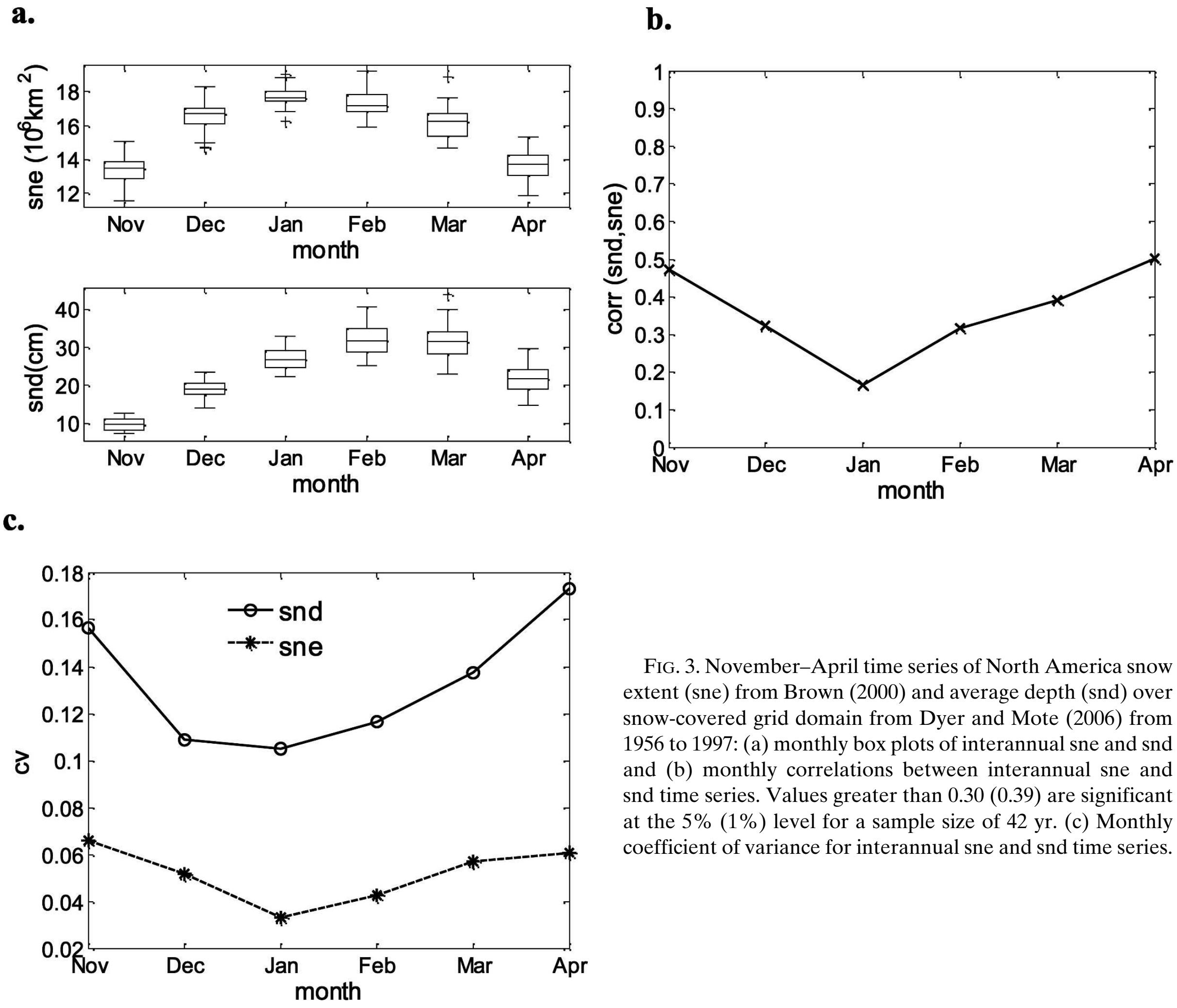


FIG. 3. November–April time series of North America snow extent (sne) from Brown (2000) and average depth (snd) over snow-covered grid domain from Dyer and Mote (2006) from 1956 to 1997: (a) monthly box plots of interannual sne and snd and (b) monthly correlations between interannual sne and snd time series. Values greater than 0.30 (0.39) are significant at the 5% (1%) level for a sample size of 42 yr. (c) Monthly coefficient of variance for interannual sne and snd time series.

storm ablation tend to affect both snow extent and snow depth; hence, the greatest correlations (>0.47) occur in November and April. During winter, snow cover is much more widespread over North America, and high-latitude regions are constantly covered by deep snowpack, so snowfall events and ablation processes can alter snow depth without necessarily affecting snow extent. Hence, the poorest correlations (<0.33) occur from December through February. Monthly scatterplots (not shown) support the linear correlation results, that is, wide scatter and a lack of any apparent (linear or nonlinear) snow extent versus snow depth relationship during winter and a more noticeable but still modest relationship during autumn and spring. These results suggest that a broad snow-covered region exists during winter in which snow depths vary independently of continental snow extent.

Finally, the monthly coefficient of variance (CV: standard deviation/mean) is presented in Fig. 3c for both North American snow extent and snow depth. The interannual variability of snow depth comprises a substantially larger percentage of its climatological mean than that for snow extent, consistently across all months. The CV ranges from roughly 0.10 to 0.18 for snow depth, but only 0.01 to 0.07 for snow extent. Hence, the relative magnitude of snow depth variability can be considered more substantial than that of snow extent variability. Given that snow extent has been shown to considerably affect climate variations, the larger CV values for snow depth suggests that North American snow depth anomalies may also be significant enough to exert a distinct influence on climate independent of snow extent anomalies.

b. Correlation maps: Gridpoint snow depth versus NA snow extent

Figure 4 presents monthly linear correlation maps of gridpoint snow depth (Dyer and Mote 2006) versus

