THE EFFECT OF SNOW COVER ON THE CLIMATE

Judah Cohen

Department of Geology, Columbia University, New York City, NY

ABSTRACT

Large scale snow cover anomalies are thought to cause significant changes in the diabatic heating of the earth's surface in such a way as to cause substantial local cooling in the surface temperatures. This theory was tested using the GISS 3-D GCM (General Circulation Model). The results of the GCM experiment showed that snow cover did not cause a significant local decrease in the surface temperature. In the surface energy budget, the absorbed shortwave radiation term was the only term which contributed to lower temperatures. With the exclusion of the latent heat sink of melting snow, all the remaining heating terms contribute to increasing the net heating over a snow covered surface. Only after the latent heat of melting snow is included in the overall heating does the energy balance at the surface become negative, with resulting temperatures only slightly cooler.

Introduction. Of all the varying surface conditions, snow cover experiences the largest fluctuations, both spatially and temporally. An isolated cyclonic event can increase the continental snow cover on the order of 1000 km. The most recognizable effect of snow cover is the change it forces on the radiation and/or energy budget of the lower atmosphere and the surface. Snow is also thought to play an indirect role in climatic fluctuations. It is theorized that since the diabatic heating of the atmosphere is a major forcing on the climate, snow can alter the dynamics of the atmosphere.

Snow is thought to influence local temperatures in several ways:
1) The high reflectivity of fresh snow can increase the surface albedo by 30-50% (see Table 1, taken from Sellers (1965)).
2) Wagner (1973) has suggested that because snow has a higher thermal emissivity than most other natural surfaces, it tends to increase the amount of infrared radiation lost.
3) Fresh snow acts as a thermal insulator because of its low thermal conductivity.
4) Melting snow is a sink for latent heat.

The purpose of this paper is to present the results of a more objective and comprehensive experiment on the effects of snow cover on the temperature and energy balance of the atmosphere near the surface.

Model Experiment. The experiment was carried out using the Goddard Institute for Space Studies (GISS) 3-D GCM (General Circulation Model). The horizontal resolution is of a medium grid, 8^0 by 10^0 (latitude by longitude), and there are nine layers in the vertical, with a top layer at 10 mb. The model was initiated using the initial atmospheric conditions of December 1977, and the model ran for the entirety of five years. The experiment for this paper was conducted for the month of March of each model year (March 1978, 1979, 1980, 1981, and 1982). Each individual March was run with the initial conditions as generated by the model, with the exception of snow cover. Each individual month of March was prescribed the same initial snow cover.

For each March two runs were made: 1) a maximum snow cover run, where on March 1, snow is present inside any grid box that has a snow cover frequency greater than one percent for the month of March (this run is labeled R984A, see Fig. 1); 2) the minimum snow cover run, where on March 1, snow is present only in those gridboxes that have a one hundred percent frequency of snow cover for the month of March (this run is labeled R984B, see Fig. 2). Data for the frequency of snow cover were obtained from the NOAA Atlas of Satellite-Derived Northern Hemispheric Snow Cover Frequency (Matson et al., (1986)).

Results. The initial results relevant to the discussion of the paper are illustrated in Figures 3-5. The differences between the two model runs in the five year monthly means for the month of March of the following quantities are presented: ground albedo, composite surface air temperature, and the composite net solar radiation at the surface.

Albedo. The values obtained for the differences in the ground albedo between the maximum snow cover run and the minimum snow cover run are presented in Fig. 3. Using the values obtained and assuming that the most important aspect of snow cover which affects local temperatures is its high albedo, a first order approximation for the temperature change due to an anomalous snow cover can be derived by using a zero dimensional energy balance i.e.,:

$$\Delta T = \frac{-\Delta \alpha S_0}{4 \sigma T_0{}^3}$$

where σ = Stefan-Boltzman constant
α = surface albedo
S_0= solar radiation incident on the surface

So for example, at 51°N latitude, using values of, $\Delta\alpha$ = 25%, S_0 = 114 W/m^2, and T_0 = 270°K, ΔT is approximately equal to minus 6°C. This value of ΔT should actually be a low estimate of the temperature change due to snow cover because only the albedo factor has been taken into account. Yet, looking at the temperature differences between the two runs, there is little difference in the surface air temperature between the two runs (see Fig. 4). All temperature differences are equal to or less than 3°C (within one standard deviation); the only exception being a small region in Central Asia, where the temperature difference reaches a value of two standard deviations.

The small temperature difference between the maximum and the minimum snow cover runs is even more surprising when looking at the the net solar radiation absorbed at the surface (Fig. 5). Values of ΔS_{abs} (difference in the absorbed short wave radiation at the ground) are on the order of -10-(-20) W/m^2. This is a large enough energy deficit to cause a temperature difference on the order of 10°C. A more comprehensive understanding of the whole energy budget is required in order to explain the lack of a temperature difference between the two model results.

Energy Balance. The energy balance of the first ground layer will be discussed rather than the energy balance of the atmosphere. The temperature differences between the first ground layer and the surface air temperatures are all within 1°C. Also the energy balance at the ground is straightforward and readily available from the computer diagnostics.

The energy balance of the first ground layer is:

$$\Delta E = SW - LW - SH - LH + DIF + PREC,$$

where ΔE = the net change in energy
SW = the net gain in short wave radiation

LW = the net loss in long wave radiation
SH = the net loss in energy due to sensible heat fluxes
LH = the net loss in energy due to latent heat fluxes
DIF = the net gain/loss of energy due to diffusion from the second ground layer
PREC = the gain or loss of energy due to the temperature difference between the ground and the falling precipitation.

The last two terms are not considered since they are small and equal for both runs.

