SNOW-MASKING DEPTH IN
A GENERAL CIRCULATION MODEL

By

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Abstract

A computer program was written to calculate snow albedos for the months of January, March, and May in western Canada. Snow depth as well as water equivalent depth data was obtained from snow cover records and climatic maps. It was found that for the months of January and March, the snow depths were all greater than 10 cm and so the snow albedo was not a function of the surface type rather only the snow cover. For May, however, snow depths of less than 10 cm were obtained and the albedo became a function of both the water equivalent as well as surface type. The method of data collection is criticized primarily because of the instances of measurements and methods of measurement. Also, the equation in which the snow albedo is calculated is criticized because it only takes into consideration snow depth and not other important factors such as snow age density and crystal structure. However, age, density, and crystal structure are difficult measures to obtain data for on a large scale typical of GCMs. Good comparisons are made with the snow albedo values of forested sites obtained in this study with those in the literature.

Acknowledgements

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CHAPTER ONE

INTRODUCTION

Surface albedo values of all different land types depend on many factors such as material composition, surface roughness, and moisture content to name a few (Dickinson, 1983). When adding snow to land surfaces the resulting albedo depends on many other different factors including depth of snow cover, as well as the type and density of vegetation (Kukla and Robinson, 1980). Surface albedo is an important climatic parameter to be studied with respect to the entire Earth-Atmosphere regime. Climatic models such as general circulation models are tools in which the study of the Earth-Atmosphere regime including parameters such as albedo are scrutinized on a global scale. It must be kept in mind, however, that climate models produce model climates. That is, they are not necessarily realistic climates that can be readily applied to situations today. There are many reasons for this. First, complex relationships exist between the earth and atmosphere which can not all be accurately prescribed in a model. Secondly, lack of observational and theoretical databases can cause gross errors in estimations of certain parameters which would lead to overall model deviations from reality. Thirdly, the lack of observational data implies that meaningful comparisons with reality may be difficult with model results and so models are tested for sensitivity rather than for accuracy.

It is the purpose of this paper to firstly calculate snow albedos for certain months of the year using a computer program especially written for this study. These results will then be examined statistically and discussed in terms of the data collection methods as well as with other methods used in calculating the snow albedo.

CHAPTER TWO

LITERATURE REVIEW

Climate models were developed to study global climate by both reconstructing and predicting weather and climate. They simulate the processes controlling the relationship between the circulation of the atmosphere and the energy balance of the planet (National Academy of Science, 1975). General circulation models (GCMs) are the most sophisticated of all climate models. They are complex three-dimensional computer models, that in simplistic terms, contain equations governing the dynamics and thermohydrodynamics of the atmosphere for a finite number of grid points. The algorithms are integrated forward in time from predetermined initial boundary conditions until a model climate is generated after a period of 40 or more days of simulated time (Williams, 1978).

GCMs yield an improved understanding of the climate system as a whole as well as the individual parameters that contribute to the Earth-Atmosphere climate regime. A better understanding of the climate system can be beneficial from an economic standpoint. For example, predictions of future climate scenarios could assist in the development of alternate agriculture practices. Also, these models can be used to monitor environmental changes induced by human activity, for example, deforestation and the carbon dioxide loading of the earth's atmosphere (Washington and Parkinson, 1986). The individual parameters that contribute to the Earth-Atmosphere regime can be examined in isolation from all others and then re-examined as they vary in response to one or all parameters (McLaughlin, 1985). One parameter of particular interest in this study is the surface albedo.

Surface albedo is the shortwave reflectivity of a terrestrial surface (Oke, 1978), whereas planetary albedo is that fraction of solar radiation reflected by the entire earth and its atmosphere as viewed from space (Dickinson, 1983). Surface albedo varies spatially and temporally. As well, it depends on many factors including material composition, surface roughness, moisture content, and the wavelength and incidence angle of incoming solar radiation (Dickinson, 1983, Kukla and Robinson, 1980). Thus, surface albedo is a significant term in the radiation and surface energy balances.

The net radiation balance is the algebraic sum of net shortwave and net longwave radiation exchange (Oke, 1978). It can be written as follows:

$$Q^* = K\ (1-\alpha) + L\downarrow - L\uparrow \qquad (1)$$

where Q^* is the net all-wave radiation,
K is the shortwave input to surface (both direct and diffuse),
α is the surface albedo,
$L\downarrow$ is the incoming longwave radiation emitted by atmosphere, and
$L\uparrow$ is the longwave emitted by the surface.
(Oke, 1978, pg.22)

According to Oke (1978), the earth experiences a 29% annual radiant energy surplus while the atmosphere has an annual radiant energy deficit of approximately the same amount. Due to the different physical and thermal properties of Earth and its atmosphere, the surplus and deficit energies cause an imbalance in the system. The processes of conduction and convection are initiated causing the transfer of Earth's surplus into the atmosphere to attain thermal equilibrium (Oke, 1978).

The net all-wave radiation flux is the basic input to the surface energy balance. The surface energy balance represents the combination of convective exchanges to and from the atmosphere (Oke, 1978). It can be written as follows:

$$Q^* = Q_H + Q_E + Q_G \qquad (2)$$

where Q^* is the net all-wave radiation,
Q_H is the upward transfer of sensible heat,
Q_E is the latent heat (of vapourization) transfer, and
Q_G is the conduction to or from the underlying surface (Oke, 1978, pg.30).

Accurate surface albedo prescription is necessary to ensure that radiation and energy balances are met. Sensitivity experiments, which are a climate model's response to external or internal forcing, have shown models to be very sensitive to changes in surface albedo (Henderson-Sellers and Wilson, 1985). There are a limited number of albedo datasets for use in GCMs in the literature. Hummel and Reck (1979), for example, developed seasonally-averaged surface albedos for cells 10° in latitude by 10° by longitude. Kukla and Robinson (1980) developed zonal mean monthly surface albedos in 2° latitudinal belts as well.

There are a number of approaches used to develop surface albedo datasets. Recently, Wilson and Henderson-Sellers (1985) developed a soil and vegetation archive for use in climate models. Over 100 atlases and map books were used to construct the land cover dataset which considers 53 land cover classes. The main data source for the soils data was the FAO/UNESCO Soil Map of the World. Soils were classified by colour, texture, and drainage. McLaughlin (1985) added an archive of terrestrial hydrographic features. There were four main map sources used for its construction. They were Atlas Mira (1:250,000 series), International Map of the World (1:1,000,000 series), National Topographic System Maps of Canada (1:50,000 and 1:250,000 series) and the Times Atlas of the World (1:5,000,000 plates). The terrestrial hydrographic dataset provided percentages of the following surface types; salt water, fresh water, swamp or marsh, salt flats, salt marshes, glacier ice, intermittent water, and dunes. Both databases have fine resolutions of 1° by 1° for the entire globe. They are important tools when used in combination with one another to generate model appropriate surface albedos and to derive land cover information for model hydrology.

McLaughlin (personal communication) is constructing a global surface albedo dataset using the above and other databases as well as albedo values from the existing literature. A computer program was written to generate weighted grid cell albedos for all months of the year. The terrestrial water types of McLaughlin (1985) were weighted as recorded in the dataset while the primary and secondary vegetation types of Wilson and Henderson-Sellers (1885) were weighted as two thirds and one third respectively of the remainder and soil albedo considered in the absence of vegetation (McLaughlin, 1985). A simple example of how this works is as follows. Suppose there is 50% dense forest and 50% fresh water in a grid cell. The albedo for a dense forest in May is 12.3% and for fresh water it is 8.0%. The weighting takes 50% of each albedo value and adds them together because each land surface type covers up 50% of a particular box. The new albedo for the box would then be [(0.5)*(0.08) + (0.5)*(.123)] = 0.1015 = 10.15%. It may differ for each month because albedo is latitude dependent. If secondary vegetation is involved, primary vegetation is assigned to two-thirds of the remainder after the hydrographic features are taken into consideration and secondary vegetation is assigned one-third of the remainder. When soils are not covered by vegetation, they are considered in the derivation. This dataset provides the background albedo (i.e. the snow free land albedo) for all months of the year. Background albedos are the most useful format to have because snow is often a prognostic variable (a model generates its own snow). The relevant surface albedos for this study will be taken from that database.

Albedo values vary seasonally. The presence of snow in the mid to high latitudes influences surface albedo. The angular and spectral distribution of incoming radiation as well as type and density of the vegetation, surface roughness, and variable depth of snow cover account for a large range of albedos for snow-covered lands (Kukla and Robinson, 1980). For example, tundra, deeply-plowed farmland, and rocky escarpments have lower surface albedos when snow-covered compared to flatlands with little or no vegetation.

An equation referenced in Henderson-Sellers and Wilson (1983), which is based on the work of Holloway and Manabe (1971), is a standard equation used in a number of some GCMs for calculating the albedo of snow and ice-covered surfaces. It is written as follows:

$$a = a(l) + [a(sw) - a(l)]d(sw)1/2 \qquad (3)$$

where a is the albedo,
$a(l)$ is the snow-free land albedo,
$a(sw)$ is the albedo of deep snow, and
$d(sw)$ is the water equivalent depth of snow
(Henderson-Sellers and Wilson, 1983, pg.1796)

Some models have a(sw) equal to 0.6 and others like the Canadian Climate Centre (CCC) GCM have a(sw) equal to 0.7 (McLaughlin, 1985). This treatment is simplistic, but seems valid. However, snow-masking depth as it relates to surface albedo can be significant for model climates and thus, will be the focus of this thesis.

Accurate surface albedo databases appear to be important when studying the climate with a GCM. For instance, Sud and Fennessy (1982) found that increasing surface albedo in the subtropics resulted in the cooling of the atmosphere. There is much room for improvement of existing albedo databases. As observationally and theoretically determined datasets improve qualitatively and spatially, GCMs will become even more powerful tools for the study of the climate system (Washington and Parkinson, 1986).