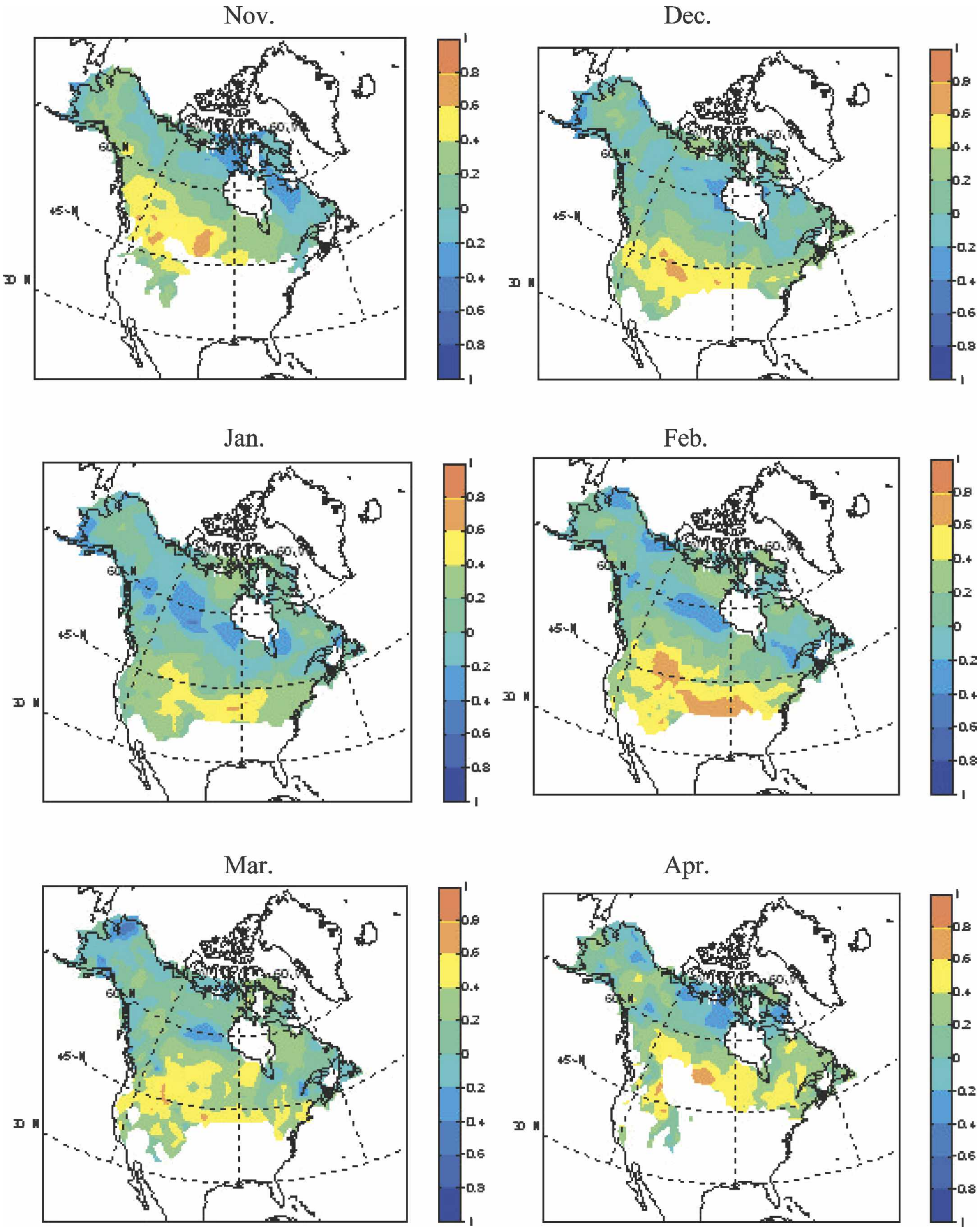


FIG. 4. Correlation maps between gridded snow depth (Dyer and Mote 2006) and North American snow extent (Brown 2000) from 1956 to 1997. Absolute values greater than 0.30 (0.39) are significant at the 5% (1%) level for a sample size of 42 yr.

North American snow extent (Brown 2000), for 1956 through 1997. All months show highly significant positive correlations ($r > 0.39, p < 0.01$) near the snow line. Regardless of season, snow is shallow and/or intermittent in the vicinity of the snow line so that snowfall events and ablation processes tend to affect both snow extent and snow depth; hence, stronger correlations constantly occur near the snow line. For all months shown, correlations drop off dramatically north of the snow line, resulting in a very broad interior region in which snow depth and snow extent are poorly correlated. Moreover, during winter months there appears to be coherent regions of significant negative correlation north of the snow line. Possible reasons for this are discussed in section 4.

Type I error (falsely rejecting the null hypothesis H_0) may occur when evaluating the significance level of the correlation results shown in Fig. 4. Furthermore, gridpoint–gridpoint correlations among the snow depth data lead to spatial dependence among the local tests, which increases the overall likelihood of a Type I error. This spatial dependence is addressed by evaluating the collective field significance over the study domain, following the Livezey and Chen (1983) method using permutation tests to assess a null hypothesis of no significant differences in the field of tests. The approach is to generate sequences of 42 (1956–97) independent Gaussian random variables and correlate them with the gridded snow depth, tabulating the number of local tests rejecting H_0 for each of the sequences. One example of January gridpoint correlations with one such random sequence is shown is Fig. 5a, in which 0.75% of the grid points yield a statistically significant correlation at the 1% level. Figure 5a does not exhibit any coherent spatial pattern, in contrast to the broad spatial patterns related to snow line vicinity apparent in Fig. 4. This procedure is repeated using 200 random sequences for each month, and the resulting null distribution of the percentage of significant gridpoint correlations is plotted in Fig. 5b. Also shown in Fig. 5b are the actual monthly percentages of grid points whose snow depth time series is significantly correlated with the actual snow extent time series; these values consistently fall in the most extreme 1% of the null distributions. Hence, the field significance for the correlation maps in Fig. 4 is satisfied, and we conclude that the resulting regions of significant correlation between gridpoint snow depth and North American snow extent are meaningful for all months.

Analogous correlation maps between remotely sensed gridded SWE over the North American prairies (Derksen et al. 2004) and North American snow extent (Brown 2000) from 1978 to 1997 are shown in Fig. 6. Note that the snow-covered region (38°–63°N) covered by this satellite dataset encompasses high-latitude areas with relatively poor station coverage in the two station-based datasets (see Fig. 1). Correlations generally decline from south to north, for three consecutive months (December, January, and February), and modest regions of negative correlation appear in interior regions during January and February. Despite the limited spatial and temporal domain and the use of SWE in lieu of snow depth, this satellite dataset is consistent with the observed inconsistencies between high-latitude snow depth and North America snow extent in Fig. 4 using station snow depth observations. This confirmation is especially helpful given that the station-based snow depth observations in this region are strongly dependent on the interpolation scheme.

c. *Composite maps: Gridpoint snow depth during extreme NA snow extent conditions*

Figures 3, 4, and 6 suggest that a broad, continental/regional-scale region is maintained throughout much of the snow season in which snow depth/SWE variations are not mutually consistent with North American snow extent variations. However, linear correlation results do not conclusively prove a lack of mutual consistency between these North American snow cover characteristics. For example, a relationship may exist but simply be nonlinear. Complementary analyses are needed to confirm the correlation results.

The wide scatter between snow extent and average snow depth mentioned in section 3a supports the notion of mutual inconsistency for North America as a whole. Within North America, a gridpoint composite analysis is employed here to complement the gridpoint correlations. For each month, 5 yr with the maximum/minimum North American snow extent are chosen from the 42 yr (1956–97) North American snow extent time series (Brown 2000). Average snow depths in five maximum snow extent years ($\overline{\mathrm{snd}}_{\mathrm{max}}$) and five minimum snow extent years ($\overline{\mathrm{snd}}_{\mathrm{min}}$) are computed for each grid cell, respectively. The differences ($\overline{\mathrm{snd}}_{\mathrm{max}} - \overline{\mathrm{snd}}_{\mathrm{min}}$) are plotted in Fig. 7 and provide a straightforward assessment of the direction and magnitude of gridpoint snow depth change that is associated with the general range of North American snow extent variability, without presuming any specific relationship between the two parameters.

