Year-to-Year Variation of Snow Cover Area in the Northern Hemisphere

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Abstract

The purpose of this study is to make an exploratory investigation of the interannual variability of winter snow cover in the Northern Hemisphere, using the satellite-derived monthly snow cover data from 1967 to 1987. The data set was supplied in digitized form by the National Oceanic and Atmospheric Administration/National Environmental Satellite Data Information Service (NOAA/NESDIS).

An empirical orthogonal function (EOF) analysis is made to find the typical pattern of snow cover variations during winter. The first component of the EOF (EOF1), which represents 46.6 % of the total variance, shows concurrent snow cover patterns between the Eurasia and North America. The time series of the EOF1 is similar to that of total winter snow cover in the Northern Hemisphere. The second component of the EOF (EOF2), which represents 23.6 % of the total variance, shows a negatively correlated pattern between the eastern and western parts of the Eurasia, and also shows a negatively correlated pattern between eastern Eurasia and North America. This EOF2 shows the importance of subcontinental-scale snow variations as a climatic control to a large continent.

We examined the time series of mean snow cover for the representative areas depicted in the EOF patterns to investigate the persistency of snow cover in more detail. Snow cover features for a specific years (*eg.* a heavy or light snow years) are likely to be sustained during December to February and disappear in March. The significant decrease of the snow cover area from February to March in a heavy snow year is prominent in eastern Eurasia. Two key regions were selected which represent continental-scale snow variation: One is the eastern part of Eurasia and the other is North America. The time series of the two key regions show an apparent 1-year lag relationship of heavy snow years; winters with extensive snow cover over Eurasia tend to be followed by relatively heavier snow cover over North America during the succeeding winters.

1. Introduction and background

Long-term memory (*eg.* ocean, snow and sea-ice) are important for interannual time-scale phenomena in the atmosphere. The long memories are generally embedded in the earth's surface and work as external forcings to the atmosphere. The potential for significant effects of surface boundary fluctuations results from the associated changes in the distribution of diabatic heating, which drives the atmospheric circulation and consequently can affect atmospheric interannual variations. Anomalies of the sea surface temperature (SST), sea-ice, snow cover and soil moisture have the potential to modify the atmospheric heating through changes in the sensible and latent heat fluxes from the surface, the reflection of solar radiation, and the emissivity in terrestrial wavelengths. The extent to which these changes

affect the atmosphere can be demonstrated by a number of factors, including the horizontal scale, the magnitude, the persistency and the location of the surface anomaly (van den Dool, 1984). In this study we hope to shed more light on the influence of continental-scale snow cover on atmospheric circulation.

Blanford (1884) first found a relation between the increase of winter snow cover in the northwestern Himalayas and the decrease of rainfall on the plains of western India. Later, Walker (1910) extended Blanford's work and found a negative correlation between the amount of the snow depth at the end of May and total summer monsoon rainfall over India during the period of 1876–1908. Both studies were based mainly on one point station snow data.

Wiesnet and Matson (1976) examined the possibility of forecasting winter snow cover in the Northern Hemisphere using the satellite-derived monthly snow cover data during the period of 1966–1975.

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They showed that several equations derived from regression analysis were sufficient to have possible applications for 30-, 60-, and 90-day forecasting of seasonal, hemispheric and continental snow cover. Adem and Donn (1981) found snow cover to be one of the most useful predictors of a long-range forecast of anomalies of temperature and precipitation in the Northern Hemisphere. Foster *et al.* (1983) investigated a relationship between the continental snow cover extent during the autumn months and the ensuing winter temperature as observed at several locations in both North America and Eurasia. The rationale for this analysis is explained as follows: radiative cooling over large snow-covered areas produces anticyclonic cells which enables arctic air to be transported to lower latitudes. As the snow-covered area begins to expand during the autumn, the greater snow cover allows for increasing southward penetration of the arctic air masses.