CHAPTER THREE

STUDY SITE

The area of particular interest in this study consisted of the provinces of British Columbia, Alberta, Saskatchewan, and part of Manitoba. More specifically, the area enclosed between 49^{0} and 58^{0} N and from 230^{0} to 264^{0} E was scrutinized (Figure 1). There were a few reasons for choosing this study area. First, as much data was collected as time allowed. Also, this was an area which was felt to represent major land surface types in Canada (Table 1). Accurate regional albedo values of these different land surface types are likely to be important in GCMs. Since there are specific areas in which the month of May records substantial snow covers as well as other areas where surfaces are bare by spring, the entire area demonstrated enough dichotomy to enable useful comparisons of the snow albedo. Specifically, the algorithm for the snow albedo which depends on the water equivalent being less than one centimetre should be important in such situations.

Figure 1 STUDY AREA

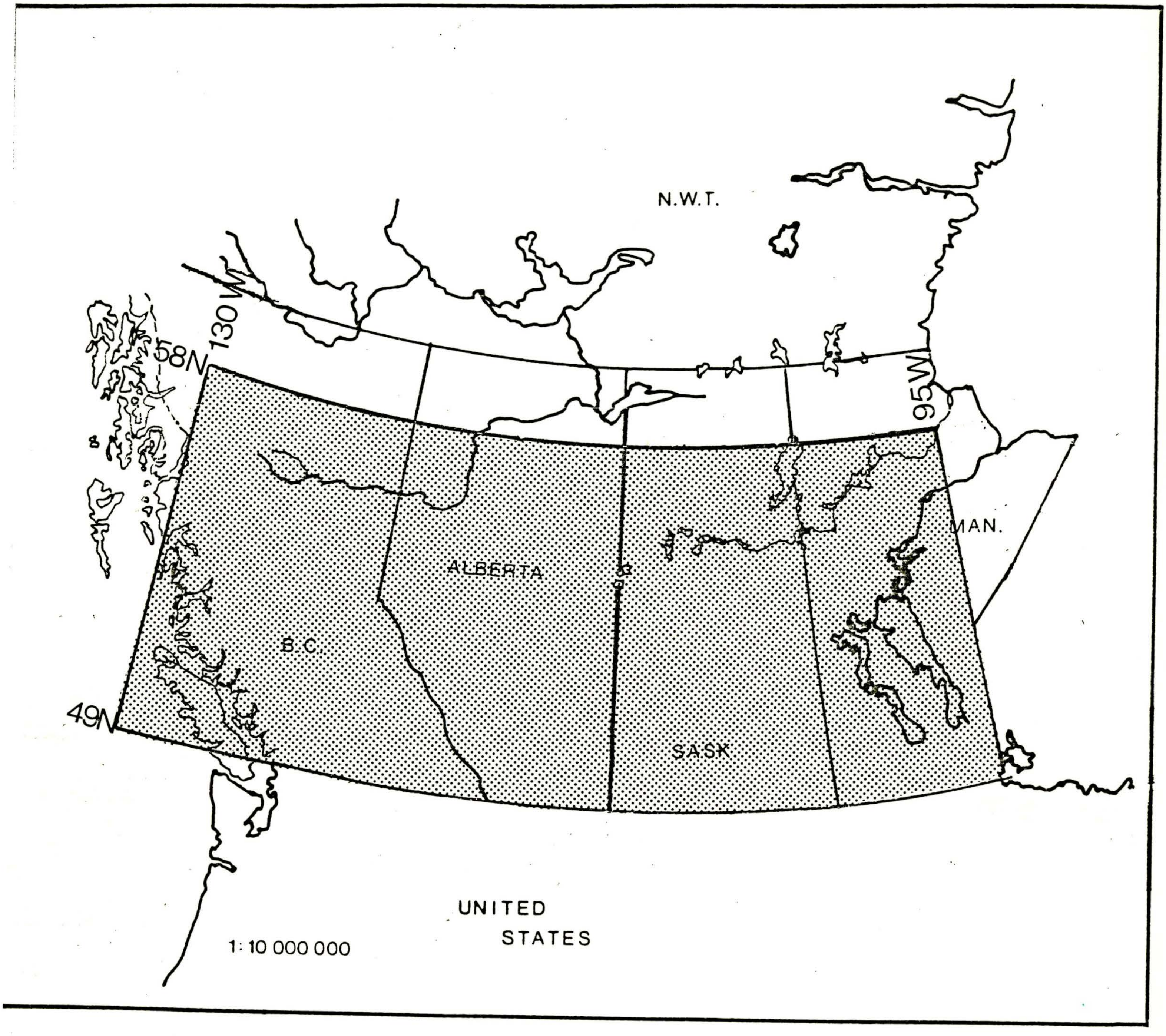


TABLE 1A

PRIMARY VEGETATION TYPES

LATITUDE										
O		58	57	56	55	54	53	52	51	50
N										
G	230	11	61	62	11	11	0	0	0	0
I	231	11	61	11	11	11	10	0	0	0
T	232	61	61	11	11	11	10	10	0	10
U	233	61	61	11	11	11	11	10	10	10
D	234	10	11	11	11	11	11	10	10	10
E	235	61	11	11	11	11	11	10	10	10
	236	10	11	11	11	11	11	11	35	10
	237	10	10	11	11	11	11	11	31	10
	238	10	10	10	11	11	11	11	31	31
	239	10	10	10	11	11	11	11	31	31
	240	10	10	10	10	10	10	11	11	11
	241	10	10	10	10	10	10	11	11	11
	242	10	10	10	10	10	13	11	11	10
	243	10	10	10	10	10	13	11	11	10
	244	10	10	10	11	10	13	11	31	10
	245	10	10	10	11	10	13	11	11	10
	246	11	10	10	11	40	40	40	40	40
	247	11	10	10	11	40	40	40	40	31
	248	11	10	11	11	11	40	40	40	30
	249	11	10	11	11	11	40	40	40	31
	250	11	11	10	11	11	40	40	40	31
	251	11	11	10	11	11	40	40	40	40
	252	11	11	11	11	11	40	40	40	40
	253	11	11	11	11	11	35	40	40	40
	254	11	11	11	11	11	35	40	40	40
	255	11	11	11	11	11	11	40	40	40
	256	11	11	11	11	11	11	40	40	40
	257	11	1	11	11	11	11	35	40	40
	258	11	11	11	11	11	11	11	40	40
	259	11	11	10	11	11	11	11	40	40
	260	10	10	10	10	10	10	10	35	40
	261	10	10	10	10	10	1	10	35	35
	262	11	10	10	11	10	10	1	11	35
	263	11	10	10	11	10	10	10	1	40
	264	11	10	11	11	10	10	10	10	10

TABLE 1B

KEY TO PRIMARY VEGETATIONS TYPES IN TABLE 1A

NUMBER	CODE
0	Open water
1	Inland water
10	Dense needleleaf evergreen forest
11	Open needleleaf evergreen woodland
13	Open mixed needleleaf and broadleaf, evergreen and deciduous woodland
30	Temperate meadow and permanent pasture
31	Temperate rough grazing
35	Pasture and tree
40	Arable cropland
61	Tundra
62	Dwarf shrub