Figure 7 shows regions with positive differences near the snow line and regions with negligible or slightly negative differences north of the snow line. Positive (negative) values indicate that deeper (shallower) snow

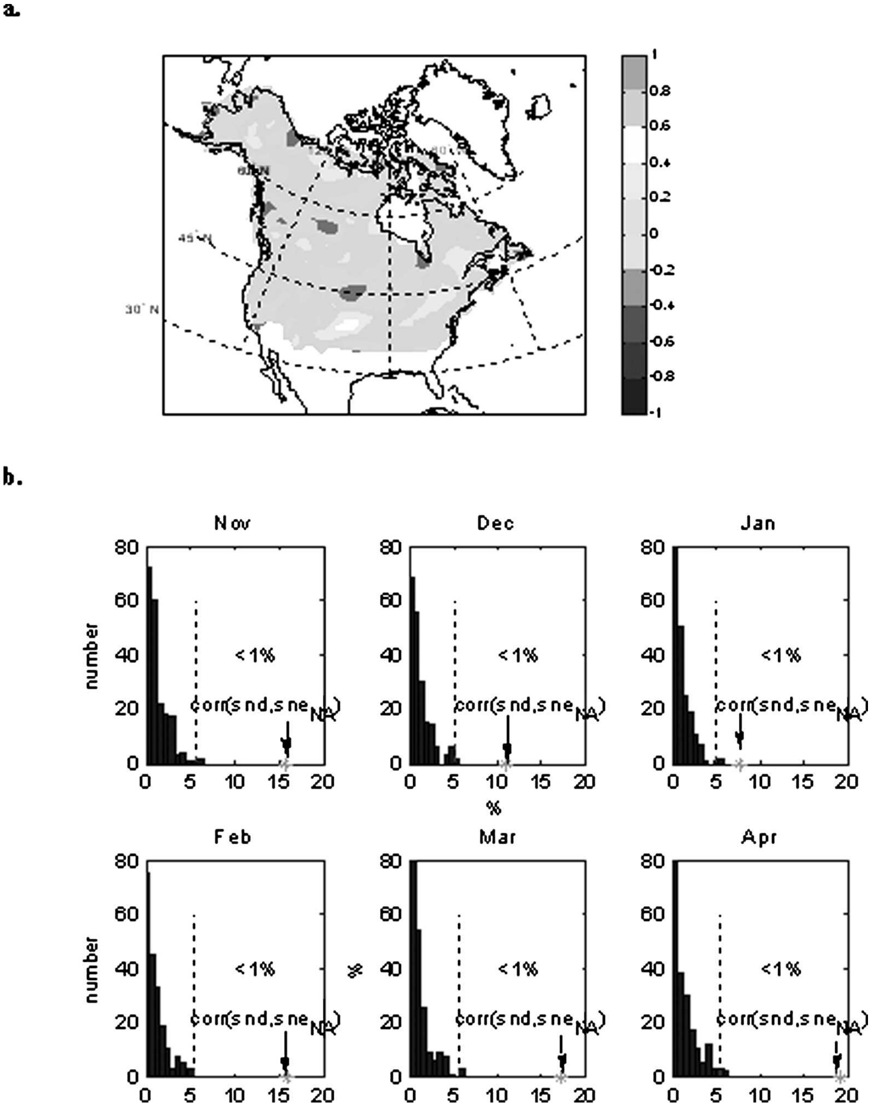


FIG. 5. (a) One example of local significant tests: Correlation between January snow depths with 42 Gaussian random numbers; 0.75% of the grid points have statistically significant correlation at the 1% level. (b) Histogram of distribution for the percentage of North American snow area showing significant local tests for correlation between snow depth and sequence of Gaussian random numbers. The largest 1% of the values is right to the dashed line. Numbers of significant local tests for correlations between snow depth and North America snow extent are indicated as asterisks.

coincides with larger continental snow extent. Thus, the composite pattern corroborates the linear correlation relation between gridded snow depth and North American snow extent addressed in Fig. 4. The ablation/accumulation of shallow snow at the snow line region more directly affects the local snow extent; thus snow depths in this region are more consistent with snow cover extent over all of North America. Insignificant differences are widespread across North America (north of 47°N) in December, January, and February, where (and when) the high-latitude land is constantly snow-covered and snow depth variations have little effect on North American snow extent. Coherent regions with negative differences are apparent at high latitudes during the winter, consistent with the negative correlation bands shown in Fig. 4. Identical conclusions drawn from the linear correlation maps and the composite maps confirm that the relationship between the two snow variables is not a statistical artifact of the linear correlation method.

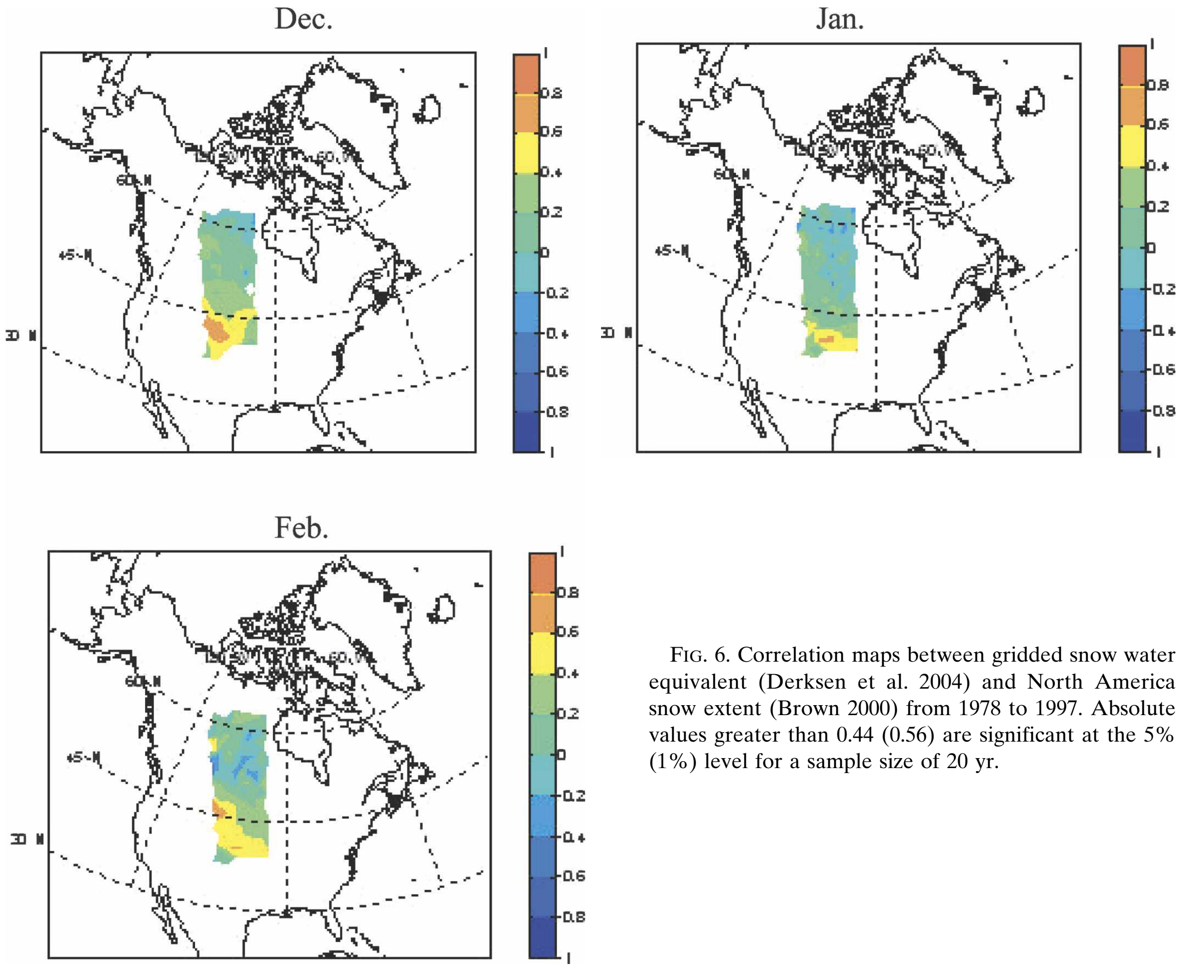


FIG. 6. Correlation maps between gridded snow water equivalent (Derksen et al. 2004) and North America snow extent (Brown 2000) from 1978 to 1997. Absolute values greater than 0.44 (0.56) are significant at the 5% (1%) level for a sample size of 20 yr.

d. SVD analysis: Gridpoint snow depth versus gridpoint snow frequency

Two-parameter SVD analysis provides yet another means of statistically evaluating the interannual relationship between North American snow extent and snow depth using spatially distributed data fields. However, snow extent is not a spatial field, so temporal snow frequency at a grid point has typically been used in lieu of spatial snow extent. In fact, spatial extents within a grid cell are commonly computed by multiplying temporal frequencies within a grid cell by the grid-cell area (Brown 2000). Using snow frequencies for SVD is complicated by the fact that snow frequencies in many grid cells within a snow-covered region exhibit little to no interannual variability (e.g., high-latitude grid cells in January will likely be snow covered 100% of the snow season every year) and, therefore, are not amenable to SVD analysis.

