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North American and Eurasian snow cover co-variability

By DAVID J. WALLAND*[1] and IAN SIMMONDS *School of Earth Sciences, University of Melbourne, Parkville, Victoria, Australia, 3052*

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ABSTRACT

The extent of snow cover over the Northern Hemisphere landmasses was computed over the period January 1973 to May 1996 using monthly data derived from the NOAA/NESDIS data set. A comparison has been made of the variability over the North American and Eurasian continents. We have found there to be significant memory in anomalies of snow cover for up to 3 months. We have also identified significant temporal associations between snow variability over North America and Eurasia, and these tended to be larger when North America was leading. Some suggestions for the link in variability are made. We have made a similar calculation using passive microwave sea-ice data from January 1979 to July 1995 in order to determine whether there is any link between the variability of sea-ice and that of continental snow cover. Over the period we have examined, there appeared to be a moderate connection between North American snow and Arctic sea-ice but no connection for Eurasia.

1. Introduction

Snow is known to be a particularly important part of the global climate system (Lamb, 1955; Walsh, 1984a). The high sensitivity of the climate system to snow cover is associated with the special properties of snow. These include its high albedo, high emissivity, and low thermal conductivity. These all tend to combine to keep the near-surface cooler than it would otherwise be. A persistent snow cover has been demonstrated to cause reductions in monthly temperatures over regions in the United States by as much as 5–10 °C (Namias, 1962; Wagner, 1973). Dewey (1977) showed that temperatures are lower for both maximum temperature (during the day when more incoming radiation was reflected) and night temperature (when the greater emissivity led to a greater amount of radiation loss from the surface). Thus, the extent of snow on the ground is of great importance and consequently, the natural variability of snow cover, and any trends it may be exhibiting at present, are of considerable interest to the climatologist.

We have computed the total snow area over the Northern Hemisphere landmasses using NOAA/NESDIS (Robinson et al., 1993) monthly data spanning January 1973 to May 1996 with a view to examining its variability. While there have been a number of studies of snow variability conducted on regional scales (Leathers and Robinson, 1993; Hughes and Robinson, 1993), there have been relatively few which have investigated behaviour on larger scales. Recently some studies have presented results exploring variability and trends on hemispheric scales (Robinson et al., 1991; Robinson et al., 1993; Groisman et al., 1994a, b). None of these studies, however, have investigated possible relationships between variability in snow cover over the Eurasian and North American continents, or tried to relate the variability in continental snow to that of sea-ice as we do here.

[1] Corresponding author.
email: djw@met.unimelb.edu.au.
* Present affiliation: CRC for Southern Hemisphere Meteorology, Monash University, Clayton, Victoria 3168, Australia.

Another important aspect of our study is that it makes use of data up to the most recent times, incorporating an additional five or six years of important data to the previously mentioned studies. This includes the period following the Mount Pinatubo eruption (June 1991) which proved to have significant consequences for global temperatures (Le Comte, 1993) and therefore, likely global snow cover. It also incorporates data from the year of the warmest global mean temperature on record (1995) (WMO, 1996). The 1980s were the warmest decade on record up until that time; it appears that with the exception of the two years following the Pinatubo eruption the 1990s will take the place as the warmest decade on record with its three remaining years recording the three warmest global mean temperatures on record.

The snow data, available on a 2 degree by 2 degree latitude-longitude grid, are derived primarily from visible band sensors aboard NOAA satellites and probably give us the best quality data set of reasonable length available at present. The data depict snow extent using a binary system of either uniform snow coverage (1) or no snow coverage (0). They are computed with the NOAA land-sea mask rather than the Robinson mask which was suggested to be more accurate (Robinson et al., 1993). NOAA, however, have recently upgraded the snow data set (the data we use here) and comparisons show that the snow areas computed with the two different land-sea masks are virtually identical (Garrett, personal communication).

The data are available as a weekly product and snow is considered to be present if on the last "suitable" day of the week (if cloud does not obscure the visible image) more than 50% of the area being averaged over is covered by snow. If on the last day the image is obscured by cloud, then the previous day is analysed and so on until a suitable day is found. Should one not be available that week, then other data are considered such as the previous week's analysis or temperature and precipitation data if they are available. From these weekly binary data, we have formulated a monthly product which gives the percentage of the month that is snow covered. The resulting "monthly" set is what we have used in this analysis.