There have been several studies for the influence of Eurasian and Himalayan snow cover upon the strength of the Indian summer monsoon in terms of the total rainfall and the dates of onset (Hahn and Shukla, 1976; Dey and Bhanu Kumar, 1982, 1983; Dickson, 1984; and Bhanu Kumar, 1987). Each of these studies showed good relationships and suggested feedback mechanisms for long-range forecasting of summer monsoon rainfall and the dates of onset. Hahn and Shukla (1976) looked at satellite-derived winter snow cover area over Eurasia and the Indian summer monsoon rainfall during the period of 1967–1975, and they found that the two quantities are negatively correlated. Hastenrath (1986) reviewed earlier studies of the circulation features over different parts of the globe, and noted that the April mean ridge position at 500 mb, 75°E over northwestern India is important for the seasonal forecast of Indian summer monsoon rainfall. This parameter appears to be a good indicator of the subsequent planetary-scale circulation (anomalous descending motion over India). Recently, Bhanu Kumar (1988) showed a strong negative correlation between Eurasian winter snow cover extent and the mean 500 mb ridge position along 75°E axis in April, which may be related to the lag effect of snow cover.

The above studies have shown interesting relationships between continental snow cover and atmospheric circulation. However, the physical mechanisms of these relationships are still unclear. As large-scale snow cover patterns are mainly controlled by the global-scale atmospheric circulation, subcontinental-scale snow fluctuations are consequently expected to be important as a climatic control to a large continent like Eurasia. The purpose of this study is to make an exploratory investigation of snow cover fluctuations and their persistency in the Northern Hemisphere so as to better understand atmospheric circulation on an interannual time scale

in the context of an atmosphere-land-ocean interaction system.

By using the monthly snow cover data described below, the seasonal march of snow cover area in the Northern Hemisphere is observed in Section 3.1. In Section 3.2, the importance of subcontinental-scale variations of snow cover is presented by the EOF analysis and regional mean snow cover time series evaluation. Moreover, the persistency of a heavy snow cover feature is investigated. Two key regions were selected which are representative of continental-scale snow variations during the northern winter for Eurasia and North America. A 1-year lag relationship of heavy snow years between the two continents is discussed in Section 3.3.

2. Data

The NOAA/NESDIS Weekly Snow and Ice charts are the first snow cover product (not snow depth !) derived exclusively from a visible satellite imagery supplemented by ground observations, and prepared on a 1:50,000,000 polar stereographic base map centered on the North Pole. Recently, these snow charts were digitized into an 89 × 89 element matrix superimposed on the polar stereographic base map since November 1966. If at least 50 % of an element square was covered by snow, the element was defined as “snow covered” and numbered as “1”. If less than 50 %, the element was defined as “snow free” and numbered as “0”. Details of the method of estimating the snow boundary, the digitization process, guidelines and suggestions for preparing the data are given by Matson and Wiesnet (1981), Dewey and Heim (1982) and Baldwin (1986).

There have been progressive improvements in the accuracy and consistency of the snow charts during the periods 1966–1970, 1971–1973, and 1974 to the present. There are some limitations in using this snow cover data mainly because of problems associated with cloudiness and low resolution. In the early years, the Himalayan region was particularly susceptible to inconsistencies (Ropelewski *et al.* 1984) and, therefore, snow cover data for this region were eliminated from this study.

Kukla and Robinson (1979) examined the accuracy of the NOAA/NESDIS weekly snow cover data by making a comparison with independent ground station reports for the United States. They concluded that the average areal differences are usually less than 10 % and hence the accuracy of NOAA/NESDIS data is adequate for climate studies. Wiesnet and Matson (1976) also evaluated the accuracy of the NOAA/NESDIS monthly snow cover data and concluded that the error in the value of areal snow cover owing to the analogue averaging of weekly data to derive the monthly snow line is approximately 2–5 % and is randomly distributed. Additional details of the accuracy and availability of

Fig. 1. (a) Time series of monthly Northern Hemisphere snow cover area (km^2). The asterisk (*) designates the January data for each year. (b) The variation of the annual cycle of monthly snow cover area in the Northern Hemisphere. A vertical line with cross bars indicates the standard deviation (68 % significant limits) for each month.

the data sets are given by Barry (1986) and Robock and Scialdone (1986).

3. Results

3.1 Seasonal progression

Figure 1a shows the time series of the Northern Hemisphere monthly snow cover area. The asterisk (*) indicates January data for each year. The winter snow cover fluctuation shows the interannual variation. Figure 1b shows the variation of the annual cycle of monthly snow cover area in the Northern Hemisphere (from 1967 to 1987). The line plot shows the climatological seasonal march. Generally, the snow cover area begins to increase in October, and its boundary advances southward until January–February when the snow cover area is at its maximum. October is the month having the most variation in snow cover extent. During the summer (June–August), most of the Northern Hemisphere snow cover is limited to Greenland, the Canadian Archipelago and high mountain regions

SNOW FREQUENCY: Jan.