Thus, the SVD domain is restricted to regions where snow frequency exhibits considerable interannual variability. Following the approach of Frei and Robinson (1999), an "active area" is identified each month as having snow frequencies between 10% and 90% for more than 50% of the time chosen. As a result, regions that are predominantly snow covered or snow free are excluded, and the SVD is effectively performed in the vicinity of the snow line. The linear correlation and composite analyses presented earlier indicate that snow extent/frequency and snow depth are strongly and positively related near the snow line, so the SVD analysis serves to confirm the robustness of this result.

The first mode of covariability for snow frequency and snow depth resulting from monthly (September–May) SVD analysis is computed using the Dyer and Mote (2006) dataset. Figure 8 shows the resulting spatial patterns for October, January, and April, representing the autumn, winter, and spring seasons. For all months analyzed, the first mode captures at least 72% of the total covariability and shows a similar spatial pattern between snow frequency and snow depth variation, such that deeper (shallower) snow is generally col-

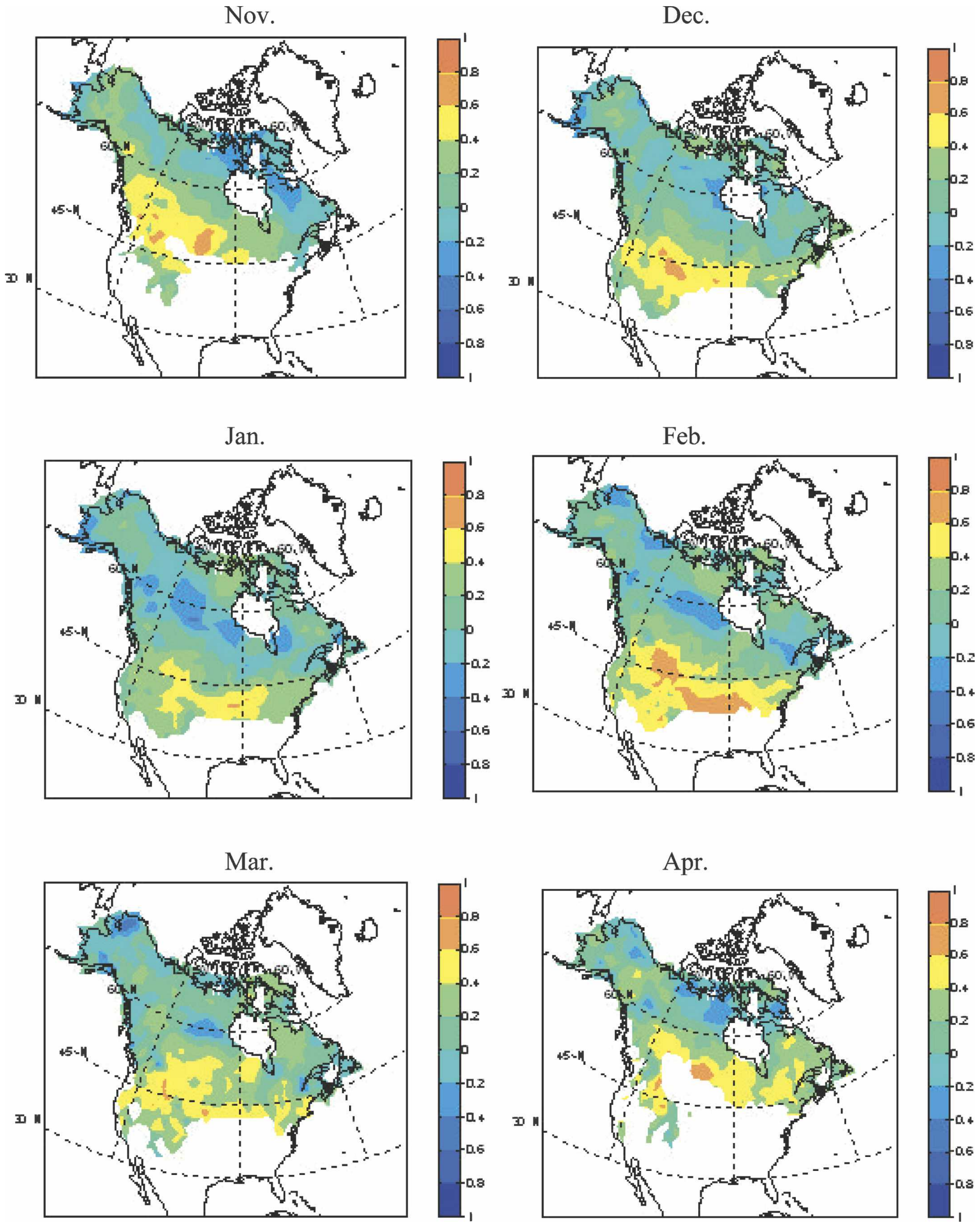


FIG. 7. Composite difference maps between average snow depth (Dyer and Mote 2006) over five maximum snow extent years ($\overline{\text{snd}}_{\text{max}}$) and five minimum snow extent years ($\overline{\text{snd}}_{\text{min}}$). For each month, five years with maximum/minimum North American snow extent are selected from the 42-yr (1956–97) North America snow extent time series (Brown 2000). Black contour lines denote the 10% significance level.