CHAPTER FOUR

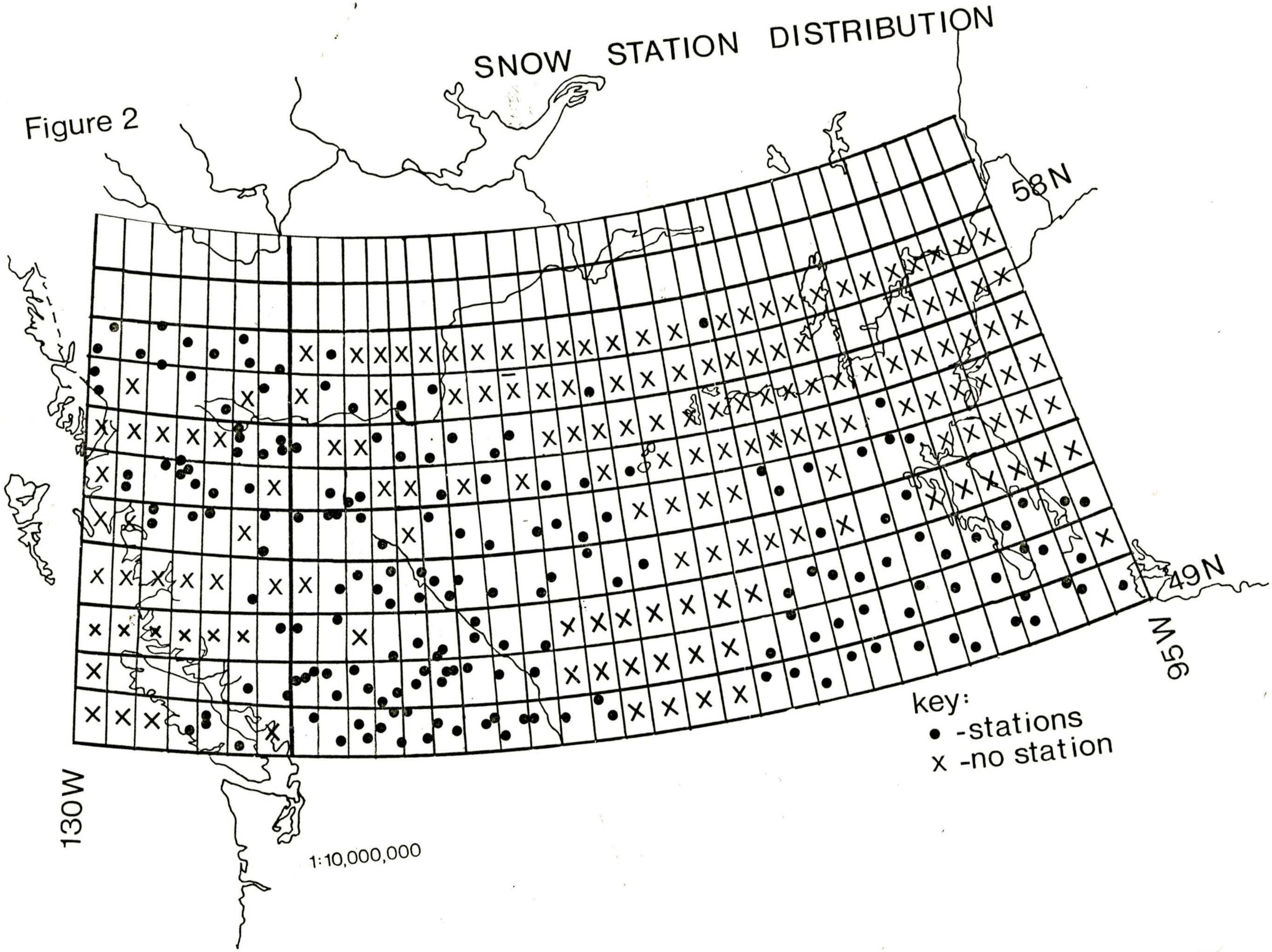
METHODOLOGY

4.1 Snow Cover Data

Data collection for this study involved obtaining snow cover depth and the water equivalent depth of the snow cover for various stations in the study area. Snow cover refers to a layer of snow on the ground surface. It is synonymous with the total accumulation of the snow lying on the ground or the total depth of all snow on the ground (Potter, 1965). The snow cover depth and water equivalent data were available from records published by Environment Canada. Some of the stations indicated records of over 40 years. However, the most years collected was 22 as data previous to that was unavailable at the time of data collection. As discussed earlier, the study site was split into the fine grid resolution of 1^o by 1^o (Figure 2). Some of these grid cells had more than 10 stations located in them while others had none. The snowfall records found in the Climatic Atlas of Canada published by Environment Canada (1984) were used to obtain data for those grid cells without stations in them. If, however, a cell had many stations, the ones with the most years of recorded data were used. Also, elevation was an important factor in deciding what stations to record. McKay (1968) pointed out that along a specific slope, elevation and snow cover are strongly related such that snow depth increases with height. In the mountainous terrain of British Columbia this factor is especially important. For example, Azure River and Blue River are two stations located in the same grid cell (52°N, 119°W). They differ by about 1000

Figure 2

SNOW STATION DISTRIBUTION



metres in elevation and experience a difference in snow depth of 200 cm. Thus as many stations per grid cell as were felt to provide a fair representation of snow cover depth were collected. In the Prairies only one station per grid cell was collected because the elevation was generally similar and snow cover depths did not differ very much.

4.2 Background Data

The snow cover data was collected in 1° by 1° grid cells because they were used in association with the soils and vegetation archive of Wilson and Henderson-Sellers (1985) and the terrestrial hydrographic dataset of McLaughlin (1985). The assumption was that the snow depth obtained from the stations in each grid cell would represent the snow depth and water equivalent depth of the entire box.

As was discussed in Chapter 2, snow and ice covered surfaces are calculated in some GCMs using the general equation based on the work of Holloway and Manabe (1971). The CCC GCM uses the former equation and then employs another equation to calculate the ground albedo. It is written as follows:

$$\alpha_G = \alpha_C(1 - \delta_C) + \alpha_S \delta_S$$

where α_G is ground albedo,
α_C is the minimum annual climatological value of ground albedo,
α_S is the albedo of a snow surface,
$(1 - \delta_C)$ is the measure of the fraction of the grid area uncovered by snow, and
δ_S is the measure of the grid area covered by snow
(McFarlane and Laprise, 1985, pg.39).

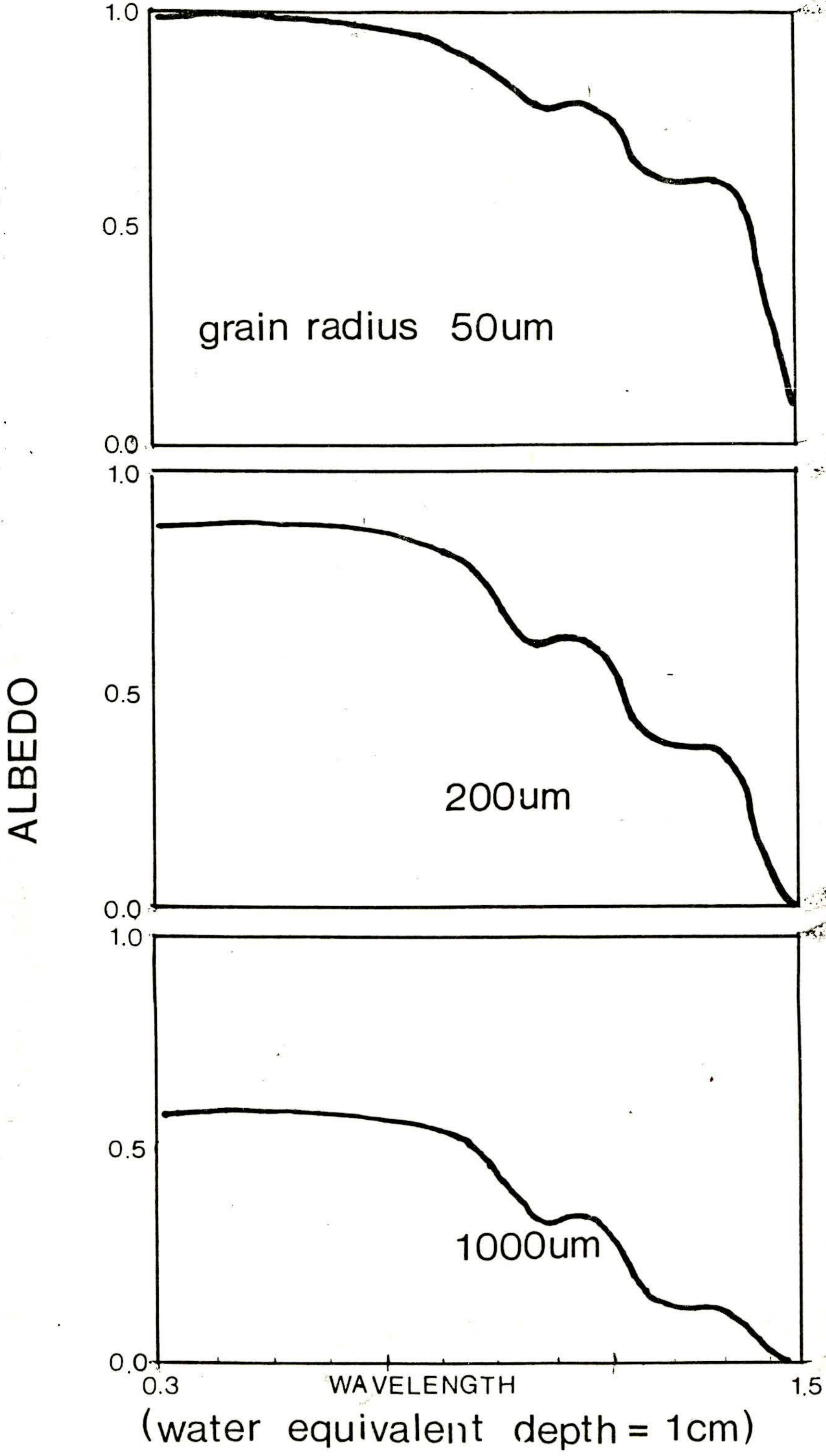
The albedo of a surface covered with deep snow is assigned a value of 0.70 (i.e. the CCC GCM assigns 0.70 as the maximum albedo value that a snow-covered surface may have). However, upon review of the literature, the maximum snow albedo in this study has been assigned a value of 0.80. Figure Three shows the snow albedo as a function of wavelength. Grain size generally increases with age and so the topmost graph represents the freshest snow while progressively older snow is depicted in the subsequent graphs (Wiscombe and Warren, 1980). It can be seen from the top two graphs that the snow albedo in the visible wavelengths (400 - 700 nm) averages around 0.80. Hummel and Reck (1979) state that the measured surface albedo of freshly fallen snow can be as high as 88% while older snow can have values of 75% or lower. Therefore, the choice of 80% for this study appears to be more realistic than the current CCC GCM convention of 70%.

In winter, the CCC GCM assumes that snow covers the entire study area, and the albedo value of all grid cells was given a value of 0.70. When using the equation discussed in Chapter Two, the water equivalent is always assigned a value of one so that the snow albedo equals 0.70. In this study, however, there were cases when the water equivalent was less than one and snow albedos were then functions of varying water equivalents. Thus the impetus for collecting the real time data was to test the validity of the standard algorithms used to calculate snow albedos.

A computer program (see Appendix 1) containing these algorithms was written for use in this study to calculate surface albedos for the months of January, March, and May for the study area. It operated similarly to the program explained earlier in

Figure 3

Snow Albedo as a Function of Wavelength



Chapter Two. That is, vegetation types as well as hydrographic features were considered in the calculation. However, water equivalent depths of snow were incorporated to calculate the snow surface albedos. The value of the albedo depended heavily on the surface type. For example, if the land cover information suggested a flat, cleared pasture for an entire grid square, total snow coverage of over 10 cm would be assumed causing the water equivalent depth to be 1.0 cm. Thus the snow albedo would equal 80%. A forest, however, was handled differently because complete snow cover can not be assumed. An estimate of snow cover actually seen by incoming solar radiation was needed. It was suggested that 20% snow cover contribution to total forest albedo would be reasonable (Lafleur, personal communication). Therefore a weighting of background albedo by per cent coverage and a weighting of snow albedo by per cent coverage was performed.

Of the 53 land cover classes constructed in the vegetation and soil data archive of Wilson and Henderson-Sellers (1985), only 12 are relevant for this study. They are found in Table 1A-1B. Snow albedos of 80% were assigned to the following surface types provided the water equivalent was greater than or equal to one; inland water, temperate meadow and permanent pasture, temperate rough grazing, arable crop land, maize, tundra, and dwarf shrub. If the water equivalent is less than 1 and greater than zero, equation 3 in Chapter Two was used to calculate a new albedo. The forested land surface types which included dense needleleaf evergreen forest, open needleleaf evergreen woodland, open mixed needleleaf and broadleaf (evergreen and deciduous woodland), and pasture and tree were always subject to the weighting procedure. Open water was assigned a latitude dependent value of 8%. If water equivalents were zero, the cell albedo assumed the background albedo.