Given that the temperature difference between the two model runs for any individual grid point is within one standard deviation, and the relatively small time scale of the GCM run, the significance of the results should be enhanced by averaging over many grid points. Therefore, it would be advantageous to discuss the energy balance for a whole latitude rather than just for a single grid point. A second reason for analyzing the energy balance for the whole latitude is that some of the terms in the energy budget are only available for the latitude as a whole. The latitude at which the rest of the paper will focus on is 51^{O}N. This latitude was chosen because due to the nature of the experiment, the largest differences in the snow cover are realized at 51^{O}N. It is assumed that the effects of snow cover will have their largest influence at 51^{O}N latitude because of two reasons: 1) the large difference in average snow depth at this latitude and 2) the large amount of land present at this latitude

Table 2 gives a list of the respective values for each energy term at 51^{O}N, for the two runs. Presented in Table 3, are the same energy terms at 59^{O}N, for comparison. Also listed (see Table 4), are the standard deviations for the energy terms of both latitudes. Since the numbers are qualitatively the same for both latitudes, there is no need to discuss the energy terms at 59^{O}N separately. However, they are shown to lend support to any conclusions made for 51^{O}N.

The difference in the energy terms between the two runs, when compared to the standard deviations, is significant i.e., greater than two standard deviations (with the exception of the emitted long wave radiation). Yet, the temperature difference at 51^{O}N is only on the order of one standard deviation, this is the same result that was obtained from looking at the individual grid points. However, by studying the energy terms, it is not the relatively small negative temperature difference between the maximum snow cover run and the minimum snow cover run that is most surprising, rather that there is any net cooling at all in the maximum snow cover run. The only energy term less in value in the maximum snow cover run than in minimum snow cover run is the shortwave radiation absorbed at the ground; contrary to the reasoning given at the beginning of the paper i.e., that snow cover increases the energy loss due to, outgoing longwave radiation, sensible heat flux and latent heat flux. Even more importantly, the energy difference between the two runs shows a net gain of energy at 51^{O}N for the maximum snow cover run! More on this result will be discussed later on in the paper.

Long Wave Radiation. The small net increase in outgoing long wave radiation in the minimum snow cover run, indicates that the high emissivity of snow is insignificant. Rather, the lower temperatures at the ground in the maximum snow cover run act to inhibit the amount of outgoing radiation emitted by the surface. Since temperature dominates the emitted long wave energy term, less energy is emitted in the snow cover case and not more.

Sensible and Latent Heat. The latitudinally averaged loss of energy due to the sensible and latent heat terms, increased from the maximum snow cover run to the minimum snow cover run, for all latitudes shown in Tables 2-3. For a more detailed examination of the sensible and latent heat terms, it is necessary to look at certain individual grid points. Two grid points were chosen:

1) i=70^{O}E (longitude), j=51^{O}N (latitude); geographically located in the Central Soviet

Union and 2) i=100°W, j=51°N; geographically located in the mid-west of Canada. These points were chosen beacause they are situated in continental regions. Such regions are far ocean influences which tend to dominate all other energy terms, and where the climate is dominated by high pressure, less cloud cover and light winds. In such regions snow cover is most likely to have the greatest impact on the energy balance.

The sensible and latent heat fluxes, from the ground into the surface layer, are computed in the model using a drag law parameterization (Deardoff 1967),

$$F_h = C_p \rho C_h V_s (T_g - T_s)$$
$$F_q = \beta \rho C_q V_s (q_g - q_s)$$

where F_h = the sensible heat flux from the ground to the surface air

F_q = the latent heat flux from the ground to the surface air

ρ = the density of air

C_p = specific heat of air

C_h = heat transfer coefficient

V_s = surface air wind (vector quantity)

T_g = ground temperature

T_s = surface air temperature

β = an efficiency factor

C_q = humidity transfer coefficient

q_g = water vapor mixing ratio of the ground

q_s = water vapor mixing ratio of the surface air layer

The transfer coefficients are computed using the Richardson number, Ri, and a drag coefficient, C_D. (For a more detailed discussion refer to Hansen et al., (1983)).

For non neutral stability,

$$C_h = 1.35 \left[\frac{(1 - d\,Ri_s)}{(1 - f\,Ri_s)} \right]^{1/2} C_D$$

where Ri_s = the bulk Richardson number for the surface layer i.e.,

$$Ri_s = \frac{z_s g (T_s - T_g)}{T_g V_s^2}$$

z_s = the height of the surface layer (prescribed equal to 30 m over land surfaces)

z_0 = the surface roughness

(d and f are coefficients for the transfer coefficients equation as a function of $\log_{10}(z_s/z_0)$, where z_0 is the surface roughness)

From the heat and humidity transfer equations one can show that the sensible and latent heat fluxes are dependent on the vertical temperature profile and the square of the magnitude of the surface wind speed. Little or no difference in the surface wind speeds between the model runs was found globally and at the individual grid points chosen there is exactly no change in the wind speed, averaged over the whole month. Therefore, the difference between the two runs in the sensible and latent heat flux terms must be only a function of the vertical temperature profile.

Figs. 6-7 are plots of the monthly averaged change in potential temperature between the ground and the surface layer and the difference between each successive layer, through the lowest four layers of the model. The vertical profile of the potential temperature is an indication of how stable the atmosphere is to convection. Fig. 6 shows the change in potential temperature for the central Soviet Union and Fig. 7 is for mid-western Canada. Each graph is for noon local time, a time at which the vertical structure of the atmosphere usually supports turbulence and convection.

All the graphs uniformly demonstrate that the vertical temperature profile slopes more negatively in the lowest layers of the atmosphere of the minimum snow cover run than in the atmosphere of the maximum snow cover run. The lower atmosphere in the minimum snow cover run becomes slightly more unstable during the most intensive heating of the day. The greater instability is further reflected in the Richardson number, as the temperature profile acquires a more negative slope the Richardson number achieves higher negative values. In turn, the drag coefficient, which is a function of the Richardson number and is always positive, becomes larger in value.

