Parameterization Experiment on the Effect of Temperature on Snow Albedo and Snow Depth

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Abstract

Dependence of snow albedo on temperature and its effect on surface temperature and snow depth has been investigated in this paper. A Global Circulation Model (PLASIM) has been simulated two times – once for a control run (without changing the dependence of snow albedo on temperature) and then for a modified run (with changes done in the dependence of snow albedo on temperature) on T21 grid resolution for a period of 20 years (1992-2011). Results reveal that the surface albedo, surface temperature and snow depth are all dependent upon each other. A negative incline in snow albedo is observed in the northern part of China where it goes below -0.04 in case of modified run. A positive incline of 0.04 and 0.04 - 0.05 has also been observed over the Himalayas and Tibetan plateau respectively for modified run. The modified run is colder than the control run (difference of -1.5 K) for the latitudes 60°N-90°N and North-west Canada. Snow depth has significantly changed in the Greenland where it has been increased to a limit of 0.6 meters in the southwest and decreased to 0.2 meters in the northeast for modified run.

Key Words: Snow albedo, Snow depth, Parameterization, PLASIM.

Introduction

It is well established observation that presence of snow cover shall decrease solar energy and hence the temperature at the planetary boundary layer, specifically due to high snow albedo impacts (Mote, 2008). Snow depth increase is largely expected to add up to the energy deficit. It has been demonstrated that regions with greater snow depths galvanizes the ground-atmosphere insulation, such that immediate sub-surface heat is retained over the regions (Yan and Gong, 2009). Regressing monthly mean temperature anomaly to average monthly snow depth has resulted in hypothesizing that almost 10 to 55 percent of the variance of monthly mean temperature anomaly could be explained in terms of the average monthly snow depth or its anomaly (Wagner, 1973).

Snow albedo feedback holds a major contribution in global warming scenarios where the strength of this feedback is strongly affected by clouds (Gorodetskaya et al., 2006). Potential deposition of aerosols has been shown to effect snow albedo changes (Lee and Liou, 2012). The study investigated snow albedo changes in Sierra Nevada Mountain ranges correlated with potential deposition of aerosols in boreal spring season using the data from Moderate Resolution Imaging Spectroradiometer (MODIS) for a ten year time period 2000-2009. Regression analysis showed that a 2.2 K rise in temperature resulted in a snow albedo decrease by 0.038 in the study area.

Empirical studies have been carried out using 40-years (1960-2000) NCEP-NCAR reanalysis datasets to determine the correlation between the snow depth and the depression of air temperature after modifying the impacts of temperature changes over the planetary boundary layer (Mote, 2008). The analysis of variance suggested that the snow cover has depressed maximum temperature on average of 1.2°C and minimum temperature on average of 1.1°C for snow depths greater than 0.01m overall. Ensemble simulations of Community Climate Model (CCM3) suggests that initial state of snow cover is of more importance than the initial state of remaining atmospheric variables in determining the climate system response since thermal effects are direct while dynamical effects are indirect on the atmospheric circulation (Marshall et al., 2001).

To project air temperature over the Northern Hemisphere (NH) landmass, snow albedo feedback (SAF) are required to restrict the snow and albedo parameterizations in General Circulation Models (GCMs) (Fernandes et al., 2009). The SAF pattern has a significant correlation with the snow cover component pattern over North America, Europe and Asia. There is an adequate linear correlation

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among the magnitude of hemispheric seasonal spring snow cover and boreal large-scale spring surface air temperature in CMIP5 models (Koenigk et al., 2014). This correlation also prolongs to the future and is independent of certain anthropogenic climate forcing scenario (Brutel-Vuilmet et al., 2013).

In this study, a GCM, Planet Simulator (PLASIM) has been used to analyze the dependence of snow albedo on temperature. The experiment has been conducted by increasing the original value of surface temperature from -263.16 K (-10°C) in the source code file of model i.e. landmod.f90 to a new higher value i.e.-272.16K (-1°C) for simulation for a period of 20 years i.e. 1992–2011 over the entire globe. Regionally, the temperature dependence of snow albedo dominates over the Arctic (Northern hemisphere polar region), whereas, in case of equatorial region, the snow albedo is on lower side.

