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Creating Temporally Complete Snow Cover Records Using A New Method for Modelling Snow Depth Changes

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Abstract

The availability of a new daily climate data set provides a unique opportunity to use daily snow cover data from multiple weather stations for regional climate analysis. Here, this set is used in the development of an empirically-based statistical method for modelling changes in snow depth for the Great Plains region of the United States. Long-term daily data from 62 cooperative weather stations with records extending back to the turn of the century are used. This method offers an alternative to traditional energy balance or temperature index methods that are often inaccurate for regions prone to shallow and ephemeral snow cover. Average daily change in snow depth at a given mean air temperature is computed for Winter and Spring for four states in the central and northern Great Plains. These changes in depth with temperature show considerable variation, both regionally and seasonally, increasing from the northern plains to the central plains, and from Winter to Spring. The relationship between snow depth change and mean temperature may be described statistically by a second order polynomial. The derived equations are used in conjunction with temperature and snowfall data to simulate snow pack behavior at four control stations in the region. Results from a sensitivity analysis indicate that gaps of varying lengths may be filled with a high degree of confidence to create temporally complete snow cover data at a station. Other uses for this methodology include simulation of snowpack behavior in regional climate change studies, and estimating basin runoff for hydrologic and agricultural studies.

Introduction

In the northern and central Great Plains of the United States and the adjacent Canadian prairie, snow represents an important hydrologic resource. It is estimated that snowfall in this region, due in part to its lower evaporation potential, is twice as valuable as a resource for commercial agriculture as rain (Greb, 1980). For example, over the Canadian prairie, snow represents only 30% of the annual precipitation, but accounts for greater than 80% of the surface runoff (Gray & Landine, 1988). Along with the hydrologic implications of snowfall in this region, climate change scenarios show an amplification of anthropogenically-induced warming in the plains region where snow cover is ephemeral (Manabe & Wetherald, 1980; Hansen, 1986). The ability to understand and model changes in the depth of prairie snowpacks is therefore important for adequate resource management, as well as for regional climate change analysis.

Two methods commonly used for estimating snow depth and snowmelt are energy balance and temperature index approaches. Energy balance models attempt to solve the fundamental equations of energy, mass and momentum. Solving these equations involves input such as solar radiation, wind speed, water equivalent of snow and net short and longwave radiation components. Much of this information is unavailable or difficult to measure for large scale operational use (Gray & Male, 1981). The temperature index method is based on a simple relationship between snowmelt and temperature above a given base temperature (usually 0°C). A melt factor term is defined to account for such things as site exposure, season, ground cover, cloudiness and the albedo of the snow. Problems with this method occur from assumptions made when defining regionally specific melt factors and an appropriate base temperature for the initiation of melt (Winston, 1965; Huber, 1983; Kuhn, 1987; Kondo & Yamazaki, 1990). In addition, the energy balance and temperature index methods are more accurate in forested alpine environments where snow cover is deep and present throughout the snow season (Granger & Male, 1979; Gray & Landine 1988). The application of both modelling approaches to the shallow snows in the prairie environment often proves to be inaccurate (Gray & Landine, 1988).

The development of our Depth Change (DC) method offers a two-step approach for modelling snowpack behavior in the Great Plains. The first step is the computation of average daily changes in snow depth for a given mean temperature using long-term historical snow cover data from multiple weather stations in a region. The availability of hundreds of cases of snow depth change from a dense network of climate stations permits the development of statistically reliable regression equations. Step two uses these equations in conjunction with snowfall data, as a means for both accumulating and decreasing the amount of snow cover on the ground. This permits the filling of missing daily snow cover data at individual climate stations, and may be used as a means for simulating regional snowpack behavior for use in climate change studies. Other uses include estimating water yields for hydroelectric power generation, forecasting streamflow volume and estimating soil moisture (Granger & Male, 1979; Gray & Landine, 1988; Carr, 1989).

Daily Historical Climate Data Set

The use of snow cover in climate change research has until recently been limited by the lack of long-term snow cover data of a high quality (Karl et al., 1989). The Daily Historical Climate Data Set compiled by Robinson (1988) provides the first daily accounting of snow cover for approximately 1100 cooperative weather stations distributed throughout the United States. Along with snow cover, each record provides daily data on snowfall, precipitation and maximum and minimum temperatures. The digital data are carefully quality controlled. They provide a unique opportunity for studies regarding long-term temporal and spatial variability of snow cover over the Great Plains.

Approximately 100 stations in the set are located in North Dakota, South Dakota, Nebraska, and Kansas. Records at these sites extend back to the turn of the century, however, even at the best climate stations between 2% and 8% of the snow cover data are missing. The amount of missing snow cover data from October-April for all stations in the region ranged from a low of 0.5% to a high of 57%, with 76% of the stations having less than 15% missing. Gaps in snow cover in a preliminary analysis of snow conditions in this region were simply filled by a nearest neighbor substitution method on a seasonal basis (Robinson & Hughes, 1991). However, given the spatial variability of snow cover in this region, this procedure is at times unreliable.