In 1978, the Nimbus-7 Scanning Microwave Radiometer (SMMR) was launched to collect, amongst other things, data on global sea-ice cover. In 1987 the data collection was continued by the Defence Meteorological Satellite Program (DMSP) Special Sensor Microwave/Imager (SSM/I) passive microwave data (Weaver et al., 1987). In our study both the SMMR and SSM/I data sets are used to compute total sea-ice area (which includes leads) from 25 by 25 km pixels over the Northern Hemisphere. The ice edge was defined as the 15% ice concentration contour. Maslanik et al. (1996) discuss some of the potential problems associated with summer melt in interpreting the passive microwave record.

The purpose of this study is to investigate the variability of snow cover over the Northern Hemisphere. We will firstly examine the climatological behaviour of the snow over the two Northern Hemisphere continents. Interannual variability will also be studied and compared over Eurasia and North America as well as trends that have been documented in the literature (Robinson et al., 1991; Groisman et al., 1994a, b). These trends are crucial to consider as snow might be expected to show some of the earliest signals of a greenhouse warming response, as it is highly sensitive to lower tropospheric temperature. We will pay particular attention to the trends in the last 5 years subsequent to these earlier studies so as to give us an up-to-the-minute picture on current variability. Sea-ice is another element of the cryosphere that might also be expected to respond rapidly to enhanced greenhouse warming. The extent of any link between the interannual and long term variability in sea-ice and continental snow cover is explored using passive microwave data (SMMR and SSM/I).

2. Climatology

We first examine, for completeness, the climatological area of snow over the Northern Hemisphere exhibited in the NOAA/NESDIS data. Fig. 1 shows the average total area of snow cover over the Northern Hemisphere continents with the monthly averages being computed from January 1973 to May 1996 (5 months in excess of 23 years of data). We define the area of land (sea-ice is excluded) snow cover as

$$A = \int_{\text{land}} \text{fr}_{\text{sn}}\,(x,y)\,\text{d}x\text{d}y,$$

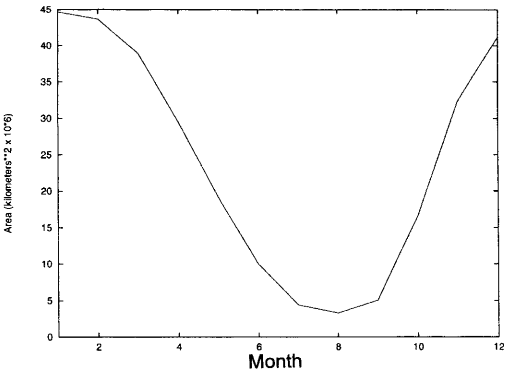

Fig. 1. Time series of average (1973–1996) monthly total snow area over the Northern Hemisphere derived from NOAA observations.

where fr_{sn} (x,y) is the snow covered fraction (or percentage of the month which is snow covered) over each grid-box $dxdy$. During the peak season, the mean total snow area in the Northern Hemisphere is approximately 45 million km^2. In summer, during August, this areal coverage diminishes to only 3.3 million km^2. The majority of this permanent snow cover exists over Greenland (the area of which is approximately 2.2 million km^2). Aside from this, there are only a few small glaciers scattered over the two major continents. The maximum and minimum in snow extent lag the extremes in radiation somewhat with maxima occurring in January/February and the minima in August due to the inertia associated with the melt and growth of snow.

3. Interannual variability

The extent of snow cover displays considerable interannual variability. To expose this, the time series of deviations from longer term monthly means (anomalies) of total snow cover, over the entire Northern Hemisphere, for all months from January 1973 to May 1996 have been calculated from the NOAA data and are shown in Fig. 2a. Superimposed on this is the least squares linear fit to the data over the period. The year-to-year variation in snow covered area lies generally within 5 million square kilometres and the linear fit has a negative trend of 1.1×10^5 $km^2 yr^{-1}$ which is significantly different from zero (at the 95% confidence level).

We next decompose this variability down to a continental scale. Figs. 2b, c show the corresponding anomaly time series over Eurasia and North America, respectively. "Eurasia" is defined to include the entire European and Asian continents and "North America" includes Greenland and North America. It is apparent that there is considerably more interannual variability present over the Eurasian continent. However, it must of course be noted that the total area is greater over Eurasia. The standard deviations of the anomalies normalized by the annual mean extent of snow (i.e., the coefficient of variation) are 0.13 over both continents. It is interesting to note that over both Eurasia and North America there is some evidence of persistence. Autocorrelations at lags of one, two and three months for North American snow anomalies give significant correlations of 0.56, 0.34 and 0.16 respectively. Over Eurasia the persistence is comparable with significant correlations of 0.52, 0.28 and 0.20.