Model and its physics

Planet Simulator (PLASIM)

The Planet Simulator is a Model of Intermediate Complexity (MIC), suitable for climate and paleoclimate simulations and time scales up to ten thousand years or more (see e.g., Fraedrich et al., 2005; Kirk et al., 2009). It runs on a wide range of hardware and operating systems including massive parallel cluster and workstations with UNIX, Solaris, Linux, MAC OS or any other UNIX style operating system. The priorities in development are set to speed, easy handling and portability. Its modular structure allows a problem dependent configuration. A graphical Model Starter (MoSt) can be used to select a model configuration from the repository, set its parameters, compile and run the model. The model can be run either in production mode for maximum performance or in interactive mode using a Graphical User Interface (GUI). This GUI is both a real time visualization interface for all model variables and a tool for tuning and experimenting with the model.

Model Physics

PLASIM grid cells are divided up into a forest-covered part and non-forest covered part. Non-forest cover is a mixture of prostrate vegetation (e.g. grass, non-shrubby tundra) and bare soil. The albedo of snow-free, non-forest cover is mixed in with that of deep snow as follows:

$$A_{NF} = A_{NF_{snow-free}} + (A_{snow} - A_{NF_{snow-free}})\frac{snowdepth}{snowdepth + 0.1}$$

Where, "NF" denotes non-forest cover, A_{snow} is the albedo of deep snow, and snow depth is in meters. The albedo of the snow-free non-forest cover is tacitly taken to equal the albedo of the entire grid under snow-free conditions.

Deep snow albedo, A_{snow} lowers with increasing surface temperature T_{sfc} as follows:

$$A_{snow} = \begin{cases} A_{snow_{max}} & if\ T_{sfc} \le -10°C \\ A_{snow_{min}} + (A_{snow_{max}} - A_{snow_{min}})\frac{T_{sfc}}{-10°C} & if -10°C < T_{sfc} < 0°C \\ A_{snow_{min}} & if\ T_{sfc} = 0°C \end{cases}$$

Forest cover is modelled to protrude from the snow pack and mask the snow beneath it. For simplicity, the forest-covered portion of the grid cell is assigned the same albedo, $A_{F_{snow}}$, regardless of surface temperature or the amount of snow accumulation. $A_{F_{snow}}$ is assigned a default value of 0.20 in the model. Earlier versions of PLASIM had $A_{F_{snow}}$ = 0.35. The lower value of 0.20 has been adopted for the reasons that it has been used in the ECHAM GCM for fully snow-covered evergreen forests.

Finally, the albedo "A" for the entire grid is taken to be the linear combination of the respective albedos for forest-covered (F) and non-forest-covered (NF) fractions:

$$A = A_{F_{snow}} * F + A_{NF} * (1 - F)$$

Methodology

PLASIM model was configured and run on spectral triangular 21 (T21), roughly equivalent to a 5.6 × 5.6 degree latitude/longitude grid. Due to computational limitations, the model has been set at low resolution. The number of run years was set as “20” years from 1992 to 2011. The simulation took several hours to complete control run. The years are fictitious when GCMs run with GCM boundary conditions. Passing of 1 year means earth has completed 1 revolution around the sun. The year e.g. 2015 does not mean actually the year 2015. In the past if the model is run with observed conditions like SSTs then we can expect the simulation of that year to be the observed year.

For execution of parameterization (see e.g. Pedersen et al., 2005), the original value of surface temperature i.e. 263.16 K (-10°C) in the model’s source code file i.e. landmod.f90 has been increased and modified as higher value i.e. 272.16K (-1°C) for simulation of a period of 20 years i.e. 1992–2011 over the entire globe. In this way the equation for deep snow albedo was modified as under:

$$A_{snow} = \begin{cases} A_{snow\,max} & if\ T_{sfc} \le -1°C \\ A_{snow\,min} + \left(A_{snow\,max} - A_{snow\,min}\right)\dfrac{T_{sfc}}{-1°C} & if\ -1°C < T_{sfc} < 0°C \\ A_{snow\,min} & if\ T_{sfc} = 0°C \end{cases}$$

This parameterization has been performed by making the modifications in the subroutines given in the source code file (Zhou et al., 2014). The dependence of snow albedo on forest cover was left unchanged.