Fig. 8 demonstrates how the value of the drag coefficient increases greatly with decreasing values of the Richardson number. As the Richardson number approaches zero, small differences can result in large differences in the magnitude of the drag coefficient, which in turn increases the amount of energy flux away from the surface. Therefore, the lower Richardson numbers attained in the minimum snow cover run would allow for substantially more sensible and latent heat to be transported away from the surface than in the maximum snow cover run. This result is best demonstrated in the values of C_h, the heat transfer coefficient, which is directly proportional to the drag coefficient. Figs. 9-10 compare the hourly monthly averaged values of the heat transfer coefficient for the two runs during the morning and the afternoon, the time at which the Richardson number reaches its lowest values and consequently the heat transfer coefficient reaches its highest values. Both figures indicate that the heat transfer coefficient is consistently larger in the minmum snow cover run, at the times at which convection mostly occurs.

This is further verified in Tables 5-6 which list the individual energy terms for the two grid points (note that the precipitation heat flux is missing because it could not be determined from the computer diagnostics). The latent and sensible heat terms are significantly larger in the minimum snow cover run. These two terms are large enough to cancel the initial large energy difference between the two runs due to the large spread in solar radiation absorbed at the surface (72 W/m^2 as opposed to 98 W/m^2 for grid point $i=70^oE$, $j=51^oN$); so that at these grid points, the net heating is equal to or greater in the maximum snow cover run than in the minimum snow cover run. This is the same result obtained for the latitudinally averaged energy balance. Therefore, the conclusions presented for the energy balance at the two specified grid points are applicable to the latitude as a whole.

Heat Capacity. To determine the magnitude of ΔT produced by any differences in the net heating, it is necessary to know the heat capacity of the first ground layer. After the heat capacity is properly calculated, the latitudinally averaged change in temperature can be computed by dividing the latitudinally averaged change in energy by the latitudinally averaged heat capacity for the first ground layer. The total heat capacity of the first ground layer is,

Heat Capacity = heat capacity of dry earth + water (kg/m^2) × specific heat of water + (ice + snow (kg/m^2)) × specific heat of ice.

At 51^oN the numerical value of the heat capacity terms are:

heat capacity of dry earth = .10 × 1129950 joules/m^2 ^oC

water × specific heat of water = 5 × 4218 Joules/m^2 ^oC

(ice+snow) × specific heat of ice = (15 + 52) × 2106 Joules/m^2 ^oC

For $51^{\circ}N$, a 1 W/m^2 change, averaged over the entire month would result in a temperature increase of $9.7^{\circ}C$. Therefore at $51^{\circ}N$ latitude, the temperature in the maximum snow cover run should be on the order of $20^{\circ}C$ warmer than in the minimum snow cover run and not $0.7^{\circ}C$ colder, as given by the diagnostics.

In the energy balance computed by the model, the latent heat term does not include the latent heat of melting; therefore the net heating term does not include the loss of energy produced by any snow melted in a particular grid box (In the rest of the paper, whenever the term net heating will be discussed, it will exclude any heating due to snow melt). In the GCM, snow can only melt once the temperature of the ground reaches $0^{\circ}C$, and the temperature of the ground can not rise above freezing if any snow still exists. Therefore the net heating difference of +2.0 W/m^2 at $51^{\circ}N$, between the maximum snow cover run and the minimum snow cover run, would first melt any snow before raising the ground temperature, if the ground temperature were at $0^{\circ}C$. The energy required to melt m mass of snow is:

$$\Delta E = mL$$

m = mass of snow
L = latent heat of melting for water

One W/m^2 of heating applied over the entire month (= 2,678,400 Joules/m^2) would melt ~ 8 kg/m^2 of snow. So for example, during the month of March of 1979, the entire snow cover of 44 kg/m^2 at grid point $i=70^{\circ}E$, $j=51^{\circ}N$ disappeared. However, not all the snow melts in the model; a significant portion is evaporated directly from the frozen state. The energy of vaporization is included in the latent heat term discussed in the general energy equation for the first ground layer. If it is assumed that one fourth of the snow cover evaporates and three fourths melts then ~ 11 kg/m^2 of snow was evaporated and ~ 33 kg/m^2 was melted. To melt 33 kg/m^2 of snow requires 4-4.5 W/m^2 of energy. For the month of March 1979, grid point $i=70^{\circ}E$, $j=51^{\circ}N$ also showed a net heating gain of 3.5 W/m^2. Therefore, after the energy to melt snow is included into the ground's energy balance, the difference in the net heating between the maximum snow cover run and the minimum snow cover run is -0.5-(-1) W/m^2. An overall difference of 0.5-1 W/m^2 would then account for the $-6^{\circ}C$ difference in temperature between the two runs incurred during March.

Five Day Experimental Runs. In the last part of the experiment, three years were chosen in which model runs were conducted for every five days of the month of March (March 1978, 1979, 1980). The purpose of breaking down the month into every five days was to record the trend of the energy and temperature values during the course of the month.

The graph of the temperature difference, ΔT, between the maximium snow cover run and the minimum snow cover run, is presented in Fig. 11 for each individual year. Also shown is the three year average in Fig. 12. In all three years, the first few days are characterized by a quick drop in temperature, which is on the order of $1^{\circ}C$. After which, the temperature difference decreases through the second week (in March 1978 it even becomes positive). During the second half of the month a negative temperature difference is also recorded, but embedded in the trend are oscillations that appear to be randomly generated; and no set pattern can be determined. Before any explanation can be given to why the temperature trend behaves as it does throughout the month, the energy term differences must be explored since the temperature trend is a direct result of the sum of all the diabatic heating terms.

Fig. 13 is the plot of the energy term differences between the maximum snow cover run and the minimum snow cover run. Also included is the difference in snow melt between the two runs, converted into equivalent energy units. For all three years, the first two and one half weeks produced qualitatively the same result. By far, the two most dominating energy terms in the energy balance difference, are, the solar radiation term and the combined sensible and latent heat terms. Within the first few days, the maximum snow cover model run accrues a large solar radiation deficit. However, the maximum snow cover run also gains a large amount of energy through the sensible and latent heat terms. The gain from the sensible and latent heat terms is as large as the energy lost from the reflected solar radiation.