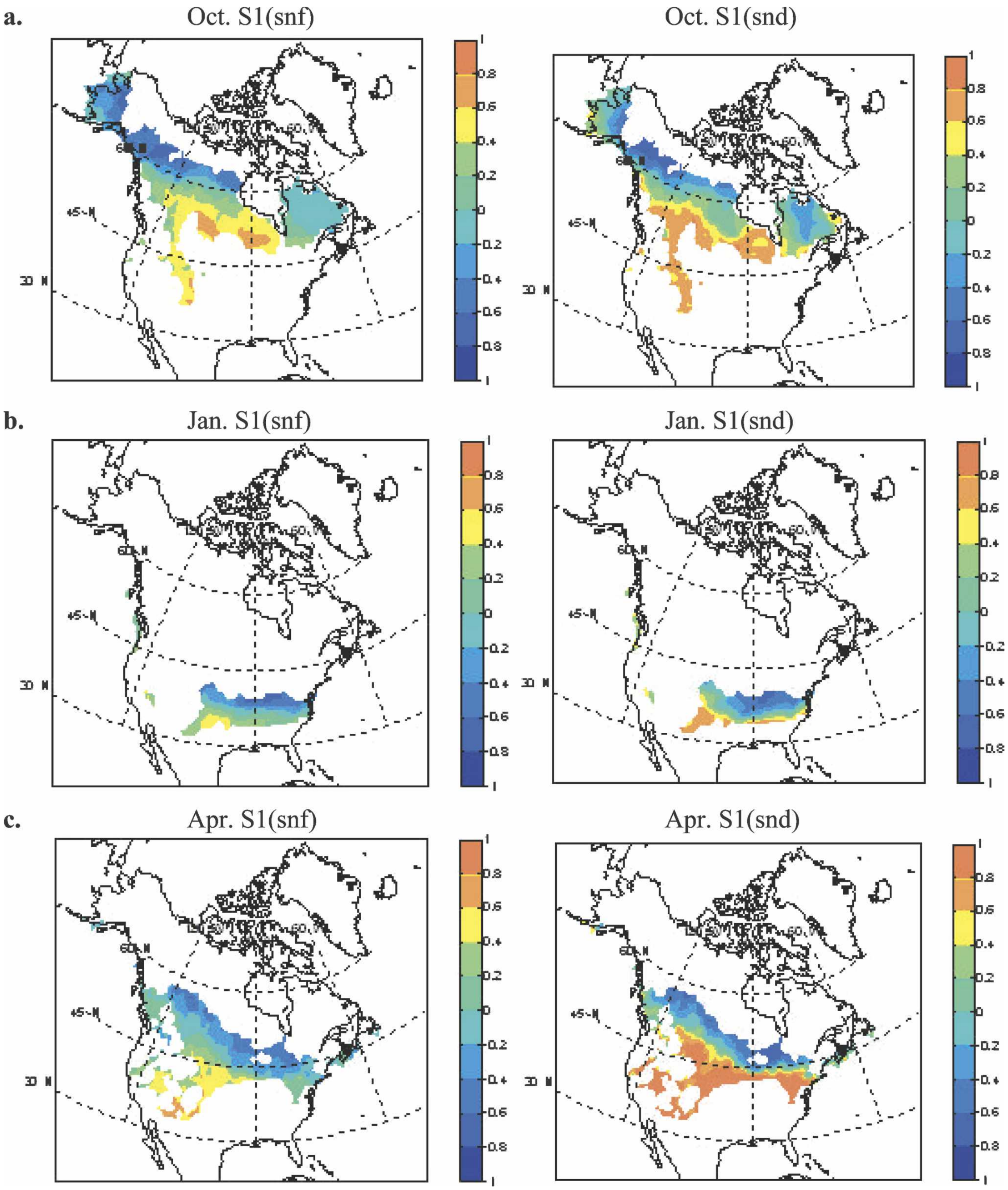


FIG. 8. Spatial patterns of the first SVD mode (S1) for monthly snow frequency (snf) and snow depth (snd) using the Dyer and Mote (2006) dataset; October, January, and April are shown. Spatial patterns are presented as homogeneous correlations map between gridded snow frequency/depth data and their expansion coefficient time series. Square covariance functions explained by the first SVD mode (SCF1) are 94.02% for October, 72.32% for January, and 94.29% for April.

located with more (less) frequent snow in the vicinity of the snow line. This is consistent with the results from correlation and composite analyses and supports the conclusion that snow events and ablation influence both snow extent and depth near the snow line, where snow is shallow or intermittent.

Monthly correlation coefficients between the paired depth and frequency expansion coefficient time series are presented in Fig. 9. Snow line region covariability is very strong in autumn and spring but noticeably less in winter. Figure 9 resembles the direct correlation between North American snow depth and extent pre-

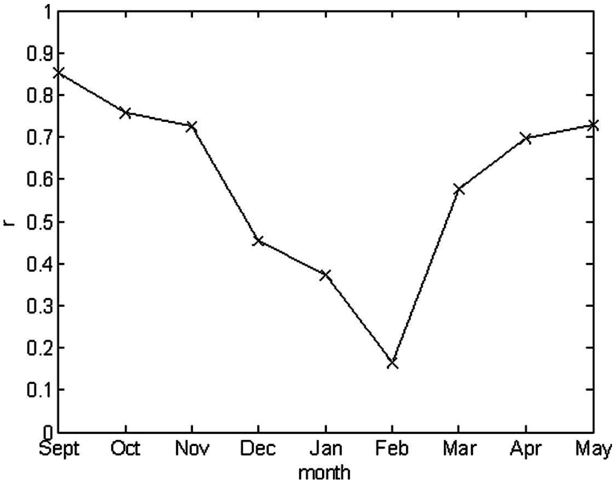


FIG. 9. Correlation between the paired expansion coefficient time series of the first SVD mode for snow frequency (snf) and snow depth (snd) using the Dyer and Mote (2006) dataset from 1956 to 2000. Correlation values greater than 0.29 (0.38) are significant at the 5% (1%) level for a sample size of 45 yr.

sented in Fig. 3b, although correlation values are generally higher in Fig. 9 because the SVD analysis isolates the patterns of covariability. Also, the low winter correlations in Fig. 3b were explained by the inclusion of high-latitude regions where depths vary but extent does not, while the SVD analysis explicitly excludes these areas. Whereas the correlation and composite analyses indicate a positive relationship between snow depth and extent near the snow line, consistent across all months, the SVD analysis further indicates that this snow line region relationship is considerably weaker during the winter.

One possible explanation for this discrepancy is the relatively small winter snow extent variability shown in Fig. 3a, which results in a very small SVD "active area" (Fig. 8) that may compromise the robustness of the SVD analysis given the 1° × 1° grid resolution. Another possible explanation is that correlations (Fig. 4) and composites (Fig. 7) depict conditions north of a snow line defined as having an average snow cover frequency of 50% over the study period, while the active area used for SVD analysis encompasses areas south of this 50% snow line. During winter, the active area extends into the southern United States, which is characterized by intermittent or trace snow depths that may affect snow extent/frequency to a greater degree than deep snow depth.

Overall, The SVD results support the earlier results that snow depth and snow frequency anomalies vary concurrently in the vicinity of the snow line. Unfortunately, the SVD analysis does not provide any further insight into the observed inconsistencies between snow extent/frequency and depth in interior regions north of the snow line. The lack of interannual snow frequency variability in regions that are consistently snow covered prohibits an effective SVD analysis between snow extent/frequency and snow depth. However, a one-parameter EOF analysis of snow depth (not shown) revealed inconsistent patterns of variability between the snow line and interior regions, which supports the general notion that snow characteristics differ over continental scales.

e. Lagged correlation maps: Gridpoint snow depth versus subsequent NA snow extent

Figure 10 presents lagged correlation maps for the April and May North American snow extent versus February and March gridpoint snow depth [see the Dyer and Mote (2006) dataset]. The maps suggest that spring snow extent is related to snow depths during the preceding late winter months in the central part of southern Canada/northern United States (i.e., the spring snow line region). Deeper (shallower) late-winter snow in these midlatitude regions will take a longer (shorter) time to melt away in the subsequent spring, resulting in a larger (smaller) spring snow extent. The very deep snow at high-latitude North America remains well into the spring season; therefore, most of this region remains uncorrelated to subsequent snow extent no matter what the lag is.