Depth Change (DC) Method

The central and northern Plains states of North Dakota, South Dakota, Nebraska and Kansas are considered subregions in this study. Each is approximately 3° in latitude by 7° in longitude. From 12 to 19 well-distributed stations in each state are used for the development of regression equations that are based on a comparison of daily changes in snow depth and mean temperature (fig. 1). One station in each region, independent of the

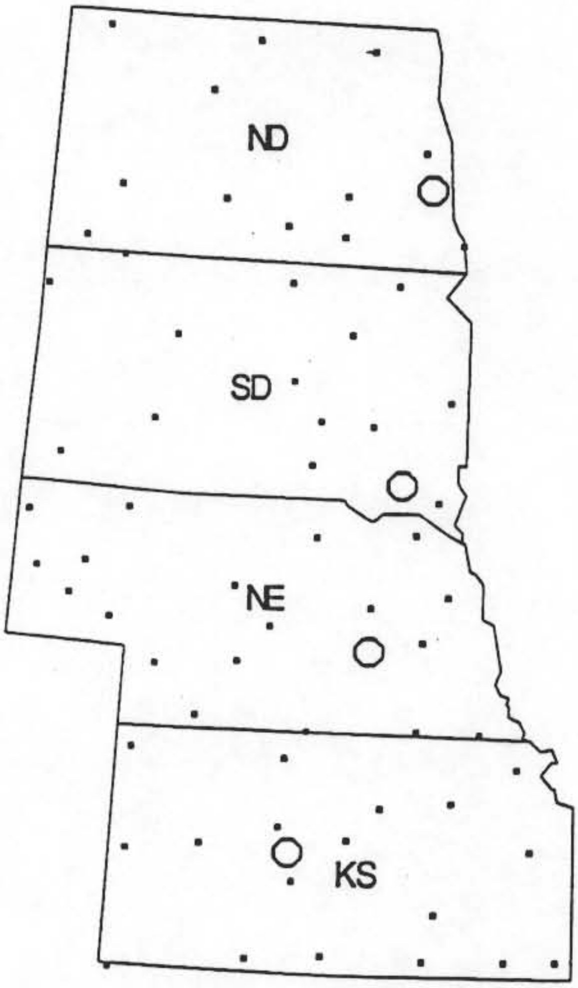


Figure 1. Distribution of Great Plains climate stations employed in this study. Stations marked with opened circles are study control stations.

original group, is used as a control station to evaluate the efficacy of using the equations to estimate changes in snow depth given a mean temperature. Snow depths between 2.5 and 65 cm are considered in this analysis. Unlike the temperature index method, our routine does not arbitrarily take 0°C as the base temperature for the initiation of snowmelt. Rather it is observed that above a mean temperature of -10°C changes in depth/day are of some importance in dictating the depth of a snowpack when observed over a period of days or weeks. The snow season is divided into two portions, the first from November through mid-February, and the second from mid-February through April.

The first step of the DC method is the determination of the change values, and associated regression equations. To accomplish this, a computer program (CHANGEVALUE) computes the average daily change in snow depth for a given mean temperature. The program allows the user to define a particular region and season to examine. For each station in a given region, the previous day's snow depth is compared to the current day's snow depth. If a decrease in depth has occurred, the change is stored along with the mean daily temperature. Days with observed snowfall are omitted from the analysis. When all the stations within the region are scanned, the average change in snow depth/mean temperature (given that a change has occurred) is computed. The values are then adjusted based on the number of times snow cover is observed and no change in snow depth occurs at that temperature value. The average number of cases found for each 0.56°C (1°F) temperature increment is approximately 180 for the Winter snow season, and 140 for the Spring. A decrease in the number of cases occurs at both ends of the temperature scale, most notably in the winter at high temperatures (Table 1). Thus, the derived change values are considered suspect at high temperatures. A regression analysis follows, using the change values and associated mean air temperatures to develop statistical snow depth change models. Eight models have been developed for this study representing the two seasons for each of the four states.

The second step of this method involves using the regression equations to estimate snow cover depths at a station. A program called DATAFILL reads every record for a given climate station and searches for missing snow cover data. If a missing value is found the program attempts to estimate it in one of three ways. If the only possible snow cover value is zero based on temperature, snowfall, and snow cover from the previous and current day's record, this is filled in first. If the mean temperature for the day is below -10°C, the current day's snow depth is set equal to the previous day's snow depth. If the mean temperature is greater than -10°C, the current snow depth value is estimated to be the previous day's snow depth plus the current day's snowfall, less the change in snow depth determined by solving the regression equation at that temperature. In this way, both daily accumulation and decreases in snow cover are estimated.

Table 1. Sample of number of cases/mean temperature (°C) found for Winter (W) and Spring (S) snow seasons.