After the first half of the month, the difference in the solar radiation term, between the two runs, continues to be negative when it is summed over the entire period. During the same time period, the difference in the sensible and latent heat terms continue to record a net gain. And, as found in the temperature curves, oscillations are embedded in the energy term curves; a result of the synoptic forcings. At the beginning of the month, the snow is relatively fresh and deep so that any forcings due to the snow cover can easily manifest themselves in the energy trends, despite the synoptic situation. As the month progresses, the snow ages and melts. The forcings due to snow cover become weaker and more diluted so that increasingly throughout the month, the synoptic forcings become of greater importance in the trend of the energy terms.

The difference in the energy contribution from the long wave radiation and the snow melt is almost an order of magnitude smaller than the other energy terms. Again, for the first half of the month the contribution from these two terms is steady; i.e., the long wave radiation shows a slight gain of energy in the maximum snow cover run, and the snow melt term shows an energy deficit in the maximum snow cover run. This pattern continues throughout the second half of the month, however the signal is not as strong.

In Fig. 14 the difference in the net heating is plotted together with the difference in the snow melt term. The net heating difference term is a summation of the following terms: the solar radiation term, the long wave radiation term, the sensible heat term, the latent heat term and the precipitation heat term.

With the exception of some brief periods, the net heating difference between the maximum snow cover and the minimum snow cover run, in all three months, was positive. This is in contrast to what would be expected from the model results. True, the snow cover did cause a significant energy deficit at the surface due to the increased amount of solar radiation reflected away from the surface. However, the snow cover also resulted in the surface to gain an excess of energy even larger than the energy lost. This is mainly due to the inability of the surface to lose energy in the form of sensible and latent heat, energy that would have been lost had the snow cover not been present.

Discussion. Any comprehensive conclusions about the effects of snow cover on the surface temperature and the energy balance must include the influence of snow cover on all the diabatic heating terms, rather than focusing on just one of the terms. There seems to be a very definite cycle forced on the energy balance by the presence of snow cover. And similar to many other forcing mechanisms found in nature, there seems to be a negative feedback built into it. The energy terms can be divided into two groups depending on what role the different energy terms play within this negative feedback cycle. The criteria for which energy term gets classified into which group is based on the relationship between the individual energy term and the surface temperature. The first group of energy terms are directly influenced by the physical properties of snow cover, its high albedo and its large latent heat of melting. Both these properties of snow cover cause the absorbed solar radiation term and the snow melt term to contribute a negative gain of energy in the net heating. This effect of snow cover causes a significant cooling in the surface temperature. This first group of energy terms are labelled the "action" energy terms because they directly act on the surface temperature.

However, not all the modifications that occur to the energy balance are a result of the direct influence of snow cover due to its high albedo and snow melt. The second group of energy terms are indirectly affected by the snow cover. These terms are not altered so much by the physical properties of snow cover as they are by the impact of snow cover on the environment. This second group of energy terms are labelled the "reaction" energy terms because they react to the temperature change induced by the snow cover. This second group consists of the emitted long wave radiation, and the sensible and latent heat flux.

It is because of this second group of energy terms that the feedback cycle produced by the snow cover is a negative one. The atmosphere has its own properties by which it can react to temperature anomalies being forced upon it: the vertical transfer of energy and mass is dependent on the vertical temperature profile. The increased stability, caused by the cooling, quickly suppresses the flux of sensible and latent heat away from the surface. The gain in the net heating is large enough to reverse the negative heating trend occuring at the surface. In its stead, an overall positive heating term (not including snow melt) is produced the remainder of the time that the anomalous snow cover remains. So in the case of an anomalous snow cover, the anomaly will work to eventually extirpate itself rather than to perpetuate itself.

Three stages are proposed for this cycle based on which group of energy terms plays the dominant role the duration of that particular stage of the cycle. The beginning and the end of the cycle are determined by the sign of the slope of the net heating difference curve (this includes snow melt):
1) The "action" stage, Stage I, during which the difference in net heating slopes negatively with respect to time.
2) The "reaction" stage, Stage II when a reversal takes place in the heating trend and the difference in net heating slopes positively with respect to time.
3) The final stage, Stage III, whereupon the difference in net heating oscillates around zero, in a seemingly random and natural mode.
The nature of the three stages is such that if the derivative of the difference in the net heating were plotted versus time, the curve would resemble a negative sine curve.

The three stages could also be described by the temperature difference, ΔT. The temperature trend must respond in the same manner as does the net heating trend to the forcings occuring because of the snow cover. However, the response of the temperature difference to any reversals in the energy forcings lags by one time period, behind the response of the net heating. Therefore, it is felt that the three stages are best characterized by the trend in the net heating since it is the net heating that is ultimately driving the temperature trend.

The first stage is characterized by the net heating becoming increasingly negative. The difference in the net heating slopes negatively as a response to the cooling effects created by the presence of snow cover: the high albedo and the snow melt. With all the other energy terms responding more slowly to the presence of snow cover, a cooling trend commences.

It is the nature of this cooling trend, however, which causes Stage I to transform into Stage II within a relatively short period of time. The cooling is not uniform throughout the atmosphere, instead it is confined to a very shallow layer at the surface. Cooling the atmosphere only near the surface increases the stability of the atmosphere. The greater stability inhibits energy, in the form of sensible and latent heat, from being transported away from the surface. And to a lesser extent, the lower temperatures reduce the amount of long wave radiation emitted by the surface. As the cooling continues to increase, the surface becomes more ineffective at ridding itself of sensible heat, latent heat, and long wave radiation, especially causing a build up of sensible and latent heat near the surface. Shortly after, the net heating slopes positively and the cooling trend is reversed. Stage II is characterized by the net heating being forced in a positive direction back towards zero.