After above parameterization, the simulation was again performed for the same period of 20 years i.e. 1992–2011 over the entire globe. The output data files from both the ‘Control Run’ (standard model run without any changes in the dependency of snow albedo upon temperature) and ‘Modified Run’ (with changes in the dependency of snow albedo upon temperature) were obtained at the completion of each long simulation. These output files were post-processed for all the relevant parameters to be analyzed - Surface Albedo (as), Surface Temperature (ts) and Snow Depth (snd). The NetCDF files of these parameters were displayed by using GrADS software.

Results and discussion

PLASIM has been used to analyze and compare different climate parameters over the entire globe. The analysis has been performed under the following two categories:

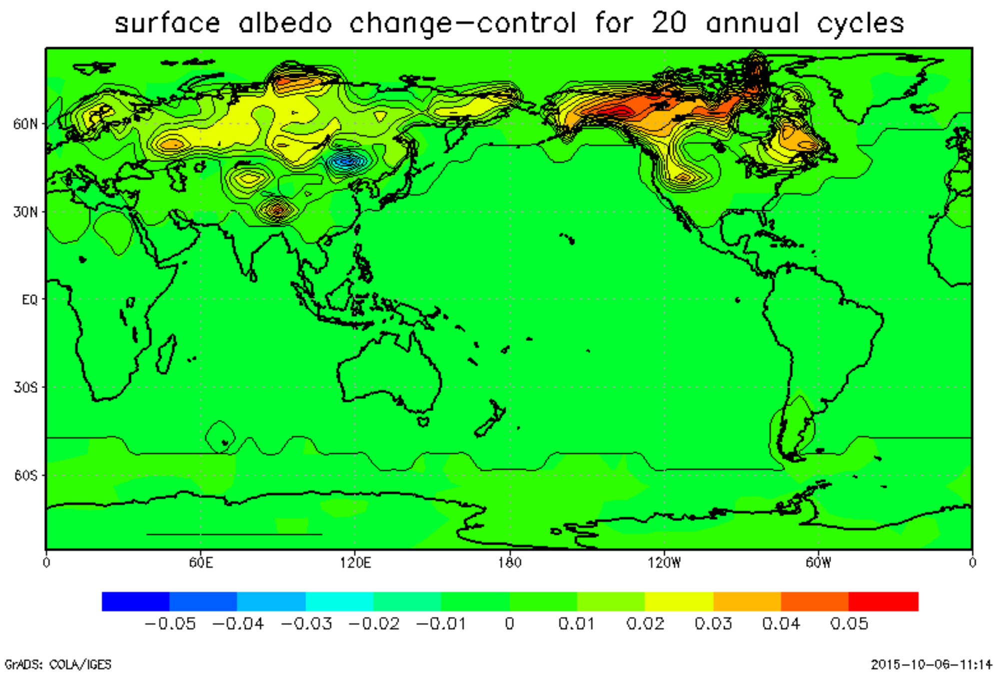

Figure 1: Difference of modified run and control run surface albedo averaged over 20 annual cycles (1992-2011). Significant changes are shown in contours.

1. For Control Run (standard model run without any changes in the dependency of snow albedo upon temperature)
2. For Modified Run (with changes in the dependency of snow albedo upon temperature)

The analysis has revealed the following results:

Since the effect of surface albedo is more prominent over the higher latitudes and less over the lower latitudes, therefore, considering the difference of surface albedo between modified run and control run over the entire globe, it has been observed that modified run is positively inclined than the control run for most parts of the North-west Canada and Russia between the latitudes 30°N-90°N. However, a negative incline is also observed in the northern part of China where it goes below -0.04 in case of modified run. A positive incline of 0.04 and 0.04 - 0.05 can also be observed over the Himalayas and Tibetan plateau respectively for modified run (Figure 1). China has the biggest afforested zone on the planet (~62 million hectares in 2008), and these timberlands are carbon sinks. The climatic impact of these new backwoods relies on upon how radiant and turbulent energy fluxes over these ranches alter surface temperature. For example, a lower albedo may bring about warming, which discredits the climatic advantages of carbon sequestration. Land-surface albedo reflects the ability that land surface reflects solar radiation and plays a very important role in surface energy balance. According to the average albedo, the sequence of albedo over all the underlying surfaces are arid meadow in the northeast of China, alpine meadow in the northwest of China, oasis farmland in the northwest, natural vegetation on the Loess Plateau, semi-arid meadow in the northeast of China, farmland in the northeast of China and fruit bearing forest in the northeast of China (Yao et al., 2014). Since North China encompasses various underlying surfaces including bare soil, cropland and grasslands (which remains a missing feature over the poles), the dependence of temperature on snow albedo over northeast China has rendered a significant drop in the modified run of snow albedo.