In contrast to prior concurrent analyses, positive associations between winter snow depth and subsequent snow extent are not strictly confined to the winter snow line region. A lagged positive relationship is apparent between winter snow depth and spring snow extent in regions coinciding with the spring snow line, which suggests that winter snow depth may be related to snow cover persistence into the subsequent spring. Since spring snow extent anomalies have been linked to summer climate conditions (Bamzai and Shukla 1999), this result also suggests that winter snow depth anomalies may play a role in summer climate.

f. Gridpoint snow depth versus gridpoint snow season duration

The persistence of snow cover can also be measured using the temporal duration of snow-covered land. We compute the annual "snow cover end Julian" day (SEJ) of each grid cell as the last day with at least one inch (2.54 cm) of snow from January through June. This index focuses on the end of the snow cover season in spring without considering the start of the snow season in autumn. Reconstructed snow extent based on a 2.54-cm threshold agrees most closely with the NOAA vis-

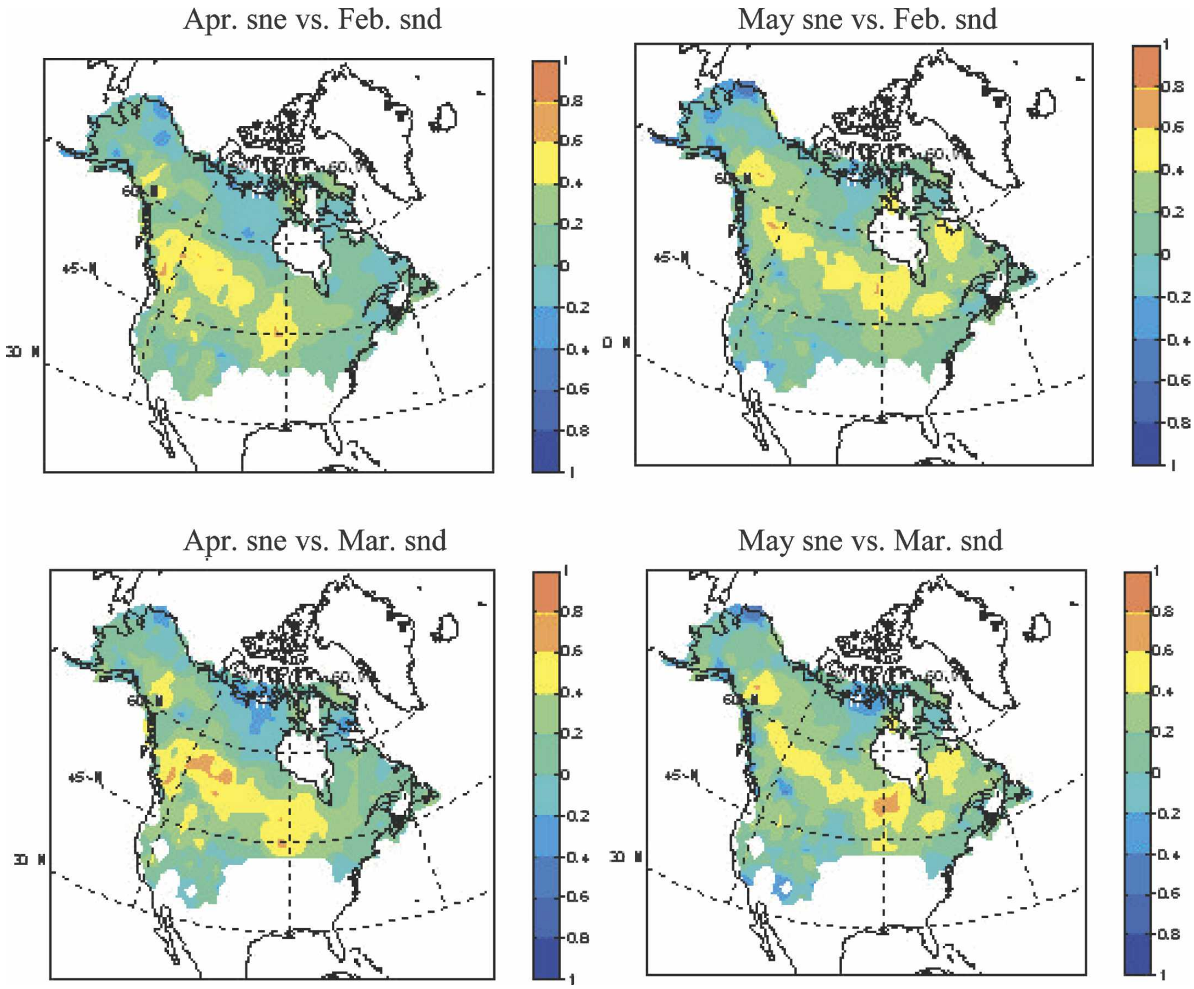


FIG. 10. Lagged correlation maps for April and May North American snow extent (sne) vs February and March gridpoint snow depth (snd) using the Dyer and Mote (2006) dataset from 1956 to 2000. Absolute values greater than 0.29 (0.38) are significant at the 5% (1%) level for a sample size of 45 yr.

ible satellite-derived snow extent (Frei et al. 1999; Brown 2000). Figure 11 presents monthly correlation maps between gridpoint snow depth and SEJ. Scattered regions of significant positive correlation ($p < 0.05$) appear from January through March, while a much broader region concentrated near the snow line appears in April. A monthly SVD analysis is also conducted on gridpoint snow depth and SEJ (not shown) and yields similar results in that regions of positive covariability are constrained to the vicinity of the snow line, although for the SVD analysis this relationship is apparent throughout more of the winter–spring period. These results for snow depth versus snow season duration are consistent with the primary assessment of snow depth versus snow extent in that mutual consistency between the variables is generally restricted to the spring season and/or the snow line region.

4. Conclusions

Extensive research has shown that snow extent plays an important role in climate variations; however, extent only describes part of the snow–climate relationship. Variations in snow depth may also have a distinct and considerable impact on climate over a range of spatial and temporal scales. The emerging availability of reliable snow depth and SWE datasets provides an excellent opportunity for research into the roles that snow depth anomalies play in climate variability. An important first step for this effort is to establish that snow depth anomalies are distinct from snow extent anomalies and are of sufficient magnitude to potentially influence climate. It is well understood that, at a given locality, snow depth and snow extent can be inconsistent over interannual time scales. This study expands upon