Fig. 2. Snow cover frequency map for January during the period of 1967–1987. The heavy line corresponds to the mean snow boundary (snow cover frequency index = 4.5). An explanation for the numbers written on the map is given at text.

(above about 3500 m).

Figure 2 shows a frequency map of snow cover with the mean snow boundary for January during the period of 1967–1987. The number indicates a snow cover frequency index for a grid box: For a grid box covered by snow for 1 or 2 years during the 21-year data period, the grid box is numbered as “0”, for a grid box covered for 3 or 4 years, the grid box is numbered as “1” and so forth. A grid box that is always or never snow-covered during the data period is omitted. Then each grid box is classified into 10 levels according to the snow cover frequency with a two-year step. The numbers are written alternately on the map. The mean snow boundary line is the 4.5 contour line of the frequency index and corresponds to highly variable snow conditions. The area near this line was covered by snow about half of the years during the 21-year data period.

3.2 Continental and subcontinental-scale variations

To see the characteristic spatial scale of snow variations, the coherence of snow cover variations with respect to each highly variable region located along the mean snow boundary on Fig. 2 was investigated. Figure 3 shows a typical example of a year-to-year similarity index of snow variations for January with respect to a key grid (41.5°N , 68.0°E). The same characteristic pattern is obtained for other key grids

SIMILARITY INDEX : Jan.
KEY GRID ; KJ=60, KL=69

Fig. 3. Similarity index of snow variations for January with respect to a key grid (41.5°N, 68.0°E: marked by black circle). For further detail see text.

along the snow boundary. The index is defined as follows: if the existence of snow in a grid for each year agrees with that of the key grid for more than 13 years of the 21-year data period, the grid is labeled as "A", which is defined as being positively correlated with the key grid. If less than 8 years, the grid is labeled as "B", which is defined as being negatively correlated. Figure 3 indicates that "A" is more focused in the western part of North America and "B" is more focused in the eastern part of Eurasia. This shows the possibility of a negative correlation in the interannual snow variability between western North America and eastern Eurasia.

To investigate certain features of the subcontinental-scale snow variations during winter, an EOF analysis was performed. Snow cover data for the original 89×89 grid matrix was averaged into an 8×8 grid matrix as partitioned on a map (ref. Fig. 4) for the Northern Hemisphere. Because the original higher resolution (89×89 grid) is not necessary to investigate the subcontinental-scale feature of snow cover variations as estimated in Fig. 3.

Figure 4 is the first component of the EOF (EOF1) during December to February, which represents 46.6% of the total variance. This shows concurrent snow cover patterns between the Eurasia and North America. The time series of the EOF1 is similar to that of total winter snow cover in the Northern Hemisphere (cf. Matson and Wiesnet, 1981). Figure 5 is the second component of the

EOF 1 (46.6%) ; Dec.-Feb.

Fig. 4. The first component of the EOF during December to February (upper). Contour intervals are 0.1 and the shaded area is below -0.1. The score of the EOF1 (bottom).

EOF (EOF2), which represents 23.6% of the total variance. This shows a negatively correlated pattern of the snow cover between the eastern and western parts of Eurasia, and also shows a negatively correlated pattern between eastern Eurasia and North America. The EOF2 pattern indicates the importance of subcontinental-scale snow variations as a climatic control to a large continent.

We examined the time series of the mean snow cover for the representative areas depicted in the EOF patterns to analyze the persistency of snow cover during the winter season. Figure 6a shows the representative areas (Eurasia and North America) of the EOF1. Figure 6b is the time series of the Eurasian mean snow cover for December, February and March. The arrows on the figure indicate a decrease in snow cover area from February to March. Generally, the snow covered area increases until January or February and decreases rapidly in March and April. It is interesting to note that heavy snow

EOF 2 (23.6%) ; Dec.-Feb.

Fig. 5. As in Fig. 4 but for the EOF2. Shaded area is below -0.1 and hatched area is above 0.1 .

years experience more rapid snow melting in March than other years (see the length of arrows in Fig. 6b). Consequently, snow cover features for a specific year (eg. a heavy or light snow year) are likely to be sustained during December–February and disappear in March. Figure 6c is the time series of the North American mean snow cover for December, February and March. Similar features can be seen in the North American time series, though they are not quite so evident.