Once the snow surface albedos were calculated for the three months, they were analyzed statistically with respect to the background albedos. A two sample, two-tailed t-test was used to determine whether the latitudinal albedo means were equal. The hypothesis tested was as follows:

H_o : $\mu_1 = \mu_2$ The snow albedo means are the same as the background albedos.
H_1 : $\mu_1 = \mu_2$ The snow albedo means are not the same as the background albedos.

Before a t-test can be performed, three assumptions must be met. First, the samples are selected randomly. Second, the populations from which the samples are selected are normally distributed and third, the variances are equal (Norcliffe, 1982). The t-test can be calculated in two ways, separately or pooled. When the variances are not equal (which was always the case in this study), the t-test is calculated separately. An F-test was used to determine if the variances were equal or not. The hypothesis tested here was as follows:

H_o : $\theta^2_1 = \theta^2_2$ The standard deviation of the snow albedo means is equal to the standard deviation of the background albedos
H_1 : $\theta^2_1 = \theta^2_2$ The standard deviation of the snow albedo means is not equal to the standard deviaton of the background albedos.

The value of F* was determined as follows:

$F^* = s^2_A/s^2_B$ where s_A is the larger of the standard deviations and s_B is the smaller.

This value was compared with a critical value of F. F* was always greater than the critical value and so the t-tests were done separately. The actual t-test was performed using MINITAB. The equation for the t-test is as follows:

$$t^* = (\bar{x}_1 - \bar{x}_2)/\sqrt{s_1^2/n_1 + s_2^2/n_2}$$

where x_1 is the mean of snow albedos
x_2 is the mean of background albedos
s_1 is the standard deviation of snow albedo
s_2 is the standard deviation of background albedo
n_1 is the number of snow albedos (35).
n_2 is the number of background albedos (35).

This value is compared with a critical value of t. If t* greater than t_{crit}, the null hypothesis can be rejected. That is the means differ (Norcliffe, 1982).

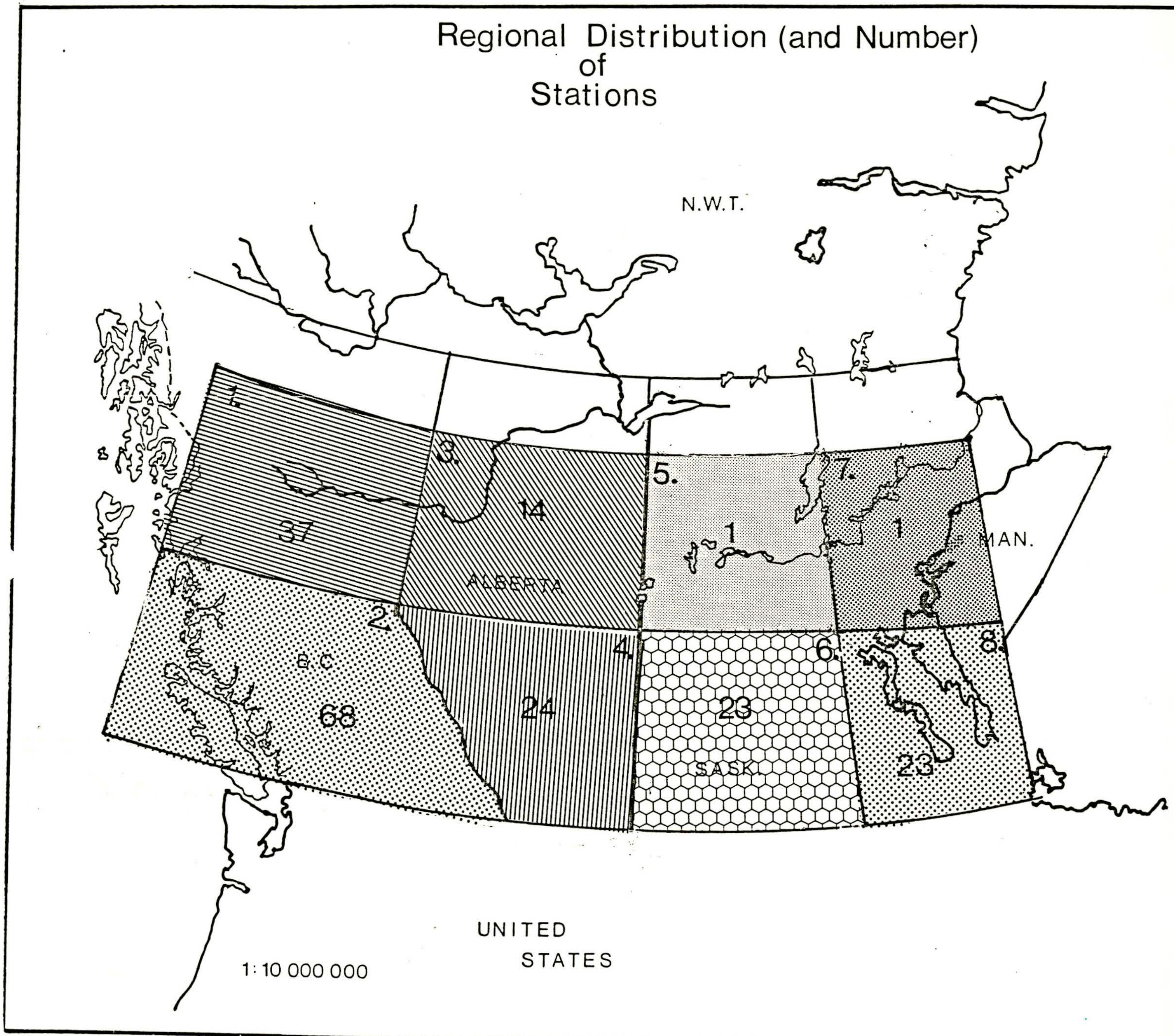
CHAPTER FIVE

RESULTS AND ANALYSIS

5.1 Snow Cover Data

Figure 2 shows the snow station distribution for the study area. Most of the stations were located in the province of British Columbia. Saskatchewan and Manitoba had few stations especially in the northern areas. This is illustrated in Figure 4 where study area is separated into eight regions. The provinces were split into a northern and southern region. All the southern regions have more stations than their northern counterpart. This is especially evident for Manitoba and Saskatchewan (only for both, one station was present in the northern region though there were 23 in the southern region). The northern regions did not have many as many stations because they are less populated and more isolated than the south. Southern British Columbia had the most stations followed by Northern British Columbia. Since British Columbia is a mountainous area and it is known that snow depth varies with elevation it was fortunate that more stations were available to collect data from. A better average of snow depth and water equivalent depth was likely obtained for measurements at different elevations rather than using a single station. Southern Saskatchewan and Manitoba did not have as many stations recorded as British Columbia but since they are relatively flat, snow depths would be more homogeneous than the mountainous terrain and fewer stations could provide reasonable data.

Figure 4

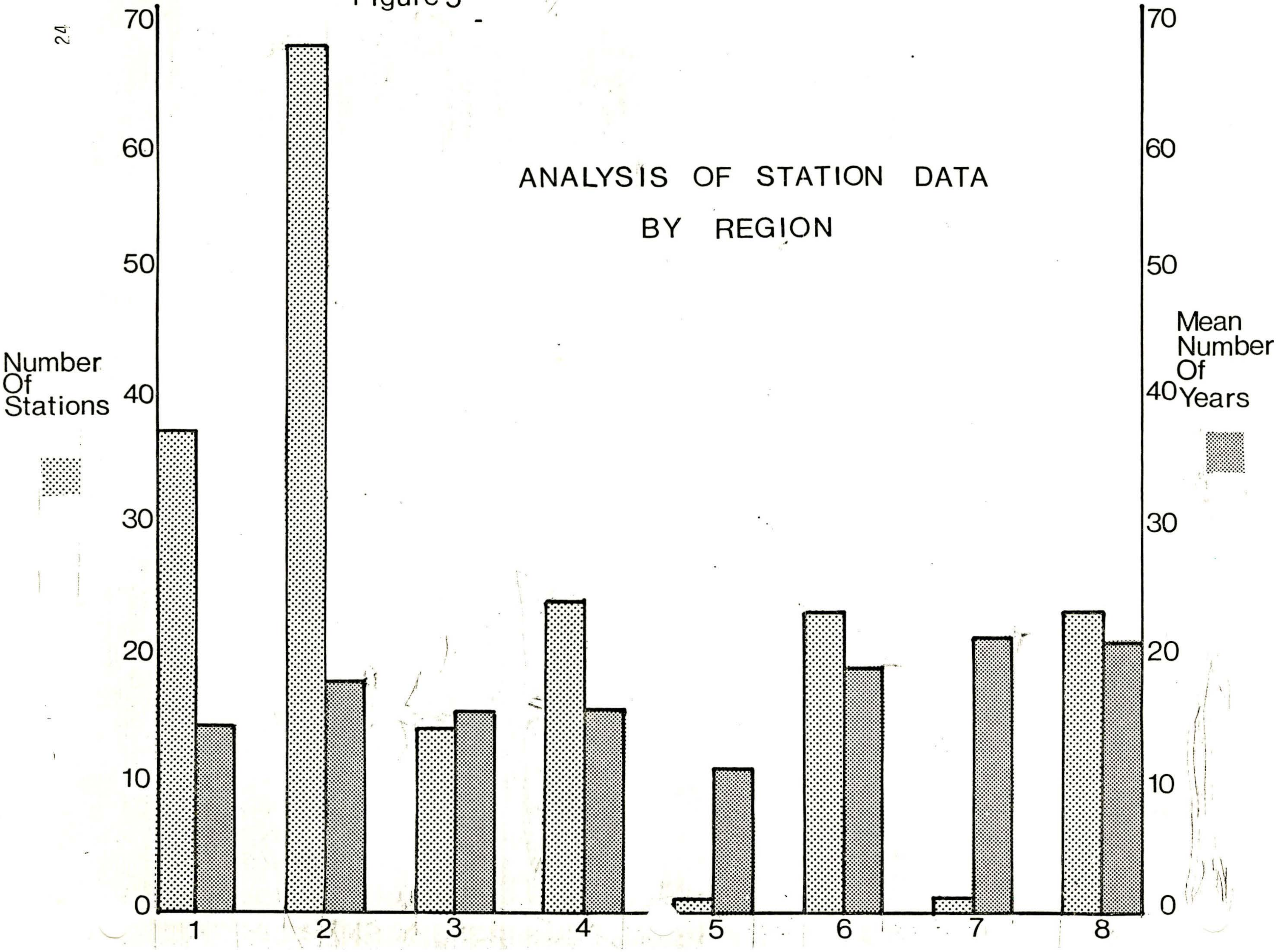


Regional Distribution (and Number) of Stations

1. Northern British Columbia
2. Southern British Columbia
3. Northern Alberta
4. Southern Alberta
5. Northern Saskatchewan
6. Southern Saskatchewan
7. Northern Manitoba
8. Southern Manitoba