Temperature	**ND (W)**	**ND (S)**	**SD (W)**	**SD (S)**
-11.1	42	31	51	39
-10.0	47	39	75	69
-8.9	60	55	104	97
-7.8	81	72	122	119
-6.7	108	97	171	159
-5.6	130	148	213	171
-4.4	165	155	275	169
-3.3	154	184	304	232
-2.2	163	224	285	245
-1.1	173	212	298	277
0	160	243	249	264
1.1	111	216	215	254
2.2	60	166	146	200
3.3	41	132	93	154
4.4	29	98	48	103
5.6	4	75	34	77

Temperature	NE (W)	NE (S)	KS (W)	KS (S)
-11.1	105	31	71	23
-10.0	130	51	71	17
-8.9	180	74	112	29
-7.8	205	96	147	37
-6.7	235	130	160	55
-5.6	296	148	191	77
-4.4	336	170	215	68
-3.3	349	190	269	79
-2.2	374	204	277	111
-1.1	365	240	276	114
0	350	231	238	124
1.1	294	240	236	149
2.2	258	204	198	140
3.3	160	156	165	99
4.4	97	116	92	74
5.6	51	97	72	59

Two related issues have been addressed in the development of this method, the first being the settling of a fresh snowpack, the second being the affect of rain on snow depth. The influence of settling on snow depth is examined by running the DC method for depth classes of 2.5-25 cm and 25-65 cm at North Dakota stations. While rapid settling is found to occur within the first few days following a snowfall, there are too few cases of snow depth change at most temperatures to quantify this impact. Similarly, although rain can have a significant impact on the depth of snow, too few cases are available in the Great Plains to adequately quantify this impact. The occurrence of these events is not excluded from the determination of the change values derived in this study.

Regional And Seasonal Variations In Change Values

For Winter and Spring in the Great Plains, the decrease in snow depth at a given mean temperature gets progressively larger as one continues southward. For example, at -4°C in Winter, depth decreases by 0.89 cm/day. The values for South Dakota, Nebraska, and Kansas are 1.24 cm/day, 1.71 cm/day, and 1.75 cm/day respectively. Also, winter values are approximately 1.5 times lower than spring values (figs. 2 & 3). For example, at -8°C in North Dakota, depth decreases by 0.36 cm/day in Winter and 0.8 cm/day in Spring. At 4°C the decrease is 2.89 cm/day and 4.26 cm/day respectively. Similar results were found for Kansas, where depth decreases at -8°C vary from 1.20 cm/day in Winter to 2.06 cm/day in Spring. Associated values at 4°C are 3.32 cm/day and 4.89 cm/day respectively (Table 2).

The relationship between snow depth change and mean temperature for all cases is best described by a second order polynomial (fig. 4). R^2 values range from a low of 0.98 in North Dakota in Winter to a high of 0.99 in Kansas in Winter, and all are significant at the 99% level. The statistical models describe the small changes in snow depth that occur at mean temperatures far below freezing, encompassing the phenomena of melt, compaction and sublimation. As mean temperatures increase, so do the daily changes in snow depth. As mentioned previously, at mean temperatures above 3.5°C, the number of cases of decreasing snow depth diminishes, particularly in Winter. This causes greater variability in computed change values. At these temperatures some of the variability results from shallow snowpacks melting away completely before the full potential of the day's temperature to melt snow is reached. An observer bias is also found for some stations, where a tendency to record 2.54 cm (1 inch) of snow on the ground existed despite persistent mean temperatures above 3.5°C.

Table 2. Sample of regionally and seasonally derived snow depth change values for -8°C, -4°C, 0°C, and 4°C

Temperature=-8°C

Region	Winter (cm/day)	Spring (cm/day)
North Dakota	0.36	0.80
South Dakota	0.57	1.14
Nebraska	1.10	1.91
Kansas	1.15	2.06

Temperature=-4°C

Region	Winter (cm/day)	Spring (cm/day)
North Dakota	0.89	1.66
South Dakota	1.24	2.05
Nebraska	1.71	2.79
Kansas	1.75	2.85

Temperature=0°C

Region	Winter (cm/day)	Spring (cm/day)
North Dakota	1.73	2.81
South Dakota	2.12	3.19
Nebraska	2.37	3.69
Kansas	3.08	4.62

Temperature=4°C

Region	Winter (cm/day)	Spring (cm/day)
North Dakota	2.89	4.26
South Dakota	3.20	4.56
Nebraska	3.08	4.62
Kansas	3.32	4.89