Another feature that we make mention of, particularly because earlier studies did not incorporate data with which it could be examined, is the period following the eruption of Mount Pinatubo (June 1991). It has been well documented (Le Comte, 1993) that global temperatures declined (after many years of rising) following the eruption and subsequent release of large quantities of volcanic aerosols that significantly reduced the amount of solar radiation reaching the earth. It appears that there is a concurrent rise in the total snow area (after many years of decline) over both Eurasia and North America. It could be argued, given the dependence of snow on the near surface temperature, that the increasing trend in snow cover may be a result of this temperature forcing. This rise, of course, as might be expected, is reasonably short lived and a return to declining snow fields occurred after 1993. We also note that 1995 which had the warmest global mean temperatures on record also showed negative anomalies in both Eurasian and North American snow cover comparable to any on record.

4. Covariability over North America and Eurasia

We have seen that the relative magnitude of snow cover variability over North America and

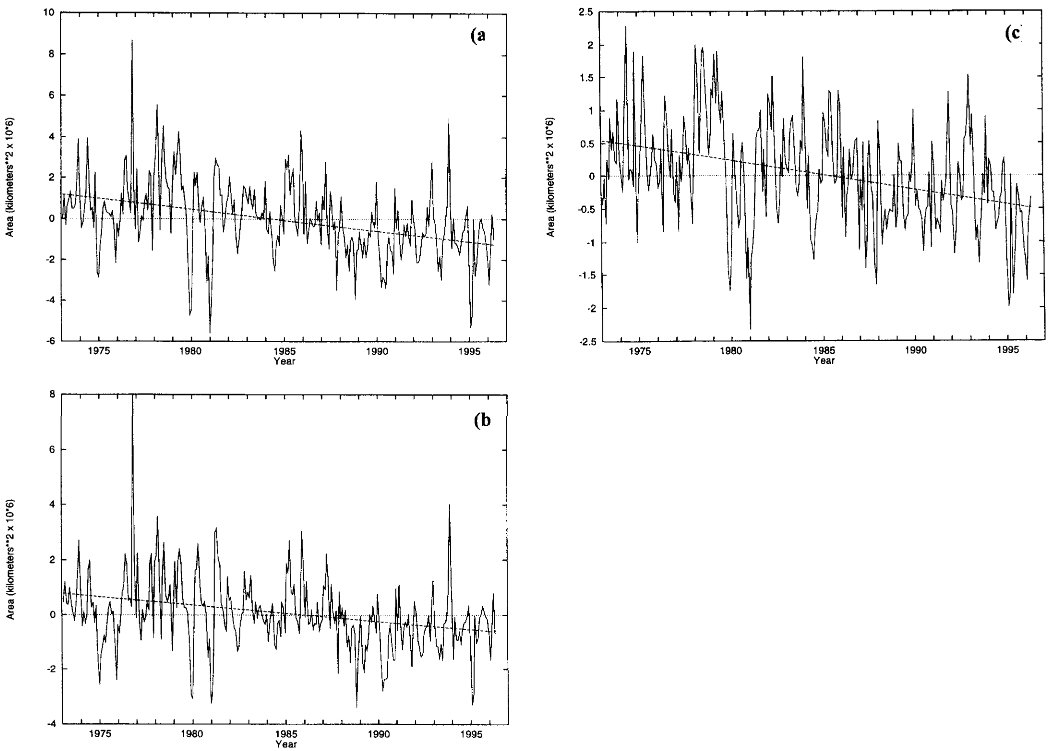

Fig. 2. Time series of monthly anomalies (1973–1996) in snow area over (a) Northern Hemisphere, (b) Eurasia, and (c) North America derived from NOAA observations. Least squares linear fit to the data superimposed.