The third stage, which can be categorized as an energy stalemate, is simply a consequence of the snow melting and aging. As the snow ages and melts, its primary influence on the energy budget, its high albedo, begins to wane (refer back to Fig. 13). As less and less energy is being lost due to the reflection off the snow cover, also lost is the forcing that the snow cover has on the energy balance. As a further consequence, less and less energy is needed from the sensible and latent heat terms to counterbalance the cooling which resulted from the high albedo. Even though energy is still being lost through snow melt, it is generally less significant than the energy lost because of the high albedo of snow cover. The weaker the forcings produced by the snow cover, the more important do the randomly generated synoptic forcings become. Without any of the energy terms driving the net heating in any organized direction the difference in the net heating simply oscillates in a natural mode. The trend of the net heating for the month of March and how it is subdivided among the stages is presented in Fig. 15.

Conclusion. Accepted theory predicts that snow cover causes a significant cooling in the surface temperatures. Snow cover has been attributed with modifying the Earth's energy balance by lowering the shortwave radiation absorbed at the surface, increasing the longwave radiation emitted by the surface, decreasing the positive flux of sensible heat from the ground and increasing the magnitude of the latent heat term. All these factors combine to produce lower temperatures over snow covered surfaces as compared to non-snow covered surfaces. Therefore, in a given locality, a positive feedback will set up between positive anomalous snow cover and negative anomalous temperatures, i.e., one will reinforce the other.

The experiment, presented in this paper started with the intention of simply corrobarating with the accepted theory of how snow cover influences climate. Even though it was felt that the results of previous studies were correct and accurate, it was also felt that the experiments that produced those results were not objective enough nor were they comprehensive enough.

Most of the prior studies conducted on the effects of snow cover on the climate, have been empirical in nature. In these studies, it was assumed that snow cover was the independent variable and temperature was the dependent variable. However in fact, snow cover is also dependent on temperarure, and both snow cover and temperature are dependent on the circulation.

Some modelling work was also conducted. However, there seems to have been significant drawbacks with these experiments as well. And in the most sophisticated modelling experiment completed to date, no significant effects of snow cover on the climate were identified (refer to Walsh et al., (1986)).

The most important advantage of this experiment as compared to previous experiments is that it employed the full use of a three dimensional GCM and no limitations were applied. Two experimental model runs were made: one with an extensive snow cover and one with a sparse snow cover. The synoptic situations in both runs were identical, except for the modifications forced solely by the presence or absence of snow cover. In this way, the dependence of snow cover and temperatures on the general circulation was cancelled out by taking the difference between the two model runs.

The results of the GCM experiment did not confirm the aforementioned assumptions. When comparing the maximum snow covered model run to the minimum snow covered model run, of all the mentioned energy terms only the absorbed shortwave radiation term necessarily contributes to lower temperatures. In contrast to current theories, if melting snow is not included, all the remaining heating terms contribute to increasing the net heating over a snow covered surface. Only after the latent heat of melting snow is included in the overall heating, does the energy balance at the surface become negative.

Previous theoretical studies have clearly identified the "action" energy terms and their respective magnitude changes. The difference between the theory presented in this study and that of all its predecessors rests entirely with the idea that the atmosphere reacts in opposition to the cooling. The atmosphere balances anomalous energy forcings, produced by the "action" energy terms, with the "reaction" energy terms. These "reaction" energy terms are effective at cancelling any cooling caused by the "action" energy terms. It is due to these "reaction" energy terms that a positive feedback between above normal snow cover and below normal temperatures does not materialize.

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FIGURE LEGENDS

Fig. 1. The initial snow depth in Kg/m^2 on March 1, for all the model years (1978-1982) for the maximum snow cover run. The snow cover did not vary from year to year.

Fig. 2. Same as in Fig. 1 but for the minimum snow cover run.

Fig. 3. The five year monthly averaged ground albedo for the maximum snow cover run minus the five year monthly averaged ground albedo for the minimum snow cover run (From now on all differences are to be understood as the maximum snow cover run minus the minimu snow cover run). Notice that the largest differences are found in Central Asia.

Fig. 4. The difference in the five year monthly averaged surface air temperature. Negative contours are dashed and positive contours are solid. Again the largest differences exist in Central Asia.

Fig. 5. The difference in the five year monthly averaged absorbed solar radiation.

Fig. 6. Graph of the vertical temperature profile for a given grid point. This figure is the five year monthly averaged change in potential temperature at 8z GMT (noon) in degrees Kelvin for Western Siberia. Shown are the individual profiles for both the maximum snow cover run (solid line) and the minimum snow cover run (dashed line). Also shown are the tops of the ground, the surface layer and the first model layer.

Fig. 7. The five year monthly averaged vertical change in potential temperature as shown in Fig. 6 but for Central Canada at 19z GMT (noon).

Fig. 8. A graph of the Richardson Number plotted as a function of drag coefficient divided

by the neutral drag coefficient (when the Richardson Number is equal to zero). Four different values of the surface roughness, z_0, are shown (actually graphed as a function of the height of the surface layer divided by the surface roughness, z_s/z_0).

Fig. 9. Graph of the five year monthly averaged hourly values of the heat transfer coefficient C_h, whose dimensions are $Wm^{-2}K^{-1}$, (the values plotted are the actual values multiplied by 10,000), during the morning and afternoon for Western Siberia. Plotted are both the maximum snow cover run (solid line) and the minimum snow cover run (dashed line).

Fig. 10. Same as Fig. 9 but for Central Canada.

Fig. 11. The five day averaged temperature difference plotted over the course of the month of March. Three different years are shown, March 1978 (solid line), March 1979 (dashed line) and March 1980 (dotted line).

Fig. 12. Same as Fig. 11 but for the average of all three years.

Fig. 13. The latitudinally averaged, five day averaged differences of the following energy terms: the absorbed solar radiation (solid line), the emitted long wave radiation (dotted line), the combined sensible and latent heat (dashed line) and the snow melt converted into equivalent energy units (uneven dashed line), averaged for March 1978, 1979, and 1980 at 51^{o}N.

