*Large Scale Effects of Seasonal Snow Cover* (Proceedings of the Vancouver Symposium, August 1987). IAHS Publ. no. 166

# Snow cover as an indicator of climate change

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**ABSTRACT** January snow cover in portions of the Midwest and Great Plains of the United States has shown significant variations during this century on year-to-year and long-term time frames. Over the past forty years, snow cover has increased in each region. This trend began in the late 1920's in the Plains, while in the Midwest the recent trend was preceded by several decade-long oscillations. Snow cover data used in the analysis included nearly complete records from twenty ground stations between 1901 and 1978 and weekly satellite-derived charts between 1967 and 1986. There is a reasonable agreement between regional analyses made with each of the independent data sets for the 1967-1978 interval. There appears to be a positive relationship between colder and snowier-than-normal and warmer-than-normal and relatively snow-free Januaries.

***La couverture de neige en tant qu'indicateur du changement climatique***

**RÉSUMÉ** La couverture de neige sur certaines parties du Middle West et des Grandes Plaines des États Unis a présenté d'importantes variations au cours de ce siècle, à l'échelle de temps interannuelle et aussi à plus long terme. Durant les quarante dernières années, la couverture de neige a augmenté dans chaque région. Cette tendance a débuté à la fin des années 1920 dans les Plaines, alors que dans le Middle West, elle est plus récente et a été précédée par plusieurs oscillations décennales. Les données de couverture neigeuse utilisées dans cette analyse comprennent des séries presque complètes de vingt stations au sol, de 1901 à

1978, et des cartes hebdomadaires basées sur les données de satellites de 1967 à 1986. Les analyses régionales issues des deux groupes indépendants de données présentent un assez bon accord pour la période 1967-1978. Il semble y avoir une relation positive entre les janviers plus froids et plus enneigées que la normale et ceux qui sont plus chauds et relativement peu enneigés.

## INTRODUCTION

Snow cover is a critical component of the climate system (Kukla, 1981; Barry, 1985). The accurate forecasting of local daily temperatures, regional climatic anomalies and the location and strength of cyclonic systems relies, in part, on knowledge of the distribution and state of regional snow cover (Dewey, 1977; Kukla, 1979; Namias, 1981; Walsh, *et. al.*, 1982; Foster *et. al.*, 1983; Wash, *et. al.*, 1981; Robinson, 1986a; Walsh & Ross, 1986). Snow-covered land exhibits major differences from snow-free ground due to the low heat conductivity, high thermal emissivity, low vapour pressure and high shortwave albedo of snow.

Models suggest that some of the largest climate impacts resulting from increases in "greenhouse" gases will take place near the present continental snowlines, thus their positions should serve as useful indicators of climate change (Lettau & Lettau, 1975; Manabe & Stouffer, 1980; Schlesinger, 1986). Despite this, we know of only a few studies which have concentrated on examining the past distribution of regional snow cover over long periods of time (>50 years) (Uttinger, 1963; Manley, 1969; Pfister, 1978). It will be ten years before a climatic data set (30 years) of satellite-derived snow cover analyses will be available for all Northern-Hemisphere lands. However, at present, long term (>75 years) snow cover data from ground stations are available for select regions. They may be used to assess past snow cover conditions and if and how any changes in snow extent are related to other climate variables.

This paper examines the January snow cover in the Midwest and Central Plains of the United States between 1901 and 1986 utilizing ground station data and satellite-derived charts. Regional snow analyses made using each of these data sets are also compared.

## DATA AND METHODS

The Midwest and Central Plains study regions and the locations of the twenty ground stations whose data are used in this study are shown in Fig. 1. In these regions: 1) the distribution of snow is variable during winter, 2) the terrain is relatively flat; therefore, the station data should be representative of the surrounding region, and 3) long-term records of snow cover are available. Daily January data from the ground stations (Table 1) were analyzed for the period from 1901 to 1978. Third-order cooperative stations were

selected to minimize the potential effects of urbanization on the long-term records. The stations are relatively evenly distributed throughout each region and have nearly complete records, with only 2% of the daily data missing over the 78 year interval. Snow cover is reported only if it is equal to or exceeds 2.5 cm (1") in depth.