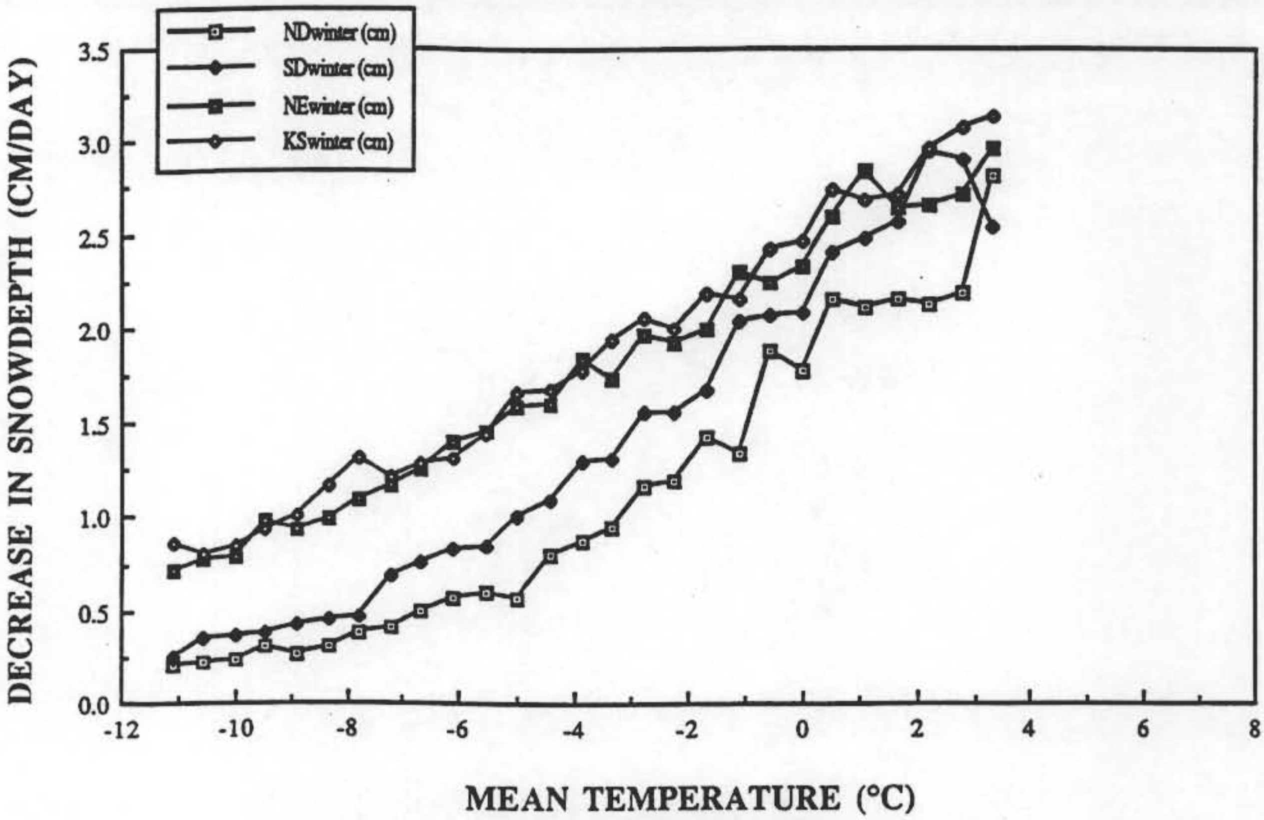


Figure 2. Association between daily snow depth change and mean temperature during Winter in the four study states.