Eurasia are quite similar. This may lead one to ask whether the amounts of snow tend to vary in phase or, in other words, if there is any covariability in snow between the two Northern Hemisphere continents. We in fact do find that the two time series of anomalous monthly snow cover are correlated with a coefficient of 0.47 (significant at the 99% confidence level). Because there is a trend in the data, it is also important to calculate the correlation between the detrended data series to ensure that it is not only this signal that we are identifying. The correlation between the two "detrended" data series is only slightly less (0.43) and still significant (at the 99% confidence level). This suggests some possible common physical mechanisms could be present which "simultaneously" influence the extent of snow cover over the two continents. The possibility that variability in snow cover over North America and Eurasia is related has been raised in the literature. For example, Gutzler and Rosen (1992) found a correlation of 0.62 between anomalies in snow cover over Eurasia and North America for the month of January over a period from 1972 to 1990. It is also consistent with the (EOF) analysis of Iwasaki (1991) whose first mode of variability described continent scale anomalies of the same sign across Eurasia and North America. These studies, however, concentrated on wintertime anomalies whereas our analyses consider data throughout the entire year. When we divide out data series up into seasonal brackets we find that all seasons show significant correlations between North America and Eurasia, but June-July-August and December-January-February show much stronger correlations (0.84 and 0.69 respectively) than March-April-May or September-October-November (0.32 and 0.34 respectively). Certainly over the wintertime this is in closer agreement with the study of Gutzler and Rosen (1992). It is not immediately clear why there should be closer agreement in the extreme seasons than in the transition seasons. However we shall discuss possible reasons later in this section.

As well as the considerable similarity between the monthly variations of snow cover over the two continents throughout the year, inspection of the time series suggests the presence of long period oscillations and, furthermore, that they appear to be closely linked. To expose these oscillations, we applied a 48-month running mean filter to the data, and the resulting time series over Eurasia and North America are presented in Fig. 3. The two time series are quite strongly correlated, with a coefficient of 0.89. Despite the degrees of freedom being greatly reduced by the filtering process, the correlation is still significant (at the 99% confidence level). There appear to be mechanisms present, operating on a longer time scale, which are influencing both North American and Eurasian snow cover.

The relative position of the peaks, however, suggests that greater correlations may be present at various lags. Accordingly, we calculated correlations at lags of up to 24 months with, firstly Eurasia leading, and then North America leading. These are shown in Fig. 4, where still higher correlations are present in the filtered data when North America leads, and a maximum correlation of 0.94 occurs when the lead is 14 months.

The reason for such co-variability between North America and Eurasia, however, still remains unclear. Walland and Simmonds (1997) show a comprehensive EOF analysis of Northern Hemisphere snow cover in January. They correlate

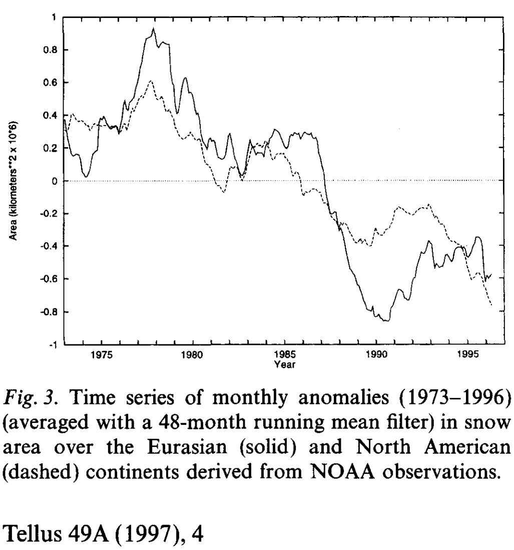

Fig. 3. Time series of monthly anomalies (1973–1996) (averaged with a 48-month running mean filter) in snow area over the Eurasian (solid) and North American (dashed) continents derived from NOAA observations.

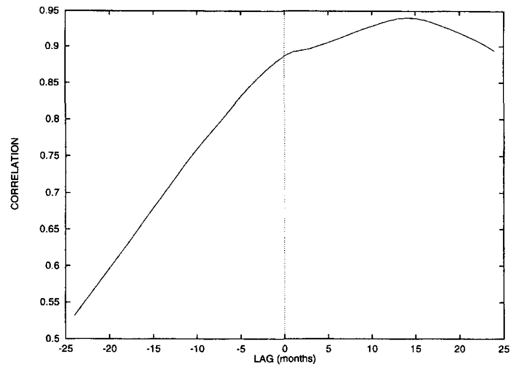

Fig. 4. Lagged correlations with North America leading Eurasia by *n* months with *n* given on the x-axis.

the first three modes of variability in the snow between North America and Eurasia and find that many of the cross correlations are quite strong. This is consistent with our findings of significant co-variability in snow cover over the two continents. The authors conduct a similar analysis for the 700 hPa geopotential height field. An analogous cross correlation of the EOFs between North America and Eurasia shows that again, there are many strong correlations. The apparent large scale organisation of the atmosphere at this level is reasoned by the authors to give the means by which the snow over the two continents could be related. Various authors, for example Klein and Walsh (1983) and Walsh (1984b), have suggested that the 700 hPa circulation is closely related to surface boundary conditions such as snow cover.