Figure 7 is similar to Fig. 6 but for the EOF2. The eastern and western parts of Eurasia are selected as the representative areas, because the variance of the east–west fluctuation in these regions is evident. Figure 7b is the time series of the eastern Eurasian mean snow cover for December, February and March. The features noted in Fig. 6b are also seen in Fig. 7b. The significant decrease of snow cover area from February to March in a heavy snow year is more prominent in eastern Eurasia than western Eurasia (Fig. 7c). The year-to-year variability

BOX AREA

Fig. 6. (a) The representative areas (Eurasia and North America) for the EOF1. (b) The time series of the Eurasian mean snow cover for December, February and March. (c) The time series of the North American mean snow cover. The dashed line is the mean snow cover (km^2) time series for December. The dot-dashed line is for March. The arrows indicates a decrease in snow cover area from February to March.

Fig. 7. As in Fig. 6 but for the EOF2.

(standard deviation) of snow cover area is also more evident in eastern Eurasia. Snow cover features for a specific year are also more sustained during December to February in eastern Eurasia. Therefore it seems that the eastern part of Eurasia is more sensitive to continental-scale and year-to-year snow variations over the Eurasian continent.

Figure 8 is the variation of the seasonal cycle of

Fig. 8. The variation of the seasonal cycle of monthly snow cover area from November to April for the eastern Eurasian region. The dashed line corresponds to the composite of heavy snow years for Eurasia.

monthly snow cover area from November to April for the eastern Eurasian region. The dashed lines on Fig. 8 correspond to the composite of heavy snow years for Eurasia. Heavy snow years are easily discerned from December to February. The significant decrease of snow cover area from February to March in a heavy snow year is also seen here. Figure 9 is the snow frequency map for February and March. The area bounded by the dashed line, which corresponds to a semi-arid region in eastern Eurasia, is an area of rapid snow melting from February to March in those years having heavy snow in Eurasia.

3.3 1-year lag relationship of heavy snow years

Figure 10 shows the normalized time series of mean snow cover for the representative areas we investigated, during December to February. Because climatological snow cover experiences a maximum advance during January to February, then snow cover features for a specific year are sustained during December to February. This period is important to evaluate snow effects on the atmospheric phenomena with an interannual time scale. The asterisk (*) indicates the relatively heavier snow year for each continent. Vertical dashed lines corresponds to Eurasian heavy snow years (1968, '72, '78, '85). It can be seen that eastern Eurasia is the representative area for the Eurasian heavy snow years ($r = 0.70$; 99 % significant limits). Since Eurasian heavy snow years are easily recognized from the eastern Eurasian time series.

From the above results, we selected two key regions which represent continental-scale snow variation during winter for two large continents in the Northern Hemisphere. One is the eastern part of Eurasia and the other is North America. It is noteworthy that the two time series show an apparent 1-year lag relationship of heavy snow years (see the asterisks (*) in Fig. 10); winters with extensive snow

SNOW FREQUENCY: Feb.

SNOW FREQUENCY: Mar.

Fig. 9. As in Fig. 2 but for February and March. The area bounded by the dashed line in eastern Eurasia corresponds to rapid snow melting from February to March in the Eurasian heavy snow years.

cover over Eurasia tend to be followed by relatively heavier snow cover over North America during the succeeding winters. The 1-year lag correlation coefficient is 0.52 (98 % significant limits) while the simultaneous correlation coefficient is 0.11.

Snow-Cover : Dec.-Feb.

Fig. 10. The normalized time series of mean snow cover for the representative areas during December to February. The asterisk (*) indicates a heavy snow year for each continent.

The relationship is, of course, not unique but one of the mechanisms for the North American heavy snow. Some years don't agree with the above relationship. Though 1978, '82, '84, '85 are relatively heavier snow cover years in North America, Eurasia did not experience heavy snow cover in the previous year. We emphasize that Eurasian heavy snow is a sufficient condition for North American heavy snow in the next year.

4. Summary and discussions

Snow cover fluctuations and their persistency during winter in the Northern Hemisphere were investigated using the monthly snow cover data supplied by the NOAA/NESDIS. Some preliminary results and the EOF analysis indicate the importance of subcontinental-scale snow fluctuations for evaluating the effect of snow on the atmospheric circulation.