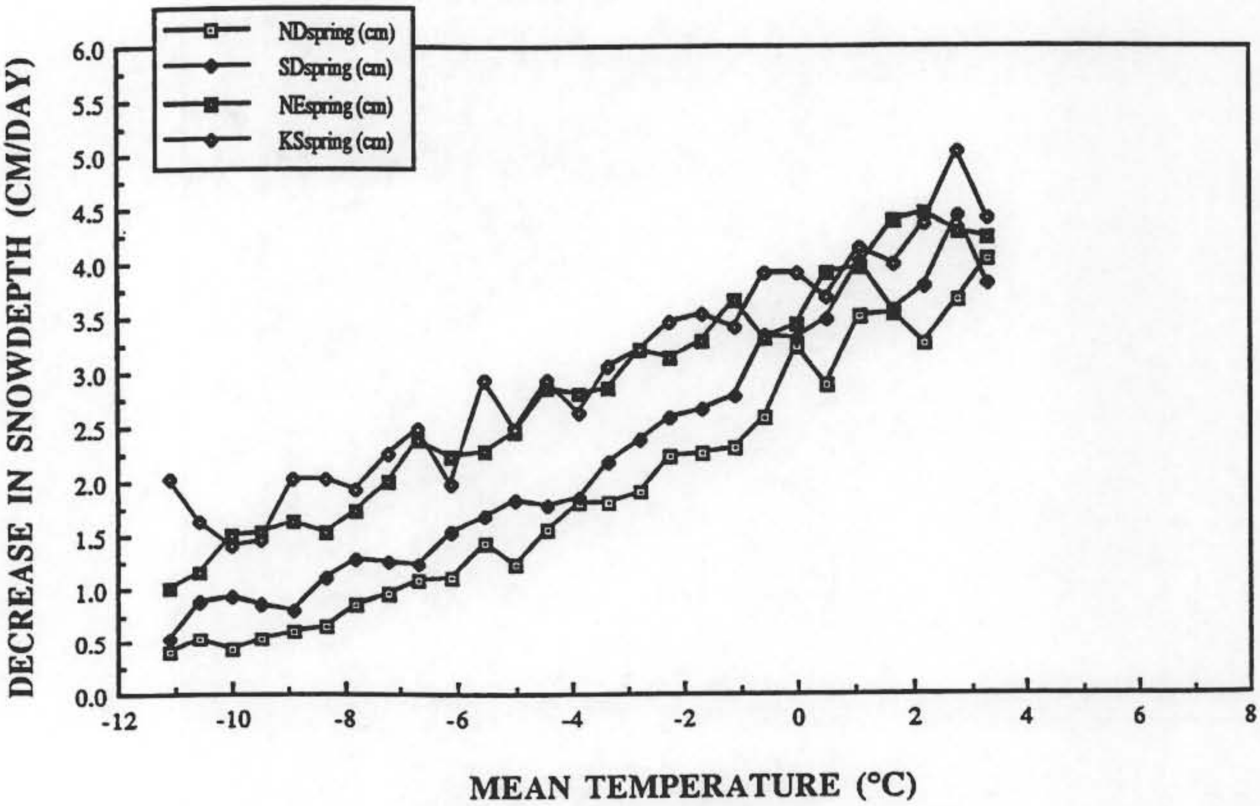


Figure 3. Association between daily snow depth change and mean temperature during Spring in the four study states.

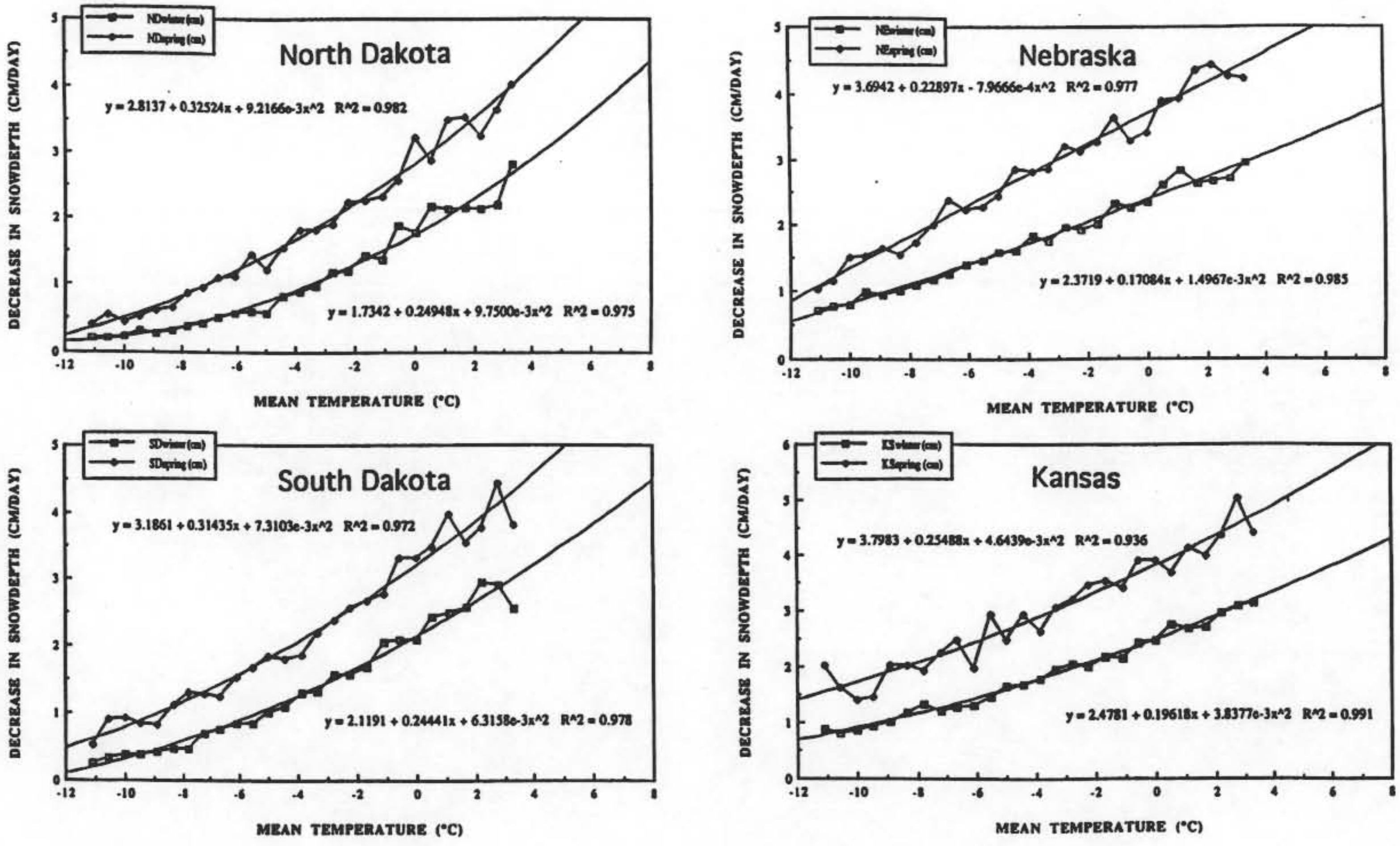


Figure 4. Association between daily snow depth change and mean temperature during Winter and Spring for the four study states. Observed results and a second order polynomial fit to these data are shown.