These circulation arguments are relevant to explaining why the correlations might be stronger in summer and winter than in the transition seasons. For a start, in summer the reason for the very strong correlation is likely related to the fact that the snow only exists right up near the poles. From geometry arguments on a sphere this means that the areas of variability are very close together and thus affected by the same circulation. In winter, however, this if of course not applicable. The strong link in winter, however, could be related to the fact that most teleconnections are at their strongest in this season, e.g., the Pacific-North American pattern. These teleconnections provide the means by which variability in snow over both continents could be linked.

Another example of such an atmospheric teleconnection has been discussed by Dickson and

Namias (1976). They proposed that during periods of extreme cold and thus, often heavy snow cover (Leathers and Robinson, 1993; Karl et al., 1994) over eastern North America, a southward shift in the zone of maximum storm intensity leads to a pressure anomaly ridge over Greenland. This is related to the extreme temperature differential on the Atlantic seaboard of North America between the cold, snow covered, continent and the relatively warm ocean. Given this anomalous ridge over Greenland, an anomalous northerly airflow will prevail on its eastward flank leading to severe winter weather over northwest Europe. Obviously, over Europe because of such severe weather, extensive snow cover would be a likely consequence. This scenario is used only as an example (previously discussed in the literature) to demonstrate the types of mechanisms that could conceivably lead to the covariability of snow across the Northern Hemisphere landmasses and the implied mechanisms may be responsible for the structure we have observed. It is also interesting that Dickson and Namias (1976) found that these periods of extremes oscillated on quite long timescales such that one might see extreme cold over Europe for much of a decade. We have seen long period oscillations in Fig. 3. It is not suggested that this, or indeed any similar teleconnection, is solely responsible for the co-variations of snow cover. Rather, it is proposed that such large-scale atmospheric teleconnections possess the ability to influence snow cover over the two continents.

Given that the variability over North America preferentially leads that over Eurasia, it would appear likely that the variations in western Asia snow cover would correlate more strongly with that over North America than would eastern Asia. This is actually apparent in the EOF analysis of snow cover of Walland and Simmonds (1997) where there was a strong correlation of the first EOFs of snow cover over Eurasia and North America. The EOF over Eurasia showed very high loadings over western Asia and Europe but quite small values (and of the opposite sign) over eastern Asia. To further examine this we recalculate our correlations of co-variability between the two continents by dividing Eurasia into a western (west of 105°E) and eastern (east of 105°E) sector and correlate each separately with North American snow cover. Not surprisingly, the western sector correlated higher with North American snow (0.44) than did the eastern sector (0.35) although both were significant. This finding lends further support to the idea that, in the mean, conditions in the North American sector influence those over Eurasia.

5. Variability and trends in snow compared with those displayed by sea-ice

For the period considered here, our data show negative trends in the total extent of snow over the Northern Hemisphere landmasses. Hemispheric trends such as these have been presented in the literature (Robinson et al., 1991; Groisman et al., 1994a, b) although this study incorporates data which extend the time series to the present and, importantly, includes several years of data following the Mt. Pinatubo eruption (June 1991). This is thought to be responsible for the reduction in global temperatures recently (the signal can be seen in the total Northern Hemisphere snow post 1991 in Fig. 2a where the snow cover appears to show an overall increase in extent for a period of a couple of years after a long period of diminishing extent). Following this interruption, however, the snow extent returns to its decreasing trend and over the past few years the trend appears to be strongly reinforced (particularly in 1995 which, as indicated earlier, showed the warmest mean global temperature on record).