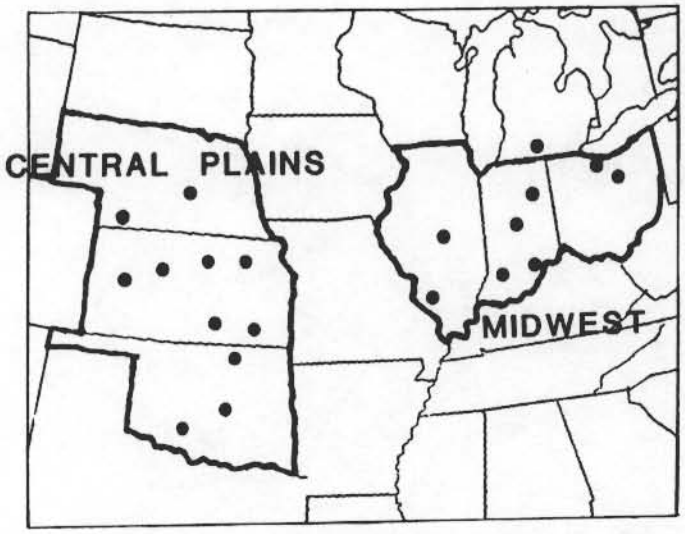


*FIG. 1 Midwest and Central Plains study regions (bordered with heavy lines). Ground stations used in the data analysis are marked with closed circles*

*TABLE 1 Ground stations employed in the study*

| *MIDWEST* | *CENTRAL PLAINS* |
|---|---|
| *Decatur, Illinois* | *Hays, Kansas* |
| *Sparta, Illinois* | *Healy, Kansas* |
| *Marion 2N, Indiana* | *Independence, Kansas* |
| *Scottsburg, Indiana* | *Manhattan, Kansas* |
| *Washington, Indiana* | *Minneapolis, Kansas* |
| *Whitestown, Indiana* | *Winfield, Kansas* |
| *Coldwater St. School, Michigan* | *Culbertson, Nebraska* |
| *Norwalk Sewage Plant, Ohio* | *Grand Island, Nebraska* |
| *Wooster Exp. Station, Ohio* | *Holdenville, Oklahoma* |
| | *Marlow, Oklahoma* |
| | *Pawhuska, Oklahoma* |

NOAA/NESDIS charts of snow cover were used to extend the record to 1986 (Baldwin, 1986). These weekly products, which have been constructed since 1967, are produced from analyses of shortwave imagery by skilled interpreters. They show the distribution of regional snow cover on the last clear-sky day of the charting interval. Snow cover is relatively easy to distinguish from snow-free ground in the study regions due to the general absence of masking vegetation (Robinson, 1986b). Texture or pattern recognition is used to distinguish snow cover from cloud. Four or five charts were available from all Januaries (chart-week ends in January), except for 1975 when there were only three.

For the 1901-1978 interval, daily ground data were analyzed and the percentage of days in each January for which a station reported: 1) no snow on the ground, 2) 2.5 cm (1") or more snow on the ground and 3) 12.7 cm (5") or more snow on the ground were determined. Within each region, individual station percentages were summed and averaged, with the resultant values assumed to be representative of monthly conditions. Regional cover was derived from the weekly NOAA/NESDIS charts from 1967-1986 by recognizing the immediate vicinity (within an approximate 10 km radius) of each station as being either: 1) snow covered, 2) snow free, or 3) on the snowline, between snow-free and snow-covered areas. Results from the weekly charts were averaged to represent station conditions for the entire month. Individual station reports were then averaged to determine monthly percent cover for the region.

The monthly regional snow cover determined from station and satellite data is considered representative of either a spatial or temporal distribution of cover during a given January. While the northern-most stations tend to be covered most frequently, snow cover at any station may be patchy in a spatial sense or distributed unevenly in a temporal sense throughout the month.