Figure 5 displays the number of stations per region along with the mean number of years of collected data for this study. The northern and southern regions of Alberta and Manitoba showed relatively the same mean number of years of collected data. The southern regions of British Columbia and Saskatchewan had a greater number of mean years than their northern counterpart. Overall however, the southern regions of Saskatchewan and Manitoba showed the greatest mean number of years of collected data. Even though most stations had 21 years of available data some individual months such as January had very few measurements. March was the month with the most data for years available. If a station had 21 years of recorded data, March would have had 20 years available while January would have had less than 5 years. The Canadian Climatic Atlas (1984) was used as a supplement for those areas without station data. For the months of January and March all the areas had a snow cover of over 10 cm and a corresponding water equivalent of 1 cm. The water equivalent depths for January and March are found in Tables 2 and 3. Table 4 contains the water equivalent depths for the month of May. Many of the stations did not record data for May likely because there was no snow by that time of the year. The mountainous terrain of British Columbia recorded values of water equivalent greater than or equal to one centimetre. The Climatic Atlas of Canada (1984) was used again as a supplement for those are without stations. It should be noted that the month of May was the only month that water equivalent were less than one centimetre and that the snow albedo varied from 80% because of

Figure 5



ANALYSIS OF STATION DATA BY REGION

TABLE 2

WATER EQUIVALENT DEPTHS (cm) FOR JANUARY

LATITIUDE (N)

LONGITUDE (E)	58	57	56	55	54	53	52	51	50
230	23.6	28.2	1.0	1.0	1.0	9999	9999	9999	9999
231	26.2	1.0	1.0	12.3	1.0	1.0	9999	9999	9999
232	20.9	23.8	1.0	35.1	66.1	1.0	1.0	1.0	9999
233	26.9	16.5	1.0	15.0	31.3	1.0	1.0	1.0	85.0
234	16.6	6.7	1.0	9.5	11.3	1.0	1.0	1.0	58.6
235	20.3	1.0	26.8	13.4	1.0	5.2	76.0	1.0	86.3
236	9.4	32.3	27.4	1.0	8.7	1.0	4.8	42.7	79.7
237	5.0	1.0	69.5	16.4	10.6	1.0	44.9	33.4	88.3
238	6.0	6.9	1.0	42.9	40.2	30.3	20.8	4.4	45.0
239	1.0	9.5	1.0	53.4	53.7	66.3	1.0	15.9	14.3
240	1.0	1.0	1.0	1.0	39.3	47.6	1.0	14.1	13.2
241	1.0	1.0	5.7	1.0	1.0	38.2	78.4	39.6	28.4
242	1.0	3.7	1.0	6.9	7.6	21.2	37.5	54.0	37.3
243	1.0	1.0	1.0	1.0	4.9	1.0	13.3	29.8	34.2
244	1.0	1.0	1.0	1.0	1.0	1.0	21.2	24.4	21.1
245	1.0	1.0	6.2	1.0	2.5	1.0	2.8	22.5	45.2
246	1.0	1.0	1.0	4.3	3.9	3.5	1.0	1.0	4.9
247	1.0	1.0	1.0	4.3	2.5	3.6	1.0	1.0	1.2
248	1.0	5.2	1.0	1.0	1.0	4.7	1.0	1.0	1.0
249	1.0	1.0	1.0	5.2	1.0	1.0	1.0	1.0	1.0
250	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
251	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
252	5.0	1.0	1.0	1.0	1.0	1.0	1.0	2.9	0.5
253	1.0	1.0	1.0	1.0	1.0	6.4	1.0	1.0	0.8
254	1.0	1.0	1.0	1.0	4.0	1.0	8.6	2.0	1.8
255	1.0	1.0	1.0	1.0	3.6	1.0	2.4	4.0	5.1
256	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	7.1
257	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.7	3.3
258	1.0	1.0	1.0	1.0	5.9	1.0	1.0	1.0	1.0
259	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
260	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
261	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	4.8
262	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	3.5
263	1.0	1.0	1.0	1.0	1.0	1.0	1.0	4.2	1.0
264	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

TABLE 3

WATER EQUVALENTS (cm) FOR MARCH

LATITUDE (N)

O		58	57	56	55	54	53	52	51	50
N										
G	230	37.0	39.8	1.0	1.0	1.0	9999	9999	9999	9999
I	231	41.1	1.0	1.0	19.9	1.0	1.0	1.0	9999	9999
T	232	34.9	33.7	1.0	54.0	105.0	1.0	1.0	1.0	9999
U	233	37.3	23.3	1.0	37.4	52.2	1.0	1.0	1.0	153.6
D	234	23.8	6.6	1.0	14.1	13.0	1.0	1.0	1.0	98.6
E	235	30.0	1.0	38.9	14.9	1.0	4.3	123.9	105.6	131.2
(E)	236	13.6	46.2	41.3	1.0	12.7	1.0	1.7	67.5	149.7
	237	8.2	1.0	101.85	23.6	13.4	1.0	66.8	54.9	130.0
	238	8.4	8.9	1.0	53.7	47.6	48.9	33.0	3.8	62.9
	239	1.0	12.0	1.0	29.1	56.9	89.0	1.0	18.8	20.3
	240	1.0	1.0	4.7	1.0	71.3	115.8	1.0	21.0	18.7
	241	1.0	7.2	8.0	1.0	1.0	57.7	114.9	56.8	42.6
	242	1.0	6.0	1.0	17.3	7.9	24.8	99.8	72.1	57.6
	243	1.0	1.0	6.6	1.0	8.0	6.4	28.0	43.5	47.5
	244	1.0	1.0	8.6	8.2	7.8	5.4	31.9	36.8	28.6
	245	1.0	1.0	10.5	1.0	3.8	1.0	1.7	35.5	70.4
	246	1.0	1.0	1.0	6.4	5.1	4.9	1.0	1.0	7.7
	247	1.0	1.0	1.0	8.4	6.6	2.7	1.0	1.0	1.1
	248	1.0	7.3	1.0	1.0	4.0	6.3	1.0	1.0	1.0
	249	1.0	1.0	1.0	7.2	1.0	3.4	1.0	1.0	1.0
	250	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	251	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	252	7.3	1.0	1.0	1.0	1.0	1.0	1.0	3.3	2.4
	253	1.0	1.0	1.0	1.0	1.0	8.3	1.0	1.0	2.6
	254	1.0	1.0	1.0	1.0	6.3	1.0	4.9	2.4	2.5
	255	1.0	1.0	1.0	1.0	5.3	4.5	35.1	67.6	38.8
	256	1.0	1.0	1.0	1.0	1.0	1.0	3.9	3.5	6.4
	257	1.0	1.0	1.0	1.0	6.9	8.1	8.9	5.5	3.5
	258	1.0	1.0	1.0	7.2	9.3	8.1	4.8	4.0	4.2
	259	1.0	1.0	1.0	1.0	7.9	1.0	7.8	4.2	3.5
	260	1.0	1.0	1.0	1.0	1.0	1.0	5.7	4.0	1.0
	261	1.0	1.0	1.0	1.0	1.0	1.0	5.9	5.6	5.5
	262	1.0	1.0	1.0	1.0	1.0	1.0	6.5	6.0	5.5
	263	1.0	1.0	1.0	1.0	1.0	1.0	7.4	6.8	7.4
	264	1.0	1.0	1.0	1.0	1.0	1.0	6.3	1.0	8.1

TABLE 4

WATER EQUIVALENT DEPTHS (cm) FOR MAY

	LATITUDE (N)								
LONGITUDE (E)	58	57	56	55	54	53	52	51	50
230	23.0	13.0	0.0	0.0	0.	9999	9999	9999	9999
231	30.4	0.3	0.3	0.0	0.0	0.0	0.0	9999	9999
232	25.8	49.5	0.3	47.0	90.3	0.0	0.0	0.0	9999
233	52.8	35.8	0.3	36.2	38.3	0.0	0.0	0.0	143.1
234	0.3	0.3	0.3	0.0	0.0	0.3	0.3	0.3	80.9
235	34.0	0.3	0.3	2.6	0.3	0.3	0.0	0.3	147.9
236	16.8	23.2	34.1	0.0	0.0	0.3	0.0	66.0	0.0
237	2.9	0.8	109.2	4.2	0.0	0.3	57.9	78.5	136.7
238	0.0	0.0	0.8	6.9	40.1	42.4	24.5	0.0	71.5
239	0.8	0.5	0.8	74.4	39.4	92.3	0.3	0.0	13.9
240	0.8	0.5	0.5	1.0	74.0	55.9	0.0	8.3	6.4
241	0.8	0.5	8.1	1.0	1.0	107.7	125.6	49.2	25.0
242	0.8	0.5	0.5	1.0	1.0	33.9	88.6	64.5	45.6
243	0.8	0.5	0.5	1.0	0.0	1.0	18.8	11.7	32.2
244	0.5	0.5	0.5	0.0	0.0	1.0	62.3	27.7	14.8
245	0.5	0.5	0.8	0.0	0.0	0.0	0.8	43.8	46.2
246	0.8	0.8	0.0	0.0	0.0	0.0	0.1	0.0	1.0
247	0.8	0.0	0.0	0.1	0.1	0.1	0.0	0.0	3.6
248	0.8	0.0	0.0	0.1	0.1	0.5	0.0	0.0	0.0
249	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.0
250	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
251	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
252	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0
253	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0
254	0.0	0.0	0.0	0.0	3.9	0.0	0.1	0.0	0.0
255	0.8	0.8	0.8	0.0	0.0	0.0	1.1	0.0	0.0
256	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
257	0.0	0.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
258	0.8	0.8	0.0	0.0	2.2	0.0	0.0	0.0	0.0
259	1.0	0.8	0.0	0.0	0.8	0.8	0.0	0.0	0.0
260	1.0	0.8	0.8	0.8	0.8	0.8	0.0	0.0	0.0
261	1.0	0.8	0.8	0.8	0.8	0.8	0.0	0.0	0.0
262	1.0	0.8	0.8	0.8	0.8	0.8	0.0	0.0	0.0
263	1.0	0.8	0.8	0.8	0.8	0.8	0.0	0.0	0.0
264	1.0	1.0	0.8	0.8	0.8	0.8	0.0	0.0	0.0

this. However, this change was not entirely due to the value of the water equivalent. Notice that the background albedo often changed on a monthly basis.