Evaluation Of The Depth Change Method

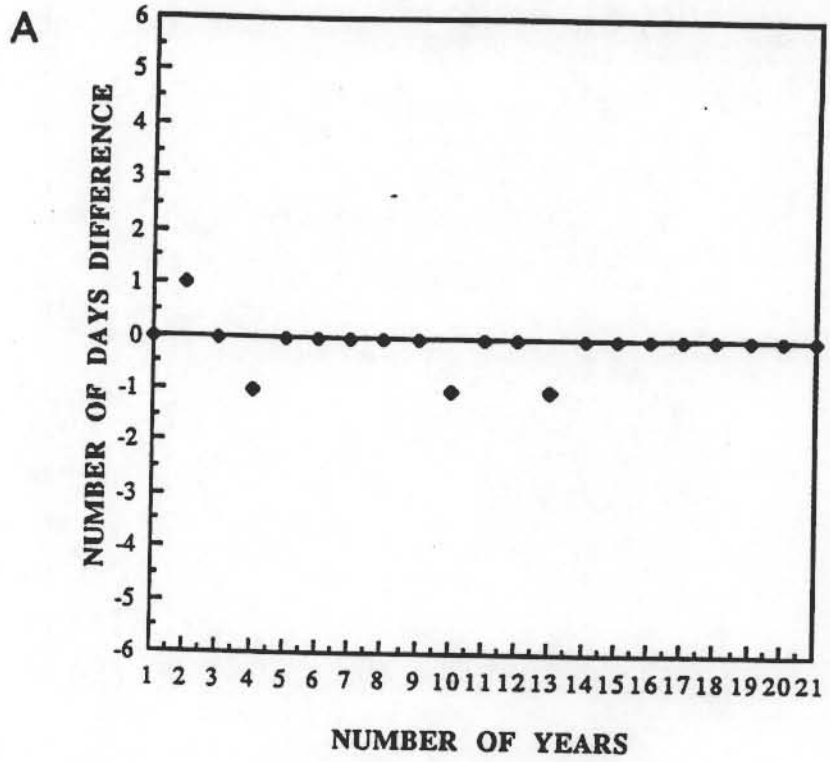
To evaluate the use of the DC method for data filling purposes, a sensitivity analysis is done using one station within each of the four states (fig. 1). These stations are not included in the formation of the regression model. A stepwise approach is used where initially two days in each month are changed from the observed snow depth value to a missing value. The missing days are then estimated by using observed temperature and snowfall data along with the appropriate regression model. Observed snowfall values are added to the existing snowpack, thereby allowing increases in the daily snow cover. Decreases in the snowpack occur through use of the temperature data and the regression equation. Once filled, the original file and filled data file are compared and differences between the two files quantified. This procedure has been repeated with 4, 8, 16, and 31 days/month changed to missing and then subsequently filled.

Results of this sensitivity analysis are illustrated using the control stations located in Amenia, ND, and Bison, KS. Comparisons between the filled file and the original file are done by summing the total number of days in Winter (DJF) with more than 2.5 cm (1 inch) of snow on the ground and differencing the numbers. The two cases shown for each station represent data filling with two days in every month filled and all days in every month filled, the latter being a complete simulation of snowpack behavior (figs. 5 & 6). Therefore, each point on the graph represents the difference in the total number of days with snow on the ground between the files for an entire Winter. The y-axis is scaled by the maximum number of filled data points in the season. For Amenia, ND with two days/month filled, there are 21 years of winter data compared, or a total of 126 days of estimated snow cover data. When the observed and modeled files are compared, only four days exist where one file indicates snow on the ground and the other does not (fig. 5a). In the case of simulating the entire winter snow season for Amenia, 14 years of snow cover data are compared to the original file. Even in this extreme case, the modeled snowpack is quite close to the actual observed conditions (fig. 5b). The largest difference between files in a year is 20 days. Of the 14 years compared, 11 years, representing 992 filled days, have fewer than 7 days/season difference. For Bison, KS the southernmost control station, 37 years of original data are compared to the filled snow cover data. For the case where two days/month are filled, only 7 of 222 modeled days indicate snow on the ground where the observed does not (fig. 6a). When the entire winter snow cover is simulated, only 3 of 37 years have fewer than one week difference between observed and modeled files (fig. 6b).

Analysis of the control stations located at Menno, South Dakota and Central City, Nebraska shows similar favorable results. For all cases, use of the regression model in conjunction with observed snowfall and temperature values proves to be an acceptable means for filling gaps of varying length within the data set.