Fig. 14. The latitudinally averaged, five day averaged differences for the net heating term (solid line) and the snow melt term (dashed line) averaged for all three years at 51^{o}N. The net heating term is the summation of the absorbed solar radiation, emitted long wave radiation, the sensible heat flux, the latent heat flux and the precipitation heat flux.

Fig. 15. The three year averaged, five day averaged net heating·difference term during the month of March for 51^{o}N. The curve is divided into three sections to illustrate how the three stages proposed in the text, are divided up, along the net heating difference curve. The first line demarcates the end of the first stage, the second line demarcates the end of the second stage and the remainder of the month is the third stage.

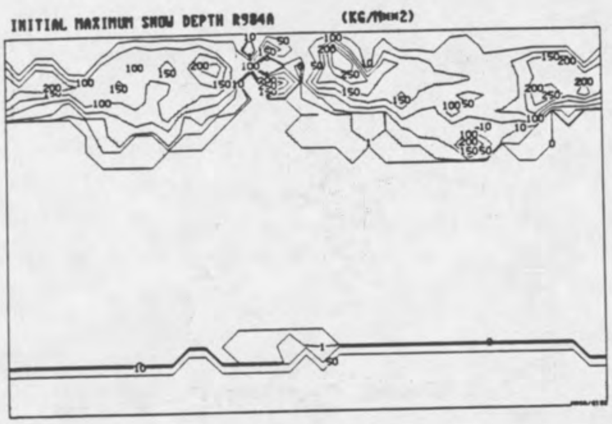


Fig. 1

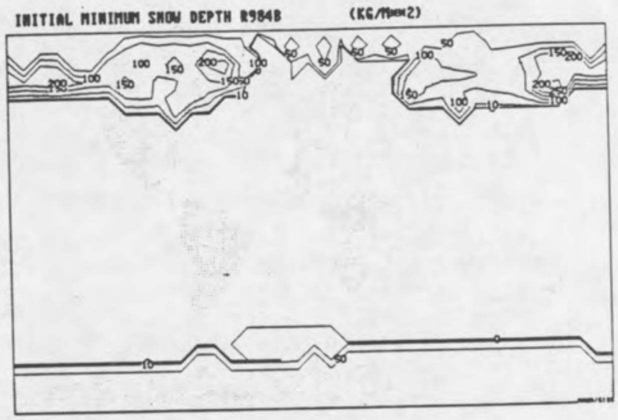


Fig. 2

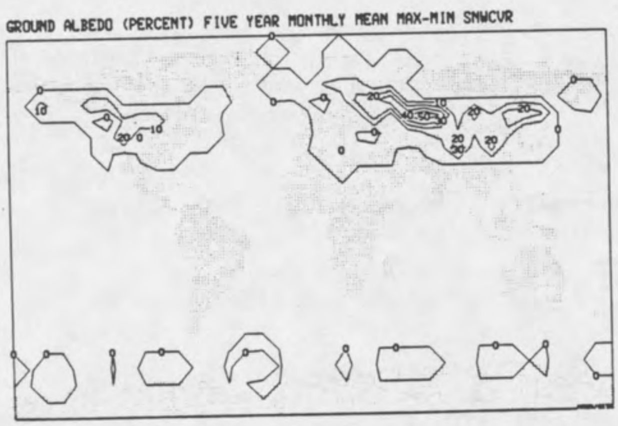


Fig. 3

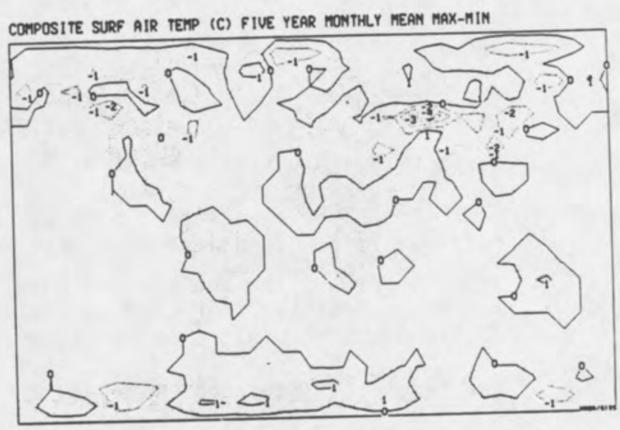
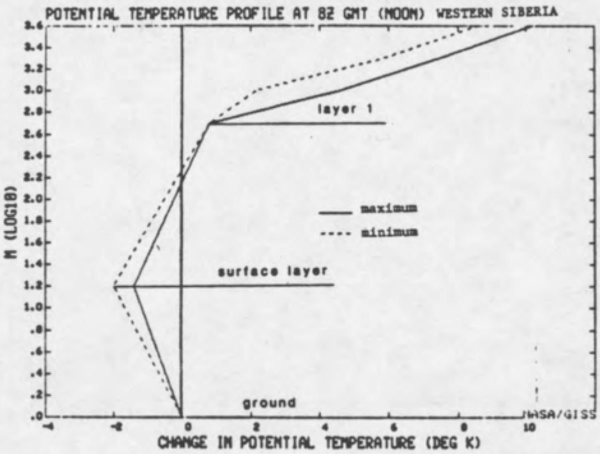


Fig. 4

Fig. 5



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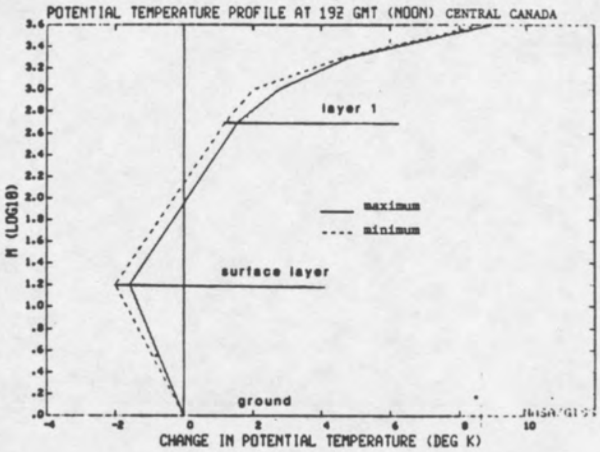