While the trends in the snow cover in the studies analysed are significant, one needs to be careful drawing conclusions as to their cause. Because the time series being analysed is rather short, it is entirely possible that such trends are purely related to natural interdecadal variability. Unfortunately, the period over which satellite data are available does not extend back further (with reliability) and so we cannot use these to comment on the variations of snow cover in earlier periods. Satellite data are the only feasible approach to obtaining a truly global snow data set. There are efforts to extend back the record of snow cover on a more regional basis and, importantly, to try and link some of these data sets together to produce a spatially larger set on continental scales (Robinson, personal communication).

Some information from earlier periods can be gleaned from the regional data that have been published, although this yields a largely inconclusive result with trends of different sign found in different regions. Robinson (1987) shows, for regions in the Central Plains and the Midwest in the United States, trends depicting increases in snow cover over the century. Such a trend is opposite to those trends seen in the later satellite observations. Barry et al. (1994) examined station data from the former Soviet Republic. Their analysis indicates decreases in the extent of snow cover for the majority of stations over most of the century. There need be no inconsistency in these findings, however, as such localised studies represent only small regions in terms of the hemispheric scales that the satellite results depict and thus could be expected to show significant subscale variability. The fact that both of these localised trends were present in the period of overlap between their record and the satellite record shows that their behaviour has been accounted for in the satellite data trends. Such variability, however, makes it difficult to ascertain whether the recent large scale negative trends in snow cover are representative of changes over the century.

Because sea-ice is also an important element of the cryosphere and has many of the same characteristics as snow, it is relevant here to also examine its variability and trends. Recent studies of Northern Hemisphere sea-ice variability have also suggested that there may be some trends in the sea-ice record although there are discrepancies between various studies depending on the period examined and the analysis undertaken. Parkinson and Cavalieri (1989) conclude there was no overall trend whereas Gloersen and Campbell (1991) find a very small trend in a similar period. More recently, Johannessen et al. (1995) find that there is a negative trend present and that it appears to be stronger in the period of SSM/I data (1987–1994) than the earlier SMMR data (1979–1987). We utilise the data from both of these satellites (Gloersen and Campbell, 1988; Gloersen et al., 1993) from January 1979 through to July 1995 to compare the sea-ice variability with that of the continental snow that we have already discussed. Serreze et al. (1995) point out that due to different sensor characteristics of the SMMR and SSM/I the two sets are not directly comparable and to avoid misleading conclusions we examine the data from the two satellites separately. The time series of monthly anomalies in total Northern Hemisphere sea-ice extent (total area including leads) is given in Fig. 5.

The trend in the areal extent of sea-ice during the two periods is not great but appears to be present and negative in agreement with the earlier studies. However, the magnitude of these trends is significantly smaller than those in continental snow cover presented above. In addition, we have found that the correlation of the relevant periods of NOAA snow and SMMR sea-ice (1979–1987) monthly anomalies yields only a small positive relationship (0.14) that is not significant at the 95% confidence level. A similar correlation with the SSM/I data gives a slightly larger value (0.18) which is significant. When we consider the relationships separately over the two Northern Hemisphere continents, it becomes apparent that there is a much stronger significant relationship between the sea-ice and North American snow cover (0.20 for the SMMR period and 0.32 for the SSM/I period) whereas there are no significant correlations between Eurasian snow cover and Arctic sea-ice. It might be expected that the continental North American snow would be more closely related to the Arctic sea-ice as the Eurasian continent is much larger and this continentality means that its interior is much less influenced by the surrounding oceans than might be the case with the North American continent. Serreze et al. (1995) discuss the possibilities of links between snow and sea-ice in a case study of an extreme minima year (1990) in sea-ice. They suggest that there is a link between Arctic sea-ice and continental snow cover.

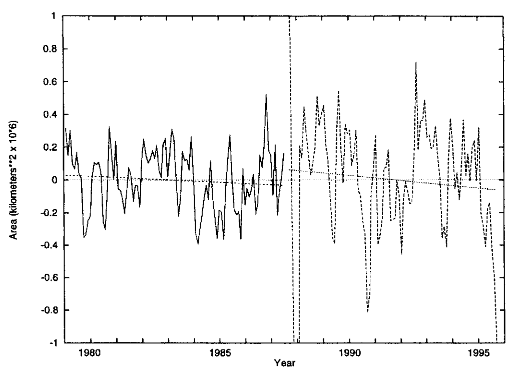

Fig. 5. Time series of monthly anomalies (1979–1995) in sea-ice area over the Northern Hemisphere derived from SMMR and SSM/I observations. Least squares linear fit to the data superimposed.