Discussion

The DC method approaches the problem of modelling snow depth change in a purely statistical manner. Unlike the energy balance and temperature index methods for modelling *snowmelt*, the DC approach models changes in *snow depth*.. This does not fully explain the success of the DC method in modelling Great Plains snow cover where the others often fail. The melt and depth difference is only important at subfreezing temperatures, where depth changes slowly. Other reasons why traditional snowmelt models are less reliable in this region are illustrated from the results of the following studies. McKay (1964) used a degree-day approach with station and snow survey data to evaluate snowpack



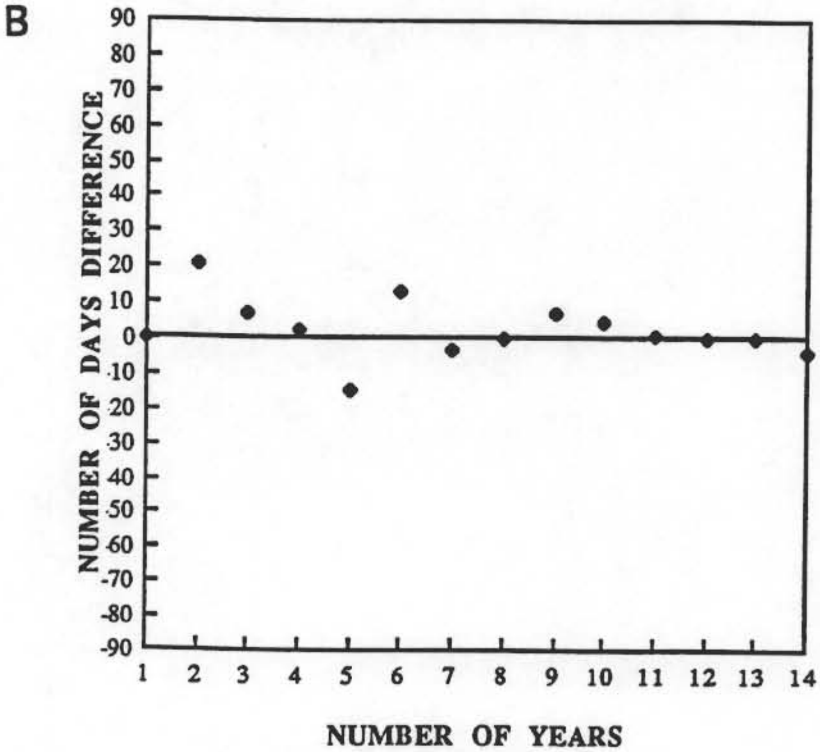
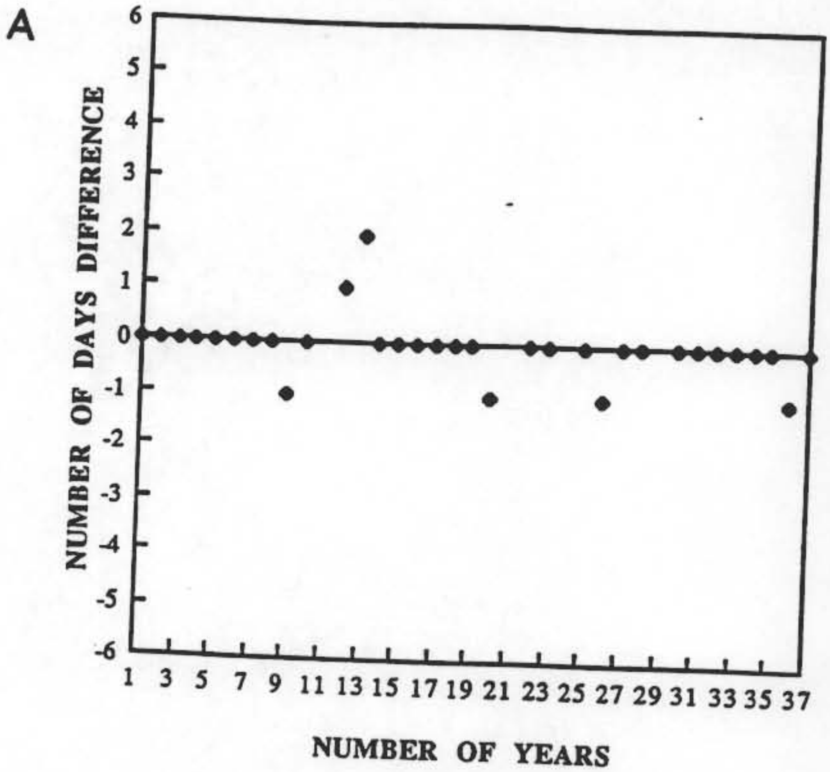


Figure 5. Comparisons between observed and modeled (filled) values of the number of days with ≥2.5cm of snow cover during the Winter (DJF) at Amenia, ND. Differences between the original and filled (filled - original) when two days per month are filled are shown in A. B shows the same, except all days are filled.