Fig. 7

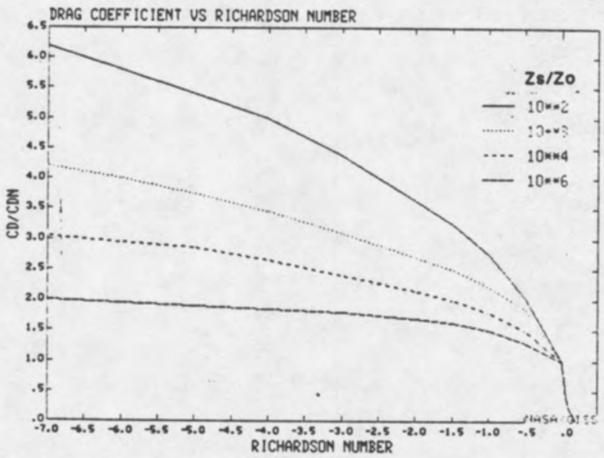


Fig. 8

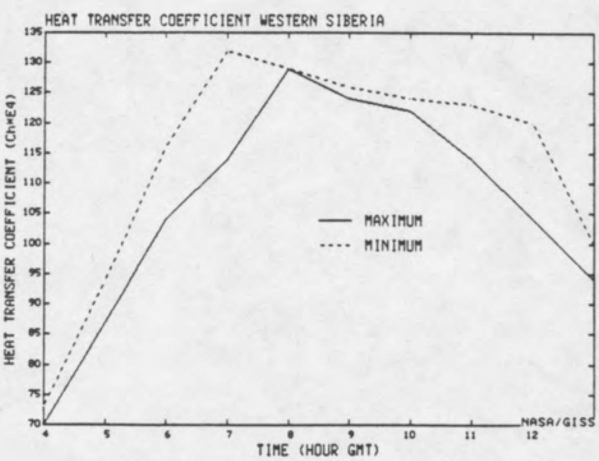


Fig. 9

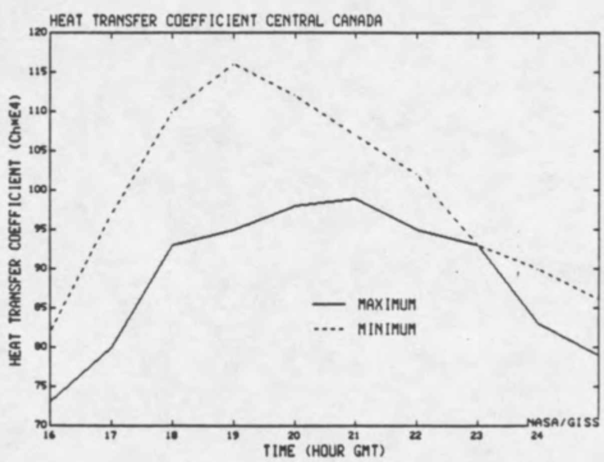


Fig. 10

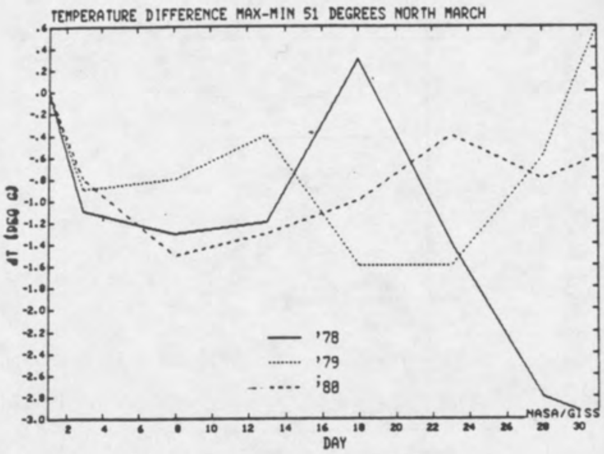


Fig. 11

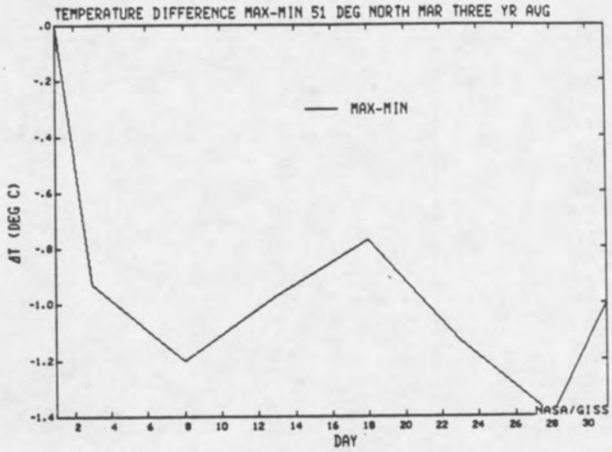


Fig. 12

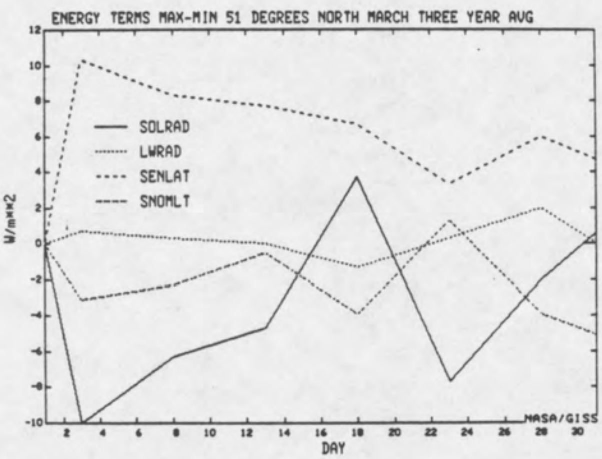
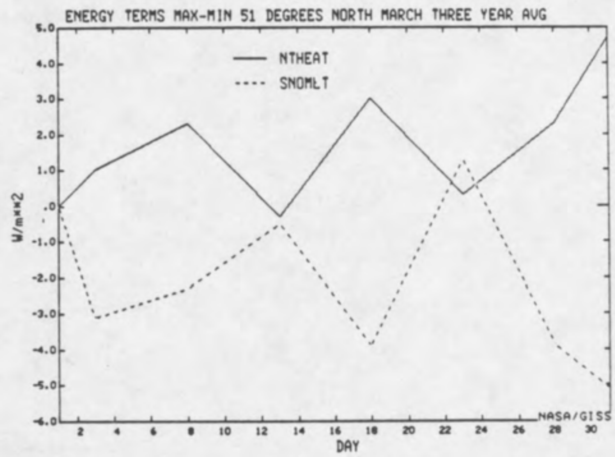


Fig. 13



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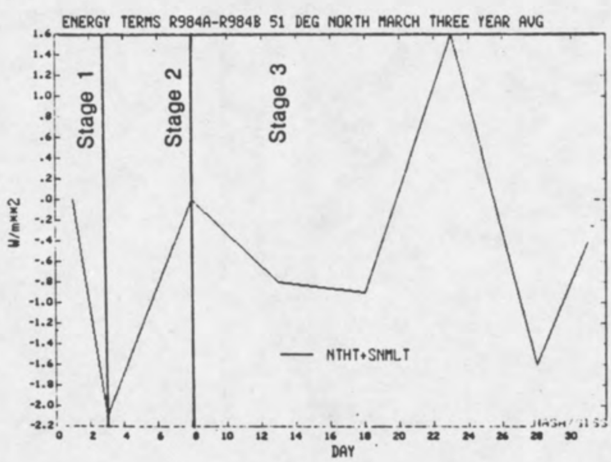

Fig. 15

Table 1.

ALBEDOS FOR THE SHORTWAVE PORTION OF THE ELECTROMAGNETIC SPECTRUM
(Wavelengths < 4.0μ)

A. Water Surfaces		*C. Natural Surfaces (cont.)*	
Winter— 0° latitude	6	Forest, coniferous	5–15
30° latitude	9	Tundra	15–20
60° latitude	21	Crops	15–25
Summer— 0° latitude	6		
30° latitude	6	*D. Cloud Overcast*	
60° latitude	7	Cumuliform	70–90
		Stratus (500–1,000′ thick)	59–84
B. Bare Areas and Soils		Altostratus	39–59
Snow, fresh fallen	75–95	Cirrostratus	44–50
Snow, several days old	40–70		
Ice, sea	30–40	*E. Planets*	
Sand dune, dry	35–45	Earth	34–42
Sand dune, wet	20–30	Moon	6.7
Soil, dark	5–15	Jupiter	73
Soil, moist gray	10–20	Mars	16
Soil, dry clay or gray	20–35	Mercury	5.6
Soil, dry light sand	25–45	Neptune	84
Concrete, dry	17–27	Pluto	14
Road, black top	5–10	Saturn	76
		Uranus	93
C. Natural Surfaces		Venus	76
Desert	25–30		
Savanna, dry season	25–30	*F. Human Skin*	