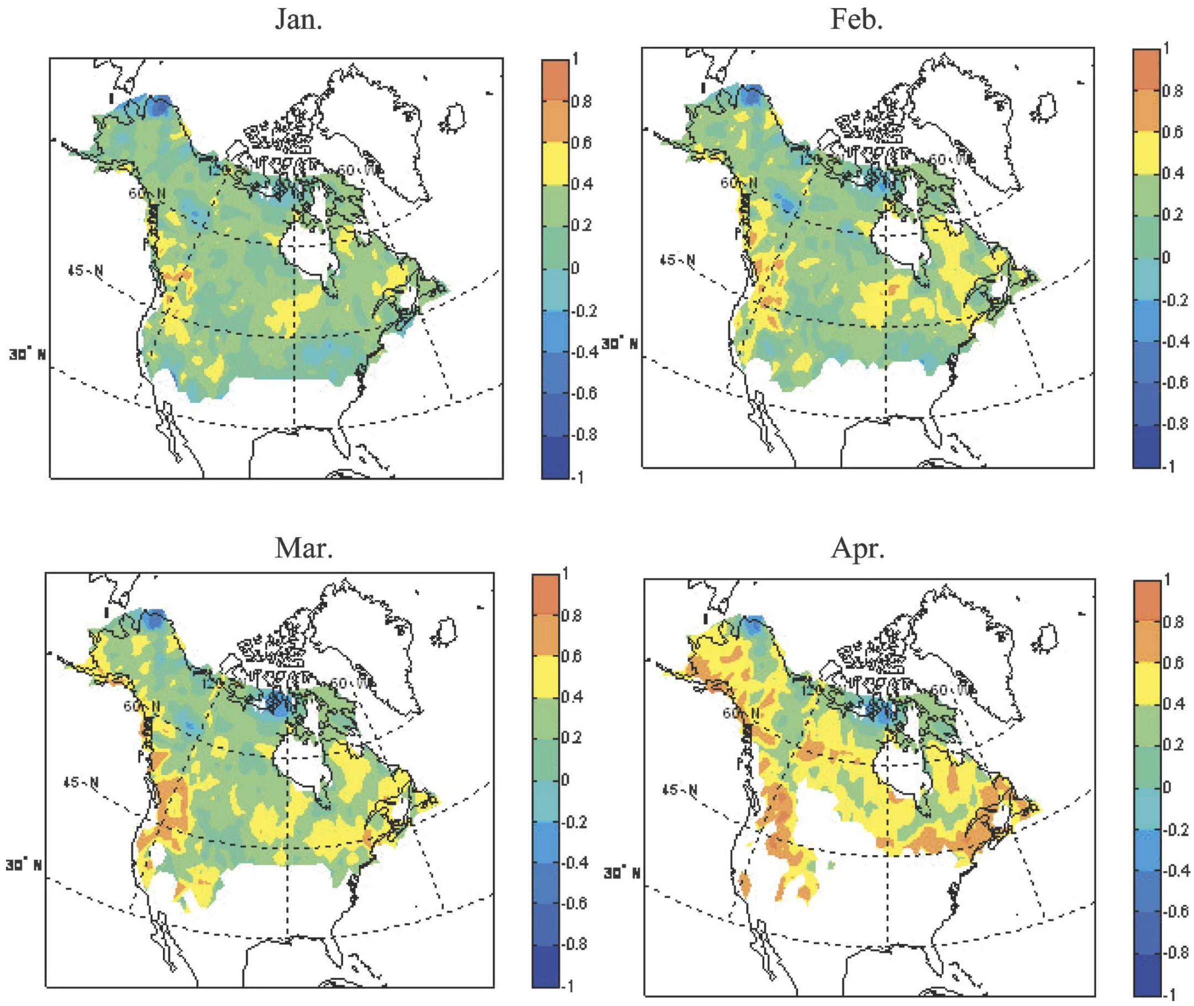


FIG. 11. Correlation maps between gridded snow depth and annual snow cover end Julian day (Dyer and Mote 2006) from 1956 to 2000. Absolute values greater than 0.29 (0.38) are significant at the 5% (1%) level for a sample size of 45 yr.

this intuitive notion by demonstrating that interannual snow depth and snow extent anomalies are not mutually consistent over broader spatial scales at which the potential for regional and continental snow depth–climate linkages are the greatest.

A mix of widely recognized and newly developed regional/continental-scale snow depth/SWE datasets have been evaluated, derived from station observational data or satellite remote sensing data. Various statistical methods are applied to assess the mutual consistency of interannual snow depth versus snow extent variations on a monthly basis. All of the datasets and statistical methods consistently exhibit differing behavior between interannual time series of North American snow extent and snow depth. Broad continental-scale regions are identified whereby these two snow cover characteristics are not mutually consistent for long, continuous stretches of the snow season. This inconsistency is especially obvious over high-latitude regions north of the snow line. Furthermore, the relative magnitude of snow depth anomalies is found to be considerably larger than that for snow extent. Regions of mutually consistent variability are generally constrained to the vicinity of the snow line and are strongest in autumn and spring.

An assessment of snow depth versus snow persistence adds an extra dimension to this study. Snow persistence is interpreted via a lagged correlation to subsequent snow extent and also using a direct snow season duration metric. Overall results are consistent with our analysis of snow extent versus snow depth; that is, during most months broad regions of snow depth variability exist over North America that are not mutually consistent with snow persistence, the major exceptions being the spring season and the snow line region. Hence, spring snow extent and snow season duration cannot be considered as integrators of snow depth conditions over the course of the snow season; snow depths can exhibit considerable variability in their own right.

Snow depth variations over this large continental region may exert a substantial effect on climate, from the overlaying temperature to regional phenomena and hemispheric modes. However, the responsible thermodynamic mechanisms may vary somewhat from the widely established surface albedo increase (decrease) and temperature decrease (increase) due to the presence (absence) of snow cover. Excessive snow depth anomalies may increase the snow albedo and the terrestrial emissivity, insulate the surface by inhibiting heat conduction from underlying soil, and thus increase subsequent snowmelt, evaporation, or sublimation. An extreme case is that, when snow is deep enough, the atmosphere and surface will no longer interact and become decoupled. All of these processes act as sinks in the surface energy balance and can lead to local climate variations, such as decreased temperatures. The suppression of spring and early summer temperature owing to excessive snow depth has been reported in Bamzai and Shukula (1999). Hence, the inclusion of snow depth may yield additional insight to our understanding of snow–climate relationships. For example, the lagged correlation analysis presented in Fig. 10 suggests that previously reported spring snow extent–summer climate relationships may be due in part to winter snow depths.

The gridpoint correlation and composite analyses also revealed a north–south spatial dipole pattern of variability, where a positive relationship between snow extent and snow depth at the snow line is accompanied by a negative relationship across a broad interior band, and vice versa. This pattern suggests a possible impact of interannual midlatitude cyclone track variations on winter snow depth/extent. Midlatitude cyclones are major sources of moisture, precipitation, and snowfall for North America. If the storm track shifts northward, there is more snowfall and greater snow depth at high-latitude regions but less snowfall and shallower snow depth near the winter snow line, and hence less extensive continental snow extent. Conversely, southward shifts of the storm track may lead to shallower snow at high latitudes but deeper snow near the winter snow line and more extensive continental snow extent.

Both the climatic causes and consequences of North American snow depth variability are the subjects of ongoing research. The observed lack of mutual consistency at continental scales presented here suggests that snow depth variations may be of sufficiently large magnitude, spatial scope, and temporal duration to influence regional hemispheric climate, in a manner distinguishable from the more extensively studied snow extent variations. The explicit consideration of both of these characteristics of continental snow cover may lead to a more fundamental understanding of large-scale snow–climate relationships.

Acknowledgments. This research is supported by a NASA Graduate Student Fellowship in Earth Systems Science. We thank Dr. David Robinson, Dr. Thomas L. Mote, Dr. Ross Brown, and Dr. Allan Frei for providing us with snow datasets and many helpful discussions. We also thank the reviewers for their insightful comments, which helped to improve the paper.

REFERENCES

Armstrong, R. L., and M. J. Brodzik, 2001: Recent Northern Hemisphere snow extent: A comparison of data derived from visible and microwave satellite sensors. *Geophys. Res. Lett.,* **28,** 3673–3676.

Baker, D. G., D. L. Ruschy, R. H. Skaggs, and D. B. Wall, 1992: Air temperature and radiation depressions associated with snow cover. *J. Appl. Meteor.,* **31,** 247–254.

Bamzai, A. S., and J. Shukla, 1999: Relation between Eurasian snow cover, snow depth, and the Indian summer monsoon: An observational study. *J. Climate,* **12,** 3117–3132.

Barnett, T. P., L. Dumenil, U. Schlese, E. Roeckner, and M. Latif, 1989: The effect of Eurasian snow cover on regional and global climate variations. *J. Atmos. Sci.,* **46,** 661–685.

Brown, R. D., 2000: Northern Hemisphere snow cover variability and change, 1915–97. *J. Climate,* **13,** 2339–2355.