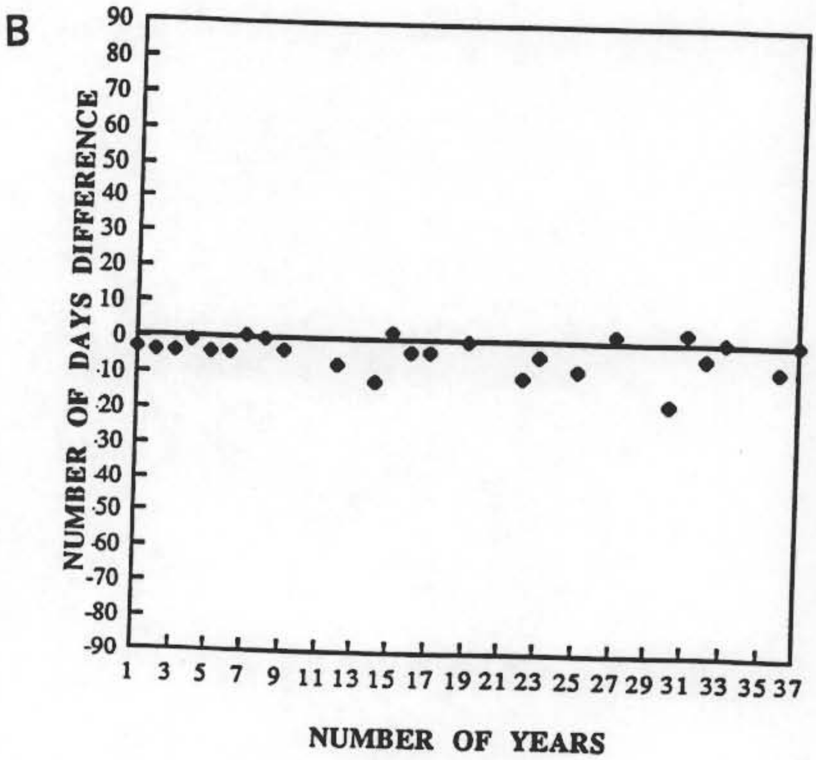


Figure 6. Same as fig. 5, except for Bison, KS.

characteristics in Saskatchewan and Manitoba, and found problems with appropriately defining the base air temperature for initiation of melt. Granger and Male (1979) used an energy budget approach to model snowmelt in the Bad Lake Watershed in Saskatchewan using temperature, humidity and vertical wind speed data for three years from 1974, 1975, and 1976. A significant problem arose due to the affect of advection of heat from the ground in areas of shallow and patchy snow. This has been noted as well by Heron and Woo (1978), Male (1980), Aguado (1983), and Gray and Landine (1988). Meier (1985) noted that modelling the seasonality of snowmelt behavior as well as being able to precisely measure all the energy fluxes involved with snowmelt is impossible for operational use at most locations.

Gray and Male (1981) cite studies by Yoshida (1962), Anderson (1973) and the Army Corps of Engineers (1956), where melt factors ranged from 0.39-0.80 cm/°C-day in the Tadami River basin in Japan to 0.13-0.37 cm/°C for sites in the United States. Thus, at 3°C these factors predict changes in snow depth ranging from 0.39 cm/day to 2.40 cm/day. This compares with depth changes in Winter at 3°C computed using the DC method ranging from 2.57 cm/day in North Dakota to 3.10 cm/day in Kansas. In Spring, these values range from 3.87 cm/day to 4.60 cm/day.

Since the DC method computes the differences in snow depth change values empirically, regional and seasonal variations in snowpack behavior are preserved. Differences found in both dimensions are most likely due largely to variations in solar radiation reaching the surface of the Earth. As one progresses northward, the shorter day length and higher solar zenith angles during the snow season result in smaller changes of snow depth at the same mean temperature. The greater difference in depth changes between South Dakota and Nebraska compared to between North and South Dakota and between Nebraska and Kansas may reflect differences in the persistence of winter snow cover in the northern and southern halves of the study area. Other reasons for regional and seasonal variations in change values may be related to differences in antecedent soil moisture, the number of full melt events that occur in a snow season and in meteorological conditions such as winds and clouds. Whether the soil underlying the snowpack is frozen or unfrozen may also in part account for variations.

Conclusions

The Depth Change (DC) method is successful at modelling seasonal changes in snow cover across the Great Plains. This method is more reliable than the energy balance and the temperature index methods because it relies on daily historical snow cover data to build statistical snow depth change models. Change values, not constrained by predefined limits, are allowed to vary considerably over a given region, allowing a flexible approach to modelling snowpack conditions. In conjunction with snowfall data, one can quite accurately recreate or fill in missing snow cover values at individual stations on a daily basis. This is important as a means to permit detailed investigations of long-term variations or potential trends in snow cover over the Great Plains, a region models suggest will be significantly affected by climate changes associated with increased levels of greenhouse gases.

Acknowledgments

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