For the twelve-year interval (1967-1978) where satellite and station data overlap, there is a reasonable agreement between the two sets when station data ($\geq$2.5 cm) are compared to satellite-derived data in the vicinity of a station on the last date of the satellite chart-week (Table 2). Differences between the two sets occur when a late-week snowfall and persistent clouds over previously snow-free ground results in a satellite chart underestimating snow cover, and when a thin aging cover results in ground-station reports of a snow-free surface (or cover $\leq$2.5 cm deep), while satellites still recognize the region as just inside or on the snowline. Due to the latter, those stations lying on a snowline on a NOAA/NESDIS chart were classified as snow free.

There is also a reasonably close agreement between monthly regional coverages compiled from daily station data and those derived from weekly satellite-derived data, using the procedures described (see Table 3).

## RESULTS

The regional percent coverages of snow for Januaries between 1901 and 1986 are shown for the Midwest and Central Plains regions in Figs. 2 and 3, respectively. A substantial year-to-year variability

TABLE 2 *Comparison of ground-station reports of snow cover and satellite-derived NOAA/NESDIS reports of snow cover in the immediate vicinity of each of the twenty study stations (within an approximate 10 km radius). For the last day of each NOAA/NESDIS chart week ending in January between 1967 and 1978. Figures are in percent of the total number of station reports. D=depth (cm)*

| | SATELLITE-DERIVED CLASSIFICATION | | | |
|---|---|---|---|---|
| GROUND STATION CLASSIFICATION | Snow Covered | On Snowline | Snowfree | Sum Ground Stations |
| Snow free | 7.7 | 6.2 | 49.9 | 63.8 |
| $2.5 \leq D \leq 12.7$ | 13.3 | 2.2 | 6.2 | 21.7 |
| $D \geq 12.7$ | 13.2 | 0.2 | 1.0 | 14.4 |
| Sum Satellite-Derived | 34.2 | 8.6 | 57.1 | |

TABLE 3 *January snow cover (%) in the Midwest and Central Plains regions between 1967 and 1978, calculated from daily ground station data (depth $\geq$2.5 cm) and weekly satellite-derived snow cover charts according to the procedures described in the text*

| YEAR | MIDWEST | | CENTRAL PLAINS | |
|---|---|---|---|---|
| | Station | Satellite | Station | Satellite |
| 1967 | 17 | 17 | 38 | 18 |
| 1968 | 68 | 78 | 21 | 36 |
| 1969 | 32 | 33 | 19 | 25 |
| 1970 | 77 | 94 | 27 | 5 |
| 1971 | 24 | 24 | 28 | 18 |
| 1972 | 13 | 0 | 13 | 0 |
| 1973 | 8 | 11 | 38 | 25 |
| 1974 | 46 | 47 | 49 | 43 |
| 1975 | 22 | 33 | 23 | 18 |
| 1976 | 48 | 61 | 11 | 5 |
| 1977 | 96 | 100 | 46 | 32 |
| 1978 | 79 | 86 | 47 | 46 |