The EOF1 shows a concurrent snow cover pattern between Eurasia and North America. The time series of the EOF1 is similar to that of total winter snow cover in the Northern Hemisphere. The EOF2 shows a negatively correlated pattern between the eastern and western parts of the Eurasia, and also shows a negatively correlated pattern between the eastern Eurasia and North America. This EOF2 shows the importance of subcontinental-scale snow variations as a climatic control to a large continent.

Through the investigation of persistency for the representative areas depicted from the EOF analysis, some notable results were obtained. Snow cover features for specific years (*eg.* a heavy or light snow

years) are likely to be sustained during December to February and disappear in March. Significant decrease of snow cover area from February to March in the Eurasian heavy snow years is observed in eastern Eurasia. Two key regions were selected which represent continental-scale snow variations during the northern winter with an interannual time scale. One is eastern Eurasia the other is North America. The time series for the two key regions show an apparent 1-year lag relationship of heavy snow years; winters with extensive snow cover over Eurasia leading to winters with relatively heavier snow cover over North America. These observational results have not been previously revealed by analyzing continental snow cover data. To confirm the relationship statistically, of course, a longer data period is needed.

The time series of the EOF1 also shows a negative correlation with the summer monsoon total rainfall over India (after Hahn and Shukla, 1976; Dickson, 1984). Yasunari (1987) suggested that the Indian summer monsoon plays an important role in connecting oceanic and land process leading to El Niño events. Snow cover fluctuations with an interannual time scale may be related to the El Niño and Southern Oscillation (ENSO) cycle (*ref.* Barnett *et al.*, 1989).

The possible physical processes responsible for the 1-year lag relationship are thought as follows; when Eurasia experiences heavy snow cover, the ground albedo and the heat of fusion (needed to melt the snow) dominate the heat budget so as to keep the ground surface air cool. Once the snow has melted the physics of the soil hydrology become important. In heavy snow years, there is much soil moisture due to snow melting. This also keeps the ground surface air cool because of high evaporative fluxes. The net result of these processes will produce anomalous thermal forcing associated with reducing the land-ocean temperature contrast, which depresses the strength of the Indian summer monsoon. This sequence of events seem to initiate the eastward extension of warm water in the SST field in the tropical Pacific region (Barnett *et al.*, 1989). The extension of warm SST may modulate the atmospheric circulation pattern mainly in the Pacific region. These conditions of the atmospheric and oceanic circulations will provide so much water vapor to North America as to have relatively heavier snow cover in the ensuing winter. In the next step, global SST variation and water budget will be estimated in association with the snow variations to confirm the above hypothesis.

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北半球における積雪面積の年々変動

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NOAA/NESDIS 編集の月平均積雪面積データを 21 年間 (1967–'87) 用いて、北半球における積雪の年々変動を調べた。

冬期について主成分分析を行うと、第一主成分 (寄与率 46.6 %) ではユーラシア大陸と北米大陸での同時降雪パターンが見られ、その時系列は北半球全域の積雪時系列とほぼ一致している。第二主成分 (寄与率 23.6 %) ではユーラシア大陸の東部と西部およびユーラシア大陸の東部と北米大陸とでの積雪変動の逆相関パターンが出現する。これは大陸より小さな規模の積雪変動の重要性を示唆する。

主成分分析で得られたパターンの変動を詳しく見るためにパターンに従って大陸をボックスに分けて時系列を調べた。一般に積雪の季節進行は 10 月に降雪開始、1~2 月に積雪ピークとなり、3~4 月にはその大部分が融解する。従って、その年の積雪の多寡を特徴づけるのは 12~2 月の積雪量である。ピーク期において例年より積雪面積の広い多雪年では、ユーラシア大陸における積雪の中低緯度への張り出しは東部半乾燥地域で大きい。また多雪年のユーラシア東部において 2 月から 3 月にかけての積雪面積の後退が特に顕著である。

以上のような時系列解析を経て、北半球の 2 大陸の積雪変動を代表する領域としてユーラシア大陸の東部と北米全域を選定した。この 2 領域の時系列を比較すると 2 大陸における多雪年の 1 年ラグが明瞭に見える。即ち、ユーラシア大陸が多雪であると翌冬には北米大陸で多雪となる。

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