While our study supports their results, it does appear that the relationship is confined to the North American sector. Even in this region the correlation is far from strong.

The fact that the variability in snow and ice is not more strongly linked should not surprise us. It is probably due to the fact that these media are influenced in rather different time and space domains. During much of the season (particularly winter) when snow and ice are present, there are only limited areas within the snow covered and sea-ice covered regions which display interannual variability. These are the marginal areas (which show differing conditions from year to year) and for snow they are located mainly in the mid-latitudes (moving further poleward as we move away from the winter season). For sea-ice these marginal areas are confined to the polar regions. One forcing mechanism for both the sea-ice and snow is derived from the atmospheric circulation and this would tend to influence the two media on the monthly timescales under consideration here. However, the great spatial separation between the two zones of marginality for snow and sea-ice means that different aspects of the circulation will be of importance.

The other medium which will influence the two elements of the cryosphere is the ocean. The ocean undoubtedly plays a significant role in the modulation of the sea-ice and snow. The ocean has, however, a much greater inertia than the atmosphere, and thus could only be expected to play a smaller role in monthly variations. It is known to play a much more important role on annual and decadal time-scales (Trenberth and Hurrell 1994; Latif and Barnett 1994). Due to the essentially independent nature of the forcings that occur on the timescales of interest to us, it is therefore not surprising that there is only moderate correlation between the variability of the two surface types and a stronger relationship over North America.

The rather different natures of snow and sea-ice trends are also not as puzzling as may appear at first. As indicated earlier, the negative trends in continental snow cover are consistent with trends in surface air temperature over the period. Jones et al. (1994), Wilson and Hansen (1994), and Vinnikov et al. (1994) all show sharp rises in the Northern Hemispheric averaged near-surface temperatures over the period for which the satellite snow data are available. More specifically, Karl et al. (1994) showed temperature increases over the contiguous United States, and Findlay et al. (1994) showed similar rises over Canada. The record of anomalies in snow cover (see Figures 2(a) and 3) shows corresponding increases in snow fields around this period.

However, over the northern polar sea-ice regions, such temperature rises are not observed and indeed it appears that there has been a cooling over this period (Angell 1988, 1994). We also make the point that one would expect the ocean to be more intimately tied to sea-ice variability than it would be to continental snow. As has been discussed, the ocean, with its greater inertia, is much slower to change, and may thus far not be providing much forcing but could do so as time evolves. Thus we might begin to see an accelerated (but somewhat delayed) response in the sea-ice as appeared to be the case in our record. The other complicating aspect that must be considered once the ocean's influence is acknowledged is that below the mixed layer the ocean carries signals from periods much earlier as well as from different regions. Once these influences present themselves, the whole forcing issue is vastly more complicated.

6. Conclusions

The extent of snow cover over land in the Northern Hemisphere has been calculated from the NOAA/NESDIS monthly snow data for the period January 1973–May 1996. From this, monthly anomalies have been derived and used to examine interannual variability of snow extent. The relative variability was found to be almost identical over North America and Eurasia with coefficients of variation both equal to 0.13. A negative trend was found in the data for the period we have examined and this was found to be significant at the 95% confidence level over both North America and Eurasia. Significant memory was also demonstrated over the two continents of the order of three months.

Variability in snow extent over the two continents was significantly correlated with a correlation coefficient of 0.47 being found between the monthly anomalies in snow cover. By removing higher frequency oscillations with a 48-month running mean time filter, longer period oscillations were identified in the data and these were found to be even more strongly correlated (0.89). Greater associations were found when these time series were temporally offset and a maximum of 0.94 occurred when North American snow led that over Eurasia by 14 months. It was suggested that the co-variability in the snow cover could be related to large scale organisation of the atmosphere over North America and Eurasia drawing on atmospheric teleconnections.

We have found only modest similarity between the variability and trends of Northern Hemisphere snow and sea-ice on monthly and annual timescales over the period examined here. There was virtually no relationship between Eurasian snow cover and Arctic sea-ice and a moderate correlation between North American snow cover and sea-ice. It was argued that the elements of atmospheric forcing affecting variability of snow and of ice are quite distinct, as the areas of marginality (which dictate the variability) are quite spatially separate. One may also argue that snow has little inertia and is able to adjust to changing climatic conditions more rapidly than sea-ice which, with its behaviour being intimately related to oceanic conditions, may respond on longer time scales.

7. Acknowledgements

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