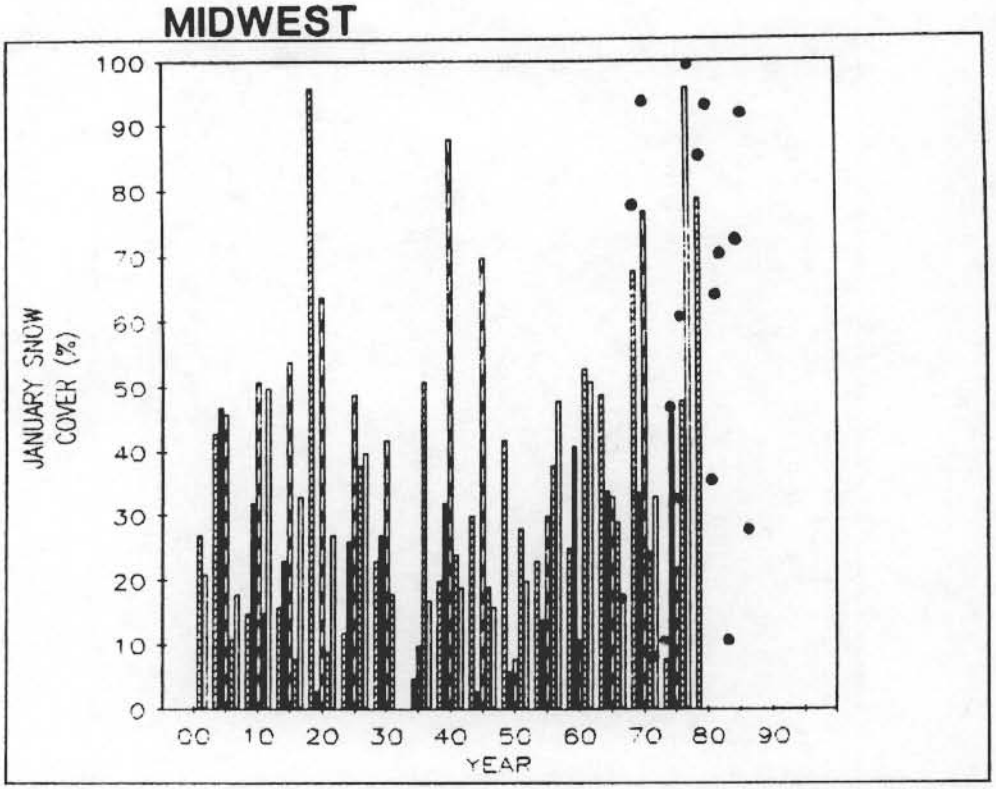


*FIG. 2 January snow cover in the Midwest study region between 1901 and 1986. The bar graph shows regional percent coverage (snow depth ≥ 2.5 cm (≥ 1")) for individual years between 1901 and 1978 based on ground station data. January coverage (closed circles) based on satellite-derived data is also shown between 1967 and 1986*

in snow cover is seen in each of the study regions. Januaries with greater than 75% regional coverage in the Midwest include 1918, 1940, 1970, 1977-79 and 1985. In the Central Plains, years with greater than 40% coverage include 1940, 1949, 1974, 1977-79 and 1984-85. Snow cover was meager in January 1916, 1919, 1921, 1932-35, 1944, 1949-50 and 1973 in the Midwest (<10% cover) and January 1904, 1907, 1911, 1914, 1923, 1928-29, 1931, 1933-35, 1938, 1946 and 1986 in the Central Plains (≤1% cover). Years between 1901 and 1978 when snow cover was not only extensive but was also deep include 1918, 1977 and 1978 in the Midwest (≥50% cover deeper than 12.7 cm (5")) and 1940 and 1974 in the Central Plains (>20% cover deeper than 12.7 cm).

Over the past forty years, a general increase in January snow cover has occurred in each region, as shown by ten-year running means plotted in Fig. 4. This trend began in the late 1920's in the Plains, while in the Midwest the recent trend was preceded by several decade-long oscillations. Earlier Midwest peaks occurred in the late 1910's to middle 1920's and in the late 1930's to middle