5.2 Albedo Values

The background albedo values for January, March and May, calculated by the method described in Chapter Two, are found in Tables 5 to 7. Using these values, as well as the water equivalent values in Tables 2 to 4, the snow surface albedos were calculated by the method described in Chapter Four. Results are found in Tables 8-10. All three months demonstrated higher albedos when snow covered the surface. Table 11 shows the results of statistical t-tests performed on the first two latitudinally-averaged rows (58° N and 57° N with all longitudes averaged). Only the two north most latitude bands were examined because during the month of May water equivalents equalled zero more often and this trend increased southward. To continue testing further south would have only evaluated the difference between two non-snow albedos. Before t-tests were performed, the variances tested not equal and so separate t-tests were utilized. All the t-tests indicated that the snow albedo means and the background albedos were significantly different.

The first two latitudes represented most of the values of water equivalent that were non-zero. Some were equal to one and others were in between. The results of all tests indicated that adding snow was statistically significant. That is, adding snow to a surface caused a significant change in the surface albedo

TABLE 5

JANUARY BACKGROUND ALBEDO(%)

LATITIUDE(N)

LONGITUDE(E)	58	57	56	55	54	53	52	51	50
230	17	18	18	14	14	25	-1	-1	-1
231	17	14	14	13	11	16	25	25	-1
232	17	14	14	13	11	11	14	16	17
233	17	13	12	13	14	11	19	13	14
234	15	13	12	16	14	10	24	15	10
235	14	12	13	14	13	10	15	17	13
236	15	12	14	13	16	15	18	23	13
237	11	15	13	13	15	15	18	11	13
238	11	11	13	13	12	16	18	18	13
239	11	13	13	13	13	15	18	20	18
240	10	10	11	11	12	15	13	14	13
241	10	11	13	11	11	16	16	14	12
242	10	14	10	11	12	19	19	12	10
243	10	10	11	11	13	15	20	13	10
244	10	10	14	11	13	13	18	11	11
245	10	12	12	13	16	15	15	13	11
246	10	10	14	16	17	17	15	16	20
247	10	10	13	16	17	17	16	18	16
248	11	12	13	16	17	16	17	18	16
249	11	13	13	16	17	16	16	18	18
250	13	11	13	17	17	15	16	23	18
251	12	13	15	16	17	15	15	21	18
252	13	14	13	14	15	15	15	15	18
253	15	13	12	14	20	15	15	15	16
254	14	14	13	14	20	15	15	15	16
255	14	14	13	14	14	15	15	15	15
256	14	14	13	14	13	15	15	15	15
257	17	16	13	13	13	15	15	15	15
258	15	15	14	14	12	14	17	16	15
259	14	13	14	13	17	17	17	17	16
260	12	11	10	11	14	15	18	16	16
261	13	13	11	11	23	18	17	19	16
262	12	11	13	12	15	23	16	18	15
263	12	13	13	13	11	10	14	17	15
264	10	11	11	14	12	12	11	12	12

TABLE 6

MARCH BACKGROUND ALBEDO (%)

LATITUDE (N)

LONGITUDE (E)	58	57	56	55	54	53	52	51	50
230	17	18	17	14	11	12	-1	-1	-1
231	17	14	14	13	10	11	12	12	-1
232	17	14	14	13	10	10	10	11	10
233	17	13	12	13	12	10	19	10	10
234	15	13	12	15	13	10	24	12	10
235	14	12	13	13	13	10	14	15	10
236	15	12	13	13	15	15	18	23	10
237	11	14	13	13	15	15	18	11	12
238	11	11	13	13	12	15	18	18	13
239	11	13	13	13	13	14	18	20	18
240	10	10	11	11	12	15	13	13	13
241	10	11	13	11	11	16	16	13	12
242	10	13	10	11	12	19	19	11	10
243	10	10	11	11	13	15	20	13	10
244	10	10	12	11	13	13	18	11	11
245	10	12	11	13	15	15	15	13	11
246	10	10	13	16	16	16	15	16	20
247	10	10	13	16	16	16	16	18	16
248	10	12	13	15	16	16	16	18	16
249	11	12	13	15	16	16	16	18	18
250	12	10	13	15	16	15	16	22	18
251	12	10	13	15	16	15	15	21	18
252	13	13	12	12	15	15	15	15	18
253	12	12	12	13	20	15	15	15	16
254	13	13	12	13	20	15	15	15	16
255	13	13	12	13	14	15	15	15	15
256	12	12	12	13	13	15	15	15	15
257	12	12	12	12	12	15	14	15	15
258	13	13	12	12	11	13	16	16	15
259	13	11	13	11	12	12	16	16	16
260	11	10	10	10	11	11	15	16	16
261	10	11	11	10	12	11	15	15	16
262	11	10	12	10	11	12	14	18	15
263	11	11	12	11	10	10	11	12	15
264	10	10	10	13	11	10	10	11	11

TABLE 7

BACKGROUND ALBEDO MAY(%)

LATITUDE(N)

O		58	57	56	55	54	53	52	51	50
N										
G	230	17	18	16	12	12	8	-1	-1	-1
I	231	17	14	14	12	12	11	8	8	-1
T	232	17	14	14	12	12	11	11	11	7
U	233	17	12	12	12	12	13	20	12	10
D	234	14	12	12	14	12	12	25	14	12
E	235	13	12	12	12	12	12	17	16	10
(E)	236	14	12	12	12	14	15	15	24	11
	237	12	14	12	12	15	15	17	14	13
	238	12	12	12	12	12	14	17	17	12
	239	12	15	12	12	12	13	17	20	17
	240	12	12	12	12	13	14	12	12	12
	241	12	12	14	12	12	15	15	12	12
	242	12	15	12	12	12	18	19	12	12
	243	11	11	12	12	12	15	19	14	12
	244	12	11	11	12	12	12	17	13	12
	245	11	13	11	14	13	13	15	15	12
	246	12	11	12	15	16	16	16	16	19
	247	12	11	12	15	17	17	17	19	17
	248	12	12	12	13	17	17	17	19	17
	249	12	12	12	13	17	17	17	19	18
	250	12	12	12	13	16	16	17	22	19
	251	12	12	11	13	16	16	16	21	19
	252	12	12	11	11	15	16	16	16	19
	253	11	12	12	11	16	16	16	16	17
	254	12	12	12	11	16	16	16	16	17
	255	12	12	12	12	13	16	15	16	16
	256	12	12	12	11	13	16	16	16	16
	257	10	11	12	12	11	13	16	16	16
	258	11	12	12	12	11	12	16	17	16
	259	12	12	12	11	11	11	16	16	17
	260	12	12	12	11	11	11	13	16	16
	261	11	12	12	11	9	10	13	12	16
	262	12	12	12	11	10	9	12	16	16
	263	12	11	12	12	11	11	11	12	15
	264	11	11	11	12	12	11	11	12	12

TABLE 8

SNOW ALBEODS FOR JANUARY(%)

LATITUDE LONGITUDE (E)	58	57	56	55	54	53	52	51	50
230	29.6	80.0	80.0	27.2	27.2	8.0	8.0	8.0	8.0
231	29.6	80.0	27.2	26.4	24.8	28.8	8.0	8.0	8.0
232	80.0	80.0	27.2	26.4	24.8	24.8	27.2	8.0	8.0
233	80.0	80.0	25.6	26.4	27.2	24.8	31.2	26.4	27.2
234	28.0	26.4	25.6	28.8	27.2	24.0	35.2	28.0	24.0
235	80.0	25.6	26.4	27.2	26.4	24.0	28.0	29.6	26.4
236	28.0	25.6	27.2	26.4	28.8	28.0	30.4	34.4	26.4
237	24.8	28.0	26.4	26.4	28.0	28.0	30.4	80.0	26.4
238	24.8	24.8	26.4	26.4	25.6	28.8	30.4	80.0	80.0
239	24.8	26.4	26.4	26.4	26.4	28.0	30.4	80.0	80.0
240	24.0	24.0	24.8	24.8	25.6	28.0	26.4	27.2	26.4
241	24.0	24.8	26.4	24.8	24.8	28.8	28.8	27.2	25.6
242	24.0	27.2	24.0	24.8	25.6	31.2	31.2	25.6	24.0
243	24.0	24.0	24.8	24.8	26.4	28.0	32.0	26.4	24.0
244	24.0	24.0	27.2	24.8	26.4	26.4	30.4	80.0	24.8
245	24.0	25.6	25.6	26.4	28.8	28.0	28.0	26.4	24.8
246	24.0	24.0	27.2	28.8	80.0	80.0	80.0	80.0	80.0
247	24.0	24.0	26.4	28.8	80.0	80.0	80.0	80.0	80.0
248	24.8	25.6	26.4	28.8	29.6	80.0	80.0	80.0	80.0
249	24.8	26.4	26.4	28.8	29.6	80.0	80.0	80.0	80.0
250	26.4	24.8	26.4	29.6	29.6	80.0	80.0	80.0	80.0
251	25.6	26.4	28.0	28.8	29.6	80.0	80.0	80.0	80.0
252	26.4	27.2	26.4	27.2	28.0	80.0	80.0	80.0	80.0
253	28.0	26.4	25.6	27.2	32.0	28.0	80.0	80.0	71.8
254	27.2	27.2	26.4	27.2	32.0	28.0	80.0	80.0	80.0
255	27.2	27.2	26.4	27.2	27.2	28.0	80.0	80.0	80.0
256	27.2	27.2	26.4	27.2	26.4	28.0	80.0	80.0	80.0
257	29.6	80.0	26.4	26.4	26.4	28.0	28.0	80.0	80.0
258	28.0	28.0	27.2	27.2	25.6	27.2	29.6	80.0	80.0
259	27.2	26.4	27.2	26.4	29.6	29.6	29.6	80.0	80.0
260	25.6	24.8	24.0	24.8	27.2	28.0	30.4	28.8	80.0
261	26.4	26.4	24.8	24.8	34.4	80.0	29.6	31.2	28.8
262	25.6	24.8	26.4	25.6	28.0	34.4	80.0	30.4	28.0
263	25.6	26.4	26.4	26.4	24.8	24.0	27.2	80.0	80.0
264	24.0	24.8	24.8	27.2	25.6	25.6	24.8	25.6	25.6