Savanna, wet season	15–20	Blond	43–45
Chaparral	15–20	Brunette	35
Meadows, green	10–20	Dark	16–22
Forest, deciduous	10–20		

Table 2.

ENERGY TERMS 51 DEGREES NORTH (W/M**2)

	MAXIMUM SNOWCOVER	MINIMUM SNOWCOVER
SHORT WAVE RADIATION	80	88
LONG WAVE RADIATION	-32	-33
SENSIBLE HEAT FLUX	-13	-17
LATENT HEAT FLUX	-28	-33
PRECIPITATION HEAT FLUX	-5	-4
NET HEATING	3	1
GROUND TEMP (DEG C)	-3.9	-3.2

Table 3.

ENERGY TERMS 59 DEGREES NORTH (W/M**2)

	MAXIMUM SNOWCOVER	MINIMUM SNOWCOVER
SHORT WAVE RADIATION	60	63
LONG WAVE RADIATION	-31	-32
SENSIBLE HEAT FLUX	-9	-11
LATENT HEAT FLUX	-14	-17
PRECIPITATION HEAT FLUX	-4	-5
NET HEATING	1	-1
GROUND TEMP (DEG C)	-8.7	-8.7

Table 4.

ENERGY TERMS STANDARD DEVIATIONS (W/M**2)

	59 DEG N	51 DEG N
S.W. RAD	2.6	2
L.W. RAD	1.8	1
S.H. FLUX	1.3	1.5
L.H. FLUX	0.5	0.7
PRC HEAT FLUX	0.4	0.2
NET HEATING	0.7	0.7
TG1 (DEG C)	1.04	0.71

Table 5.

ENERGY TERMS WESTERN SIBERIA (W/M**2)

	MAXIMUM SNOWCOVER	MINIMUM SNOWCOVER
SHORT WAVE RADIATION	72	98
LONG WAVE RADIATION	-31	-39
SENSIBLE HEAT FLUX	-18	-29
LATENT HEAT FLUX	-19	-28
NET HEATING	3	2
GROUND TEMP (DEG C)	-8.8	-3.4

Table 6.

ENERGY TERMS CENTRAL CANADA (W/M**2)

	MAXIMUM SNOWCOVER	MINIMUM SNOWCOVER
SHORT WAVE RADIATION	75	87
LONG WAVE RADIATION	-26	-32
SENSIBLE HEAT FLUX	-13	-17
LATENT HEAT FLUX	-20	-30
NET HEATING	16	8
GROUND TEMP (DEG C)	-3	-2.4