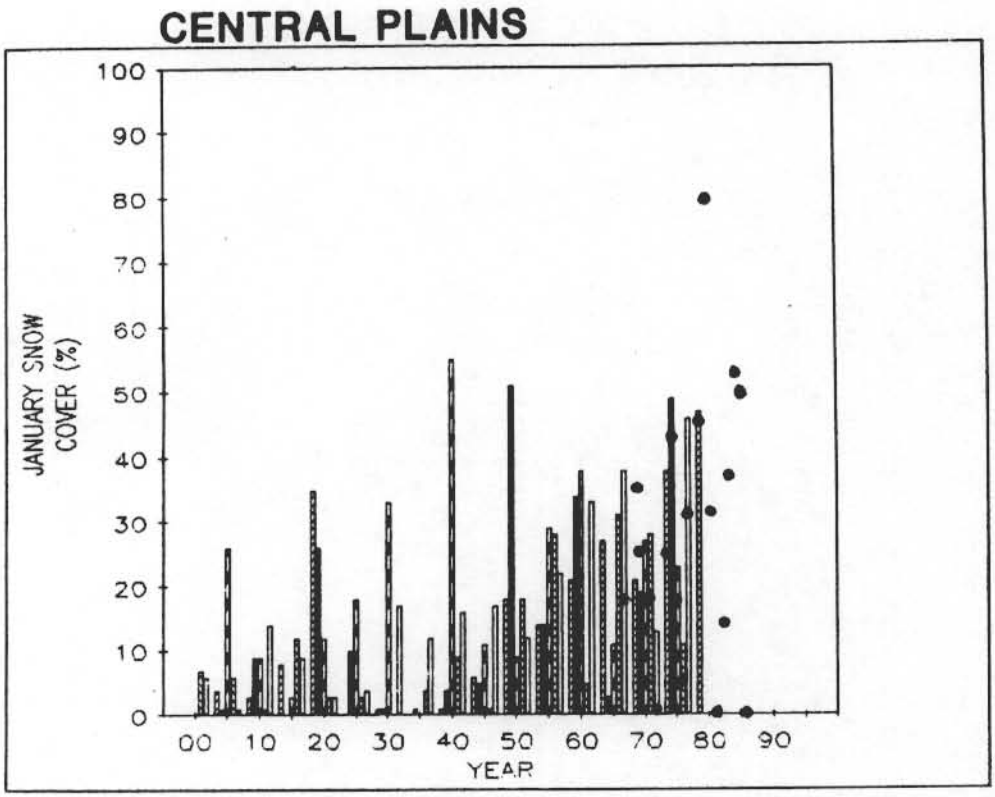


*FIG. 3 January snow cover in the Central Plains study region between 1901 and 1986. The bar graph shows regional percent coverage (snow depth ≥ 2.5 cm (≥ 1")) for individual years between 1901 and 1978 based on ground station data. January coverage (closed circles) based on satellite-derived data is also shown between 1967 and 1986*

1940's. The former peak was also noted in the Central Plains; however it, as well as the earlier ones in the Midwest, was more a function of just a few heavy snow cover years (1918, 1919, 1925), rather than a relatively consistent string of snowy years, as has been the case in recent decades. None of the earlier peaks approached the coverage of recent years.

## DISCUSSION

If snow cover is to be useful as a means of recognizing and monitoring anthropogenic climate change, and if alterations of climate are to be most significant over regions where changes in the duration and frequency of snow cover occur, then variations in snow cover should show some relationship with other climate variables.

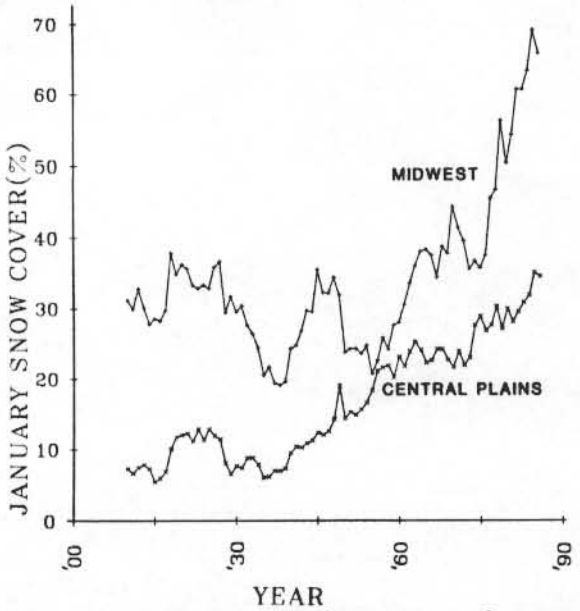


*FIG. 4 Ten-year running means of January snow cover for the Midwest (+) and Central Plains (X) study regions. Means are placed over the last year of the ten-year interval and are based on station data (snow depth ≥ 2.5 cm) up to 1969-1978 and in later series on satellite-derived data*