TABLE 9

SNOW ALBEDOS FOR MARCH(9a)

LATITUDE(N) LONGITUDE(E)	58	57	56	55	54	53	52	51	50
230	29.6	80.0	80.0	27.2	24.8	8.0	8.0	8.0	8.0
231	29.6	80.0	27.2	26.4	24.0	24.8	8.0	8.0	8.0
232	80.0	80.0	27.2	26.4	24.0	24.0	24.0	8.0	24.0
233	80.0	80.0	25.6	26.4	25.6	24.0	31.2	24.0	24.0
234	28.0	26.4	25.6	28.0	26.4	24.0	35.2	25.6	24.0
235	80.0	25.6	26.4	26.4	26.4	24.0	27.2	28.0	24.0
236	28.0	25.6	26.4	26.4	28.0	28.0	30.4	34.4	24.0
237	24.8	27.2	26.4	26.4	28.0	28.0	30.4	80.0	25.6
238	24.8	24.8	26.4	26.4	25.6	28.0	30.4	80.0	80.0
239	24.8	26.4	26.4	26.4	26.4	27.2	30.4	80.0	80.0
240	24.0	24.0	24.8	24.8	25.6	28.0	26.4	26.4	26.4
241	24.0	24.8	26.4	24.8	24.8	28.8	28.8	26.4	25.6
242	24.0	26.4	24.0	24.8	25.6	31.2	31.2	24.8	24.0
243	24.0	24.0	24.8	24.8	26.4	28.0	32.0	26.4	24.0
244	24.0	24.0	25.6	24.8	26.4	26.4	30.4	80.0	24.8
245	24.0	25.6	24.8	26.4	28.0	28.0	28.0	26.4	24.8
246	24.0	24.0	26.4	28.8	80.0	80.0	80.0	80.0	80.0
247	24.0	24.0	26.4	28.8	80.0	80.0	80.0	80.0	80.0
248	24.0	25.6	26.4	28.0	28.8	80.0	80.0	80.0	80.0
249	24.8	25.6	26.4	28.0	28.8	80.0	80.0	80.0	80.0
250	25.6	24.0	26.4	28.0	28.8	80.0	80.0	80.0	80.0
251	25.6	24.0	26.4	28.0	28.8	80.0	80.0	80.0	80.0
252	26.4	26.4	25.6	25.6	28.0	80.0	80.0	80.0	80.0
253	25.6	25.6	25.6	26.4	32.0	28.0	80.0	80.0	80.0
254	26.4	26.4	25.6	26.4	32.0	28.0	80.0	80.0	80.0
255	26.4	26.4	25.6	26.4	27.2	28.0	80.0	80.0	80.0
256	25.6	25.6	25.6	26.4	26.4	28.0	80.0	80.0	80.0
257	25.6	80.0	25.6	25.6	25.6	28.0	27.2	80.0	80.0
258	26.4	26.4	25.6	25.6	24.8	26.4	28.8	80.0	80.0
259	26.4	24.8	26.4	24.8	25.6	25.6	28.8	80.0	80.0
260	24.8	24.0	24.0	24.0	24.8	24.8	28.0	28.8	80.0
261	24.0	24.8	24.8	24.0	25.6	80.0	28.0	28.0	28.8
262	24.8	24.0	25.6	24.0	24.8	25.6	80.0	30.4	28.0
263	24.8	24.8	25.6	24.8	24.0	24.0	24.8	80.0	80.0
264	24.0	24.0	24.0	26.4	24.8	24.0	24.0	24.8	24.8

TABLE 10

SNOW ALBEDO FOR MAY(%)

LATITUDE(N)

LONGITUDE (E)	58	57	56	55	54	53	52	51	50
230	29.6	80.0	16.0	12.0	12.0	8.0	8.0	8.0	8.0
231	29.6	50.2	21.2	12.0	12.0	11.0	8.0	8.0	8.0
232	80.0	80.0	21.2	25.6	25.6	12.0	11.0	8.0	21.6
233	80.0	80.0	19.5	25.6	25.6	13.0	20.0	12.0	24.0
234	21.2	19.5	19.5	14.0	12.0	19.5	31.0	21.2	25.6
235	80.0	19.5	19.5	25.6	19.5	19.5	17.0	23.0	24.0
236	27.2	25.6	25.6	12.0	14.0	22.1	15.0	35.2	11.0
237	25.6	25.4	25.6	25.6	15.0	22.1	29.6	80.0	26.4
238	12.0	12.0	23.8	25.6	25.6	27.2	29.6	17.0	80.0
239	23.8	23.7	23.8	25.6	25.6	26.4	23.9	20.0	80.0
240	23.8	21.6	21.6	25.6	26.4	27.2	12.0	25.6	25.6
241	25.6	21.6	27.2	25.6	25.6	28.0	28.0	25.6	25.6
242	23.8	24.2	21.6	25.6	25.6	30.4	31.2	25.6	25.6
243	23.0	20.8	21.6	25.6	12.0	28.0	31.2	27.2	25.5
244	21.6	20.8	20.8	12.0	12.0	25.6	29.6	80.0	25.6
245	20.8	22.5	23.3	14.0	13.0	13.0	26.3	28.0	25.6
246	23.8	23.0	12.0	15.0	16.0	16.0	36.2	16.0	80.0
247	23.8	11.0	12.0	19.1	36.3	36.3	17.0	19.0	80.0
248	23.8	12.0	12.0	17.2	21.0	62.0	17.0	19.0	17.0
249	12.0	12.0	12.0	13.0	21.0	36.3	36.3	38.3	18.0
250	12.0	12.0	12.0	13.0	16.0	36.2	36.9	22.0	19.0
251	12.0	12.0	11.0	13.0	16.0	36.2	36.2	21.0	19.0
252	12.0	12.0	11.0	11.0	15.0	36.2	36.2	16.0	19.0
253	11.0	12.0	12.0	11.0	16.0	16.0	36.2	16.0	17.0
254	12.0	12.0	12.0	11.0	28.8	16.0	36.2	16.0	17.0
255	23.8	23.8	23.8	12.0	13.0	16.0	80.0	16.0	16.0
256	23.8	23.8	12.0	11.0	13.0	16.0	16.0	16.0	16.0
257	22.1	70.8	12.0	12.0	11.0	13.0	16.0	16.0	16.0
258	23.0	23.8	12.0	12.0	24.8	12.0	16.0	17.0	16.0
259	25.6	23.8	12.0	11.0	23.0	23.0	16.0	16.0	17.0
260	25.6	23.8	23.8	23.0	23.0	23.0	13.0	16.0	16.0
261	24.8	23.8	23.8	23.0	21.3	70.6	13.0	12.0	16.0
262	25.6	23.8	23.8	23.0	22.1	21.3	12.0	16.0	16.0
263	25.6	23.0	23.8	23.8	23.0	23.0	11.0	12.0	15.0
264	24.8	24.8	23.0	23.8	23.8	23.0	11.0	12.0	12.0

value, even in May. It should be noted that a test was not performed on the significance of the water equivalent being between zero and one because the background albedos varied between the months concerned. There were too few instances when the background albedo remained the same for the three months involved in this study for a test to be performed.

TABLE 11

RESULTS OF THE STATISTICAL TESTS

58 N LATITDE (ALL LONGITUDES)

JANUARY	Number	Mean	Standard deviation	F*	F_{crit}	t*	t_{crit}
snow albedo	35	30.61	15.44	39.73	1.68	6.75	2.03
backgroun albedo	35	12.77	2.45	$F^* > F_{crit}$		$t^* > t_{crit}$	
MARCH							
snow albedo	35	30.08	15.58	48.94	1.68	6.75	2.03
background albedo	35	12.11	2.23	$F^* > F_{crit}$		$t^* > t_{crit}$	
MAY							
snow albedo	35	26.68	17.42	93.13	1.68	4.79	2.03
background albedo	35	12.49	1.81	$F^* > F_{crit}$		$t^* > t_{crit}$	

57 N LATITUDE (ALL LONGITUDES)

JANUARY							
snow albedo	35	33.55	19.27	107.32	1.68	6.39	2.03
background albedo	35	12.66	1.86	$F^* > F_{crit}$		$t^* > t_{crit}$	
MARCH							
snow albedo	35	33.01	19.49	128.77	1.68	6.40	2.03
background albedo	35	11.86	1.72	$F^* > F_{crit}$		$t^* > t_{crit}$	
MAY							
snow albedo	35	33.5	19.80	190.3	1.68	4.42	2.03
background albedo	35	12.34	1.44	$F^* > F_{crit}$		$t^* > t_{crit}$	

CHAPTER SIX

DISCUSSION

Before discussing the albedo results, it is necessary to discuss the snow depth and water equivalent depths. More specifically, it is important to describe the accuracy of the data from the records themselves. Snow data measurements have been questioned by Goodison (1981) and Potter (1965) among others. The depth of freshly fallen snow is measured by a standard snow ruler at a number of representative points and the average of these is recorded to the nearest 0.2 cm. The water equivalent is generally obtained by dividing the snowfall amount by 10. Principle climate stations, as well as some ordinary stations, are equipped with Nipher Shielded Snow Gauges where the actual water equivalent of the snowfall is obtained by melting the contents of the gauge. This method is more accurate than the former since the depth of freshly fallen snow and its water equivalent can vary primarily as a function of temperature. Problems occur however, in obtaining compatible measurements either when using different methods of measurement at a single site or when using similar equipment at different sites with varying exposures (Goodison, 1981). Further, Potter (1965) recognized problems with snow cover measurements due to the fact that many of the principle observing stations are located at airports where it is difficult to obtain a representative series of measurements. Most airport sites are exposed rather than sheltered or forested consequently redistribution by wind leads to errors in measurement.