Chang, A. T. C., J. L. Foster, R. E. J. Kelly, E. G. Josberger, R. L. Armstrong, and N. Mognard, 2005: Analysis of ground-measured and passive-microwave-derived snow depth variations in midwinter across the northern Great Plains. *J. Hydrometeor.,* **6,** 20–33.

Cohen, J., 1994: Snow cover and climate. *Weather,* **49,** 150–156.

——, and D. Rind, 1991: The effect of snow cover on climate. *J. Climate,* **4,** 689–706.

——, and D. Entekhabi, 1999: Eurasian snow cover variability and Northern Hemisphere climate predictability. *Geophys. Res. Lett.,* **26,** 345–348.

——, and ——, 2001: The influence of snow cover on Northern Hemisphere climate variability. *Atmos.–Ocean,* **39,** 35–53.

Davis, R. E., M. B. Lowit, and D. R. Legates, 1999: A climatology of snowfall-temperature relationships in Canada. *J. Geophys. Res.,* **104** (D10), 11 985–11 994.

Derksen, C., R. Brown, and A. Walker, 2004: Merging conventional (1915–92) and passive microwave (1978–2002) estimates of snow extent and water equivalent over central North America. *J. Hydrometeor.,* **5,** 850–861.

Dewey, K. F., 1977: Daily maximum and minimum temperature forecasts and the influence of snow cover. *Mon. Wea. Rev.,* **105,** 1594–1597.

Dyer, J. L., and T. L. Mote, 2006: Spatial variability and trends in snow depth over North America. *Geophys. Res. Lett.,* **33,** L16503, doi:10.1029/2006GL027258.

Ellis, A. W., and D. J. Leathers, 1999: Analysis of cold airmass temperature modification across the U.S. Great Plains as a consequence of snow depth and albedo. *J. Appl. Meteor.,* **38,** 696–711.

Frei, A., and D. A. Robinson, 1999: Northern Hemisphere snow extent: Regional variability 1972–1994. *Int. J. Climatol.,* **19,** 1535–1560.

——, ——, and M. G. Hughes, 1999: North American snow extent: 1900–1994. *Int. J. Climatol.,* **19,** 1517–1534.

——, J. A. Miller, and D. A. Robinson, 2003: Improved simulations of snow extent in the second phase of the Atmospheric Model Intercomparison Project (AMIP-2). *J. Geophys. Res.,* **108,** 4369, doi:10.1029/2002JD003030.

Foster, J., M. Owe, and A. Rango, 1983: Snow cover and temperature relationships in North America and Eurasia. *J. Climate Appl. Meteor.,* **22,** 460–469.

Gong, G., D. Entekhabi, and J. Cohen, 2002: A large-ensemble model study of the wintertime AO/NAO and the role of interannual snow perturbations. *J. Climate,* **15,** 3488–3499.

——, ——, and ——, 2003: Modeled Northern Hemisphere winter climate response to realistic Siberian snow anomalies. *J. Climate,* **16,** 3917–3931.

——, ——, ——, and D. Robinson, 2004: Sensitivity of atmospheric response to modeled snow anomaly characteristics. *J. Geophys. Res.,* **109,** D06107, doi:10.1029/2003JD004160.

Groisman, P. Y., T. R. Karl, and R. W. Knight, 1994: Observed impact of snow cover on the heat balance and the rise of continental spring temperatures. *Science,* **263,** 199–200.

Karl, T. R., P. Y. Groisman, R. W. Knight, and R. R. Heim, 1993: Recent variations of snow cover and snowfall in North America and their relation to precipitation and temperature variations. *J. Climate,* **6,** 1327–1344.

Kumar, A., and F. Yang, 2003: Comparative influence of snow and SST variability on extratropical climate in northern winter. *J. Climate,* **16,** 2248–2261.

Leathers, D. J., and D. A. Robinson, 1993: The association between extremes in North American snow cover extent and United States temperature. *J. Climate,* **6,** 1345–1355.

——, A. W. Ellis, and D. A. Robinson, 1995: Characteristics of temperature depressions associated with snow cover across the northeast United States. *J. Appl. Meteor.,* **34,** 381–390.

Livezey, R. E., and W. Y. Chen, 1983: Statistical significance testing and its determination by Monte Carlo techniques. *Mon. Wea. Rev.,* **111,** 46–59.

Marshall, S., R. J. Oglesby, and A. W. Nolin, 2003: The predictability of winter snow cover over the western United States. *J. Climate,* **16,** 1062–1073.

McCabe, G. J., and M. D. Dettinger, 2002: Primary modes and predictability of year-to-year snowpack variations in the western United States from teleconnections with Pacific ocean climate. *J. Hydrometeor.,* **3,** 13–25.

Namias, J., 1985: Some empirical evidence for the influence of snow cover on temperature and precipitation. *Mon. Wea. Rev.,* **113,** 1542–1553.

Robinson, D. A., 1999: Northern Hemisphere snow extent during the satellite era. Preprints, *Fifth Conf. on Polar Meteorology and Oceanography,* Dallas, TX, Amer. Meteor. Soc., 255–258.

Robok, A., M. Mu, K. Vinnikov, and D. Robinson, 2003: Land surface conditions over Eurasia and Indian summer monsoon rainfall. *J. Geophys. Res.,* **108,** 4131, doi:10.1029/2002JD002286.

Saito, K., and J. Cohen, 2003: The potential role of snow cover in forcing interannual variability of the major Northern Hemisphere mode. *Geophys. Res. Lett.,* **30,** 1302, doi:10.1029/2002GL016341.

Saunders, M. A., B. Qian, and B. Lloyd-Hughes, 2003: Summer snow extent heralding of the winter North Atlantic Oscillation. *Geophys. Res. Lett.,* **30,** 1378, doi:10.1029/2002GL016832.

Serreze, M. C., M. P. Clark, D. McGinnis, and D. Robinson, 1998: Characteristics of snowfall over the eastern half of the United States and relationships with principal modes of low-frequency atmospheric variability. *J. Climate,* **11,** 234–250.

Shepard, D., 1968: A two-dimensional interpolation function for irregularly-spaced data. *Proc. 23rd Association for Computing Machinery National Conf.,* Washington, DC, Association of Computing Machinery, 517–524.

Sobolowski, S., and A. Frei, 2006: Lagged relationships between North American snow mass and atmospheric teleconnection indices. *Int. J. Climatol.,* **27,** 221–231.

Snedecor, G. W., and W. G. Cochran, 1989: *Statistical Methods.* Iowa State University Press, 503 pp.

Wagner, J. A., 1973: The influence of average snow depth on monthly mean temperature anomaly. *Mon. Wea. Rev.,* **101,** 624–626.

Walsh, J. E., D. R. Tucek, and M. R. Peterson, 1982: Seasonal snow cover and short term climatic fluctuations over the United States. *Mon. Wea. Rev.,* **110,** 1474–1485.

Watanabe, M., and T. Nitta, 1998: Relative impacts of snow and sea surface temperature anomalies on an extreme phase in the winter atmospheric circulation. *J. Climate,* **11,** 2837–2857.

Yasunari, T., A. Kitoh, and T. Tokioka, 1991: Local and remote responses to excessive snow mass of Eurasia appearing in the northern spring and summer climate: A study with the MRI GCM. *J. Meteor. Soc. Japan,* **69,** 473–487.

Ye, H., 2001: Quasi-biennial and quasi-decadal variations in snow accumulation over Northern Eurasia and their connections to the Atlantic and Pacific Oceans. *J. Climate,* **14,** 4573–4584.