Figure 5 suggests positive relationships between extensive January cover and colder-than-normal temperatures in each of the central U.S. study regions. Conversely, warm Januaries appear to be associated with little snow cover. These relationships are stronger in the Midwest than in the Central Plains. Snow departures were derived from an eighty-six year average of regional cover, and temperature departures are from an unweighted average of departures (1895-1983) for each state (Karl *et. al.*, 1984). State departures fall into one of five categories, which for the purposes of this study, were ranked as: 1) much below normal (containing 10% of the months, 2) below normal (20% of the months), 3) normal (40%), 4) above normal (20%) and 5) much above normal (10%). There are exceptions to these relationships, which may be partly explained by the availability of precipitation and whether it falls in frozen or liquid form. Regarding a long-term relationship between snow cover and precipitation, the increases in January snow cover since the 1940's are accompanied by a decrease in January precipitation (Karl *et al.*, 1986). The overall light cover of earlier decades, compared to the recent period, occurred during a period where winter precipitation exceeded values of recent decades (Diaz & Quayle, 1980).

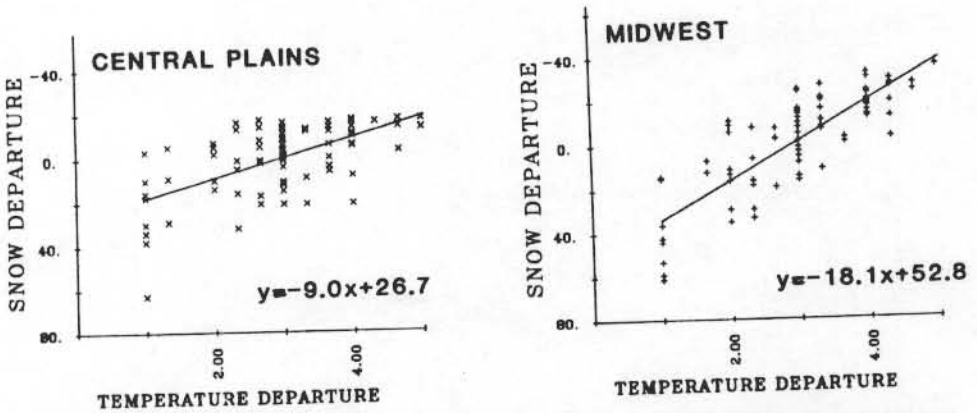


*FIG. 5 January departures of snow cover versus January temperature departures for the Midwest and Central Plains study regions (1901-1983). Departure categories for temperature are based on the 1895-1983 mean, and range from much below normal (1) to much above normal (5) as described in the text. Snow departures are derived from the 1901-1986 mean coverage of 34.8% in the Midwest and 17.1% in the Central Plains. Snow means are based on station data from 1901-1978 and satellite-derived data from 1979-1986. Regressions have correlations of -0.83 (Midwest) and -0.60 (Central Plains)*

It must be stressed that the above relationships should only be considered tentative at this time. Further investigations, incorporating denser data networks and other variables (eg. 700 mb heights, cloudiness, storm tracks), along with case studies, are needed before more exact relationships may be put forth and the nature of these relationships defined.

## CONCLUSIONS

Daily ground station data have been used to extend the record of regional snow cover back into the pre-satellite era in select regions of the central United States. Significant interannual fluctuations in the extent of January snow cover are common during the 20th century. A significant increase in snow cover has occurred in the Central Plains and in the Midwest since the late 1940's. This trend began in the late 1920's in the Plains, while, in the Midwest, the recent trend was preceded by several decade-long oscillations. Relationships between departures of snow cover and temperature and snow cover and precipitation have been suggested, although at this time it is not possible to fully confirm or specifically define the nature of these relationships.

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## REFERENCES

Baldwin, T.E. (1986) Northern Hemisphere snow and ice chart of NOAA/NESDIS. In: *Glaciological Data: Snow Watch '85* (ed. by G. Kukla, R.G. Barry, A. Hecht & D. Wiesnet), 109-113. Report GD-18, World Data Center-A for Glaciology, Boulder, Colorado.

Barry, R.G. (1985) The cryosphere and climate change. In: *Detecting the Climatic Effects of Increasing Carbon Dioxide* (ed. by M.C. MacCracken & F.M. Luther), 109-148. U.S. Dept. of Energy, DOE/ER 0235.

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

Diaz, H.F. & Quayle, R.G. (1980) The climate of the United States since 1895: spatial and temporal changes. *Mon. Wea. Rev.* 108, 249-266.