When dealing with a 1° by 1° grid cell the actual area involved is several thousand square kilometres. One or two stations with collected snow depth data per grid does not represent the snow depth of the entire area for reasons discussed above as well as the fact that the area is simply too large for one measurement to be representative even if the landscapes are similar. Most climate models have even larger grid resolutions. For example, the CCC GCM uses a grid resolution of 5.5° latitude by 5.6° longitude. Hummel and Reck (1979) developed a global surface albedo model in which albedos are given for elements 10 on a side. These larger cells increase the area involved immensely. Snow depth, as a result, would not be handled as rigorously as it was in this study which involved the collection of recorded data from stations in a 1° square cell. Also, many areas had poor representation of snow stations. The methodology is questionable because of the inadequate collection of snow data for many areas in the study.

The addition of snow has been shown to significantly change the albedo values. The depth of snow cover is an important influence on the snow albedo (Kukla and Robinson, 1980). Once the snow reaches a certain depth or accumulates a certain thickness, the effects of the underlying surface become negligible. This depth however is dependent on other factors such as age and grain size radius. For example, 20 cm of fluffy new snow with grain radius 50 um becomes semi-infinite at 2 cm while 50 cm of old melting snow with grain radius 1000 um becomes semi-infinite at 20 cm (Wiscombe and Warren, 1980). In composing a model for spectral albedo of snow, Wiscombe and Warren (1980) adjust for the grain size for deep snow and liquid equivalent depth for thin snow. Age and grain size radius are difficult measurements to obtain on both small and large scales and as a result many models do not account for such factors. For example, in this study 10 cm of snow cover was assumed to produce a semi-infinite cover for both January and March. Ten centimetres, however, does not seem likely to cover all natural surfaces to the point of becoming semi-infinite unless it is freshly fallen snow. Equation 3 in Chapter Two calculates a new albedo value if the water equivalent is between 0 and 1 cm because the snow surface is thin and the effects of the underlying surface come into play. Some surface albedos in May (Table 10) were calculated this way.

Snow albedo depends on factors other than those previously mentioned. Angular and spectral distribution of incoming radiation as well as type, density, and roughness of vegetation also influence the snow surface albedo. The influence of the zenith angle can be seen by the different monthly background albedos. However, there are very few albedo measurements of snow-covered forest in the literature to allow for comparisons to the values obtained in this study. Hummel and Reck (1979) have assigned a snow albedo 0.36 to 0.47 to coniferous forests with snow. In this study evergreen forests have an albedo of 0.25 to 0.30. However, these values may be lower because hydrographic features are taken into consideration. Mixed coniferous and deciduous forests have a winter albedo of 0.345 according to

Hummel and Reck (1979) while this study calculates a value of 0.28 to 0.32. Lack of other values, however, prevent further comparisons even though the above mentioned compare favourably.

In summary, it has been found that the records of snow depth data are suspected to be inaccurate due to the errors involved in measuring snow depth. Further, using one of two stations of recorded data per grid cell is not a representative depth of the entire cell. The presence of snow has been shown to be significant in changing the albedo values. Depth of snow strongly influences albedo, however, other factors need further study. Age and grain size are important influences, but they are difficult to obtain and unrealistic for GCMs at present. The albedos of snow covered forests obtained in this study seem to agree fairly well with those of Hummel and Reck (1979).

CHAPTER SEVEN

CONCLUSIONS

The purpose of this paper was to examine snow albedo values determined using real time snow depth and water equivalent depth data. The accuracy of data from snow records has been questioned by Goodison (1981) and Potter (1965). Errors in the measurements may have led to inaccurate snow depth records. Also, the assumption that the data from one or two stations per grid cell is representative of the entire grid cell may be invalid considering the large area involved and the possible errors from measurements themselves. However, for certain months of the year, such as January this assumption may be valid. This is especially true when equations such as the one in Chapter Two limit the effect of snow depth. Months in which snow depth is usually greater than 10 cm such as January (as evidenced by both the data collected from the stations as well as Climatic Atlas (1984)) ended up assuming an albedo equal to whatever was previously assigned except when weighting procedures were used (In this study snow albedo equals 80%). The general feeling was that in May, more careful depth measurements were needed because there are many areas with less than 10 cm of snow on the ground.

The depth of snow cover is an important influence on the snow albedo. If the snow cover becomes thick enough, the effects of the underlying surface become negligible. The actual depth in which this occurs depends on such factors as grain radius and age. Newer snow, which usually has a smaller grain radius, requires less depth to become semi-infinite than does older snow. It is stressed that age and grain radius data are difficult to obtain on both large and small scales and are usually ignored in most models. In this study, for example, snow depth was the only factor used in determining the snow albedos. The snow depth was given an arbitrary value of 10 cm in which the snow albedo would not change even if the snowpack became thicker. Age and grain radius were not taken into consideration and so the snow albedo results obtained in this study may not be accurate, but are likely more realistic than what most GCMs resolve. This is the perhaps one reason why climate models give model climates. Incomplete and/or hypothetical treatment of important factors lead to unrealistic results. On the other hand, some factors may very well be difficult, if not impossible, to obtain pertinent data about on a large scale. It is hoped that future works will see databases improve as a result of better observational data as well as more sophisticated theoretical techniques and global climate models will produce realistic climates.

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APPENDIX ONE

```
      PROGRAM ANNASNOW
C
C   COMPUTES SNOW-COVERED GROUND ALBEDOS
C
      INTEGER PVEG, P
      CHARACTER MONAME*5, ALBFILE*30, SNOWFILE*30, OUTFILE*30
      DIMENSION SNOWDEPTH(50:58,230:264), ALBEDO(50:58,230:264),
     +PVEG(50:58,230:264), CELL_ALBEDO(230:264)
C
C   FIRST, ASK THE USER WHAT MONTH TO RUN THIS FOR.
C
      WRITE(*,*) ' ENTER THE NAME OF THE MONTH TO RUN THIS FOR:'
      READ(*,'(A5)') MONAME
C
C   FIRST READ AND STORE THE SNOW DEPTH FILES, SINCE THEY'RE IN
C   A FUNNY FORMAT:  LONGITUDE INSTEAD OF LATITUDE.
C   (DISCARD THE FIRST LINE)
C
      SNOWFILE = 'SNOWDEPTH.'//MONAME
      OPEN(1, FILE = SNOWFILE, STATUS='OLD')
      READ(1,*)
      DO 10 LONGIT=230,264
        READ(1,5,END=99,ERR=89) (SNOWDEPTH(LATIT,LONGIT),
     +  LATIT=58,50,-1)
    5   FORMAT(4X,9F8.2)
   10 CONTINUE
      CLOSE(1)
C
C   NOW READ IN THE ALBEDO DATA AND PVEG CODES, WHICH ARE
C   STORED IN LINES OF LATITUDE.
C
      ALBFILE = 'ANNA_'//MONAME(1:3)//'.ALL'
      OPEN(2,FILE=ALBFILE,STATUS='OLD')
      OPEN(3,FILE='ANNA_PVEG.DAT',STATUS='OLD')
      DO 20 LATIT = 58,50,-1
        READ(2,25,ERR=89,END=99) (ALBEDO(LATIT,L),L=230,264)
        READ(3,35,ERR=89,END=99) (PVEG(LATIT,L),L=230,264)
   25   FORMAT(1X,35F3.0)
   35   FORMAT(35I2)
   20 CONTINUE
      CLOSE(2)
      CLOSE(3)
C
C   NOW THAT WE HAVE ALL THE DATA READ IN AND STORED, WE INVOKE
C   ANNA-MAY'S ALGORITHM IN A DO-LOOP, AND WRITE OUT THE DATA:
C
      OUTFILE = 'SNOW_ALBEDO.'//MONAME
      OPEN(4,FILE = OUTFILE, STATUS = 'NEW', RECL = 215)
      DO 50 LATIT = 58, 50, -1
        DO 60 LONGIT = 230, 264
          IF(SNOWDEPTH(LATIT,LONGIT).GE.1.0) THEN
            SNOWALBEDO = 80.
          ELSE
            SNOWALBEDO = ALBEDO(LATIT,LONGIT) + (80.0 - ALBEDO(LATIT,
     +               LONGIT)) * SQRT(SNOWDEPTH(LATIT,LONGIT))
          ENDIF
C
```

```
ANNASNOW

C  IF WE HAVE OCEAN WATER, ASSIGN ALBEDO = 8 PERCENT.
C
          P = PVEG(LATIT,LONGIT)
          IF(P.EQ.0) THEN
            CELL_ALBEDO(LONGIT) = 8.0
          ELSEIF(P.EQ.1.OR.P.EQ.30.OR.P.EQ.31.OR.P.EQ.40.OR.P.EQ.44
     +      .OR.P.EQ.61.OR.P.EQ.62) THEN
            CELL_ALBEDO(LONGIT) = SNOWALBEDO
          ELSE
            CELL_ALBEDO(LONGIT) = ALBEDO(LATIT,LONGIT) * 0.80 +
     +        SNOWALBEDO * 0.2
          ENDIF
 60     CONTINUE
      WRITE(4,45) LATIT, CELL_ALBEDO
 45   FORMAT(1X,I4,35F6.2)
 50   CONTINUE
      CLOSE(4)
      STOP ' SUCCESS, SUCCESS!! HOW SWEET IT IS!!'
 89   WRITE(*,*) ' ERRORS IN READING A DATA FILE'
      STOP ' UNSUCCESSFUL RUN'
 99   WRITE(*,*) ' END - OF FILE ENCOUNTERED ON INPUT'
      STOP ' UNSUCCESSFUL RUN'
      END
```

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NO BOT. TRIM