Foster, J., Owe, M. & Rango, A. (1983) Snow cover and temperature relationships in North America and Eurasia. *J. Cli. Appl. Met.* 22, 460-469.

Karl, T.R., Knight, R.W., Koss, W.J., & Quinlan, F.T. (1984) *Atlas of Monthly and Seasonal Temperature Departures from the Long-term Mean (1859-1983) for the Contiguous United States, Winter.* Historical Climatology Series 3-2, NCDC, NESDIS, NOAA.

Karl, T.R., Kukla, G. & Gavin, J. (1986) Relationship between decreased temperature range and precipitation trends in the United States and Canada, 1941-80. *J. Cli. Appl. Met.* 25, 1878-1886.

Kukla, G.J. (1979) Climatic role of snow covers. In: *Sea Level, Ice and Climatic Change* (Proc. Canberra Symp. Dec. 1979) 79-107. IAHS Publ. 131.

Kukla, G.J. (1981) Snow covers and climate. In: *Glaciological Data: Snow Watch 1980* (ed. by G. Kukla, A. Hecht & D. Wiesnet), 27-39. Report GD-11, World Data Center-A for Glaciology, Boulder, Colorado.

Lettau, H.H. & Lettau, K. (1975) Regional climatonomy of tundra and boreal forests in Canada. In: *Climate of the Arctic* (ed. by G. Weller & S.A. Bowling), 209-221. University of Alaska, Fairbanks.

Manabe, S. & Stouffer, R.J. (1980) The seasonal variation of the hydrologic cycle as simulated by a global model of the atmosphere. *J. Geophys. Res.* 85, 5529-5554.

Manley, G. (1969) Snowfall in Britain over the past 300 years. *Weather* 24, 428-437.

Namias, J. (1981) Snow covers in climate and long-range forecasting. In: *Glaciological Data: Snow Watch 1980* (ed. by G. Kukla, A. Hecht & D. Wiesnet), 13-26. Report GD-11, World Data Center-A for Glaciology, Boulder, Colorado.

Pfister, C. (1978) Fluctuations in the duration of snow cover in Switzerland since the late seventeenth century. In: *Proceedings: Nordic Symposium, Climatic Changes and Related Problems* (ed. by K. Frydendahl), 1-8. Danish Meteorological Institute, Copenhagen.

Robinson, D.A. (1986a) Initiation of spring snowmelt over arctic lands. In: *Proceedings of the Symposium: Cold Regions Hydrology* (ed. by D.L. Kane), 547-554. American Water Resources Association.

Robinson, D.A. (1986b) Remotely sensed albedo of snow-covered lands. In: *Proceedings of the Second Conference on Satellite Meteorology/Remote Sensing and Applications*, 173-176. American Meteorological Society, Boston, Massachusetts, U.S.A.

Schlesinger, M.E. (1986) $CO_2$-induced changes in seasonal snow cover simulated by the OSU coupled atmosphere-ocean general circulation model. In: *Glaciological Data: Snow Watch '85* (ed. by G. Kukla, R.G. Barry, A. Hecht & D. Wiesnet), 249-270. Report GD-18, World Data Center-A for Glaciology, Boulder, Colorado.

Uttinger, H. (1963) Die dauer der schneedecke in Zurich. *Arch. Meteor. Geophys. Bioklim.* B12, 404-421.

Walsh, J.E., Tucek, D.R. & Peterson, M.R. (1982) Seasonal snow cover and short-term climatic fluctuations over the United States. *Mon. Wea. Rev.* 10, 1474-1485.

Walsh, J.E. & Ross, B. (1986) Snow cover, cyclogenesis and cyclone trajectories. In: *Glaciological Data: Snow Watch '85* (ed. by G. Kukla, R.G. Barry, A. Hecht & D. Wiesnet), 22-35. Report GD-18, World Data Center-A for Glaciology, Boulder, Colorado.

Wash, D.H., Edman, D.A. & Zapotocny, J. (1981) GOES observation of a rapidly melting snowband. *Mon. Wea. Rev.* 109, 1353-1356.