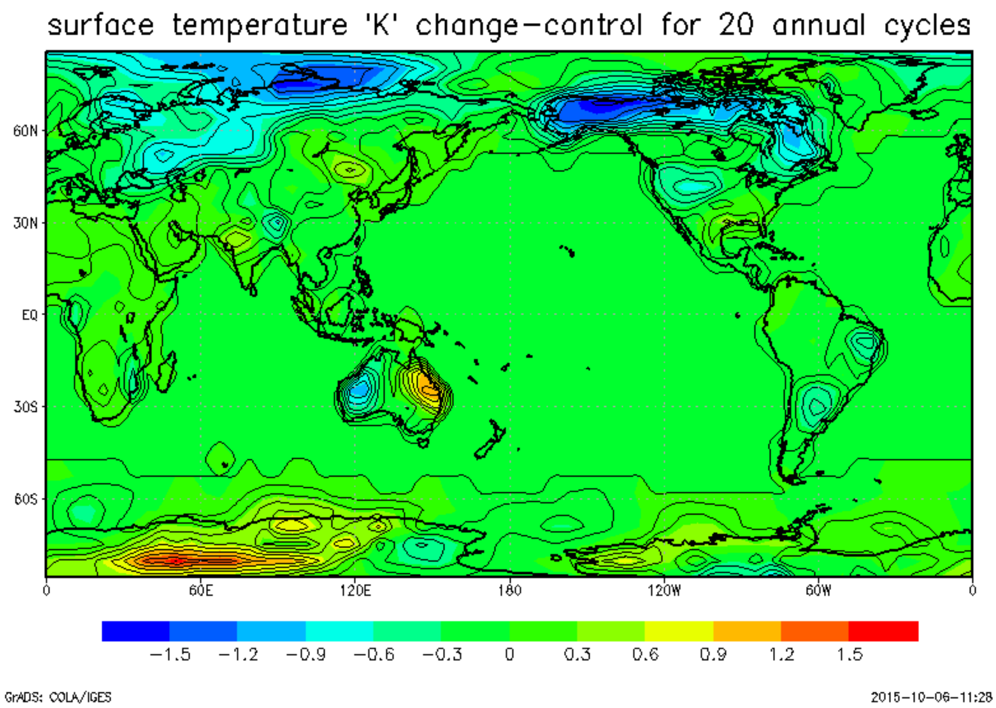

Figure 2: Difference of modified run and control run surface temperature (K) averaged over 20 annual cycles (1992-2011). Significant changes are shown in contours.

The analysis of the difference of surface temperature in Kelvins between modified run and controlled run over the entire globe shows that there is a negative incline in the northern polar region between latitudes 60°N-90°N and North-west Canada where a temperature difference of -1.5 K is observed which shows that the surface temperature in case of modified run is colder than the control run

(Figure 2). This means that the modified run is colder than the control run for the latitudes 60°N-90°N and North-west Canada. However, in the southern hemisphere, positive incline of 1.5 K is observed which shows that the surface temperature in case of control run is colder than the modified run. This means that the modified run is warmer than the control run in the southern hemisphere.

Taking into consideration the difference of snow depth in meters between modified run and controlled run over the entire globe, it has been observed that the snow depth on the average has been increased to about 0.2 meters in case of modified run (Figure 3). Snow depth has significantly changed in the Greenland where it has been increased to a limit of 0.6 meters in the southwest and decreased to 0.2 meters in the northeast for modified run. The snow depth has also decreased to about 0.6 meters in some regions of Antarctica in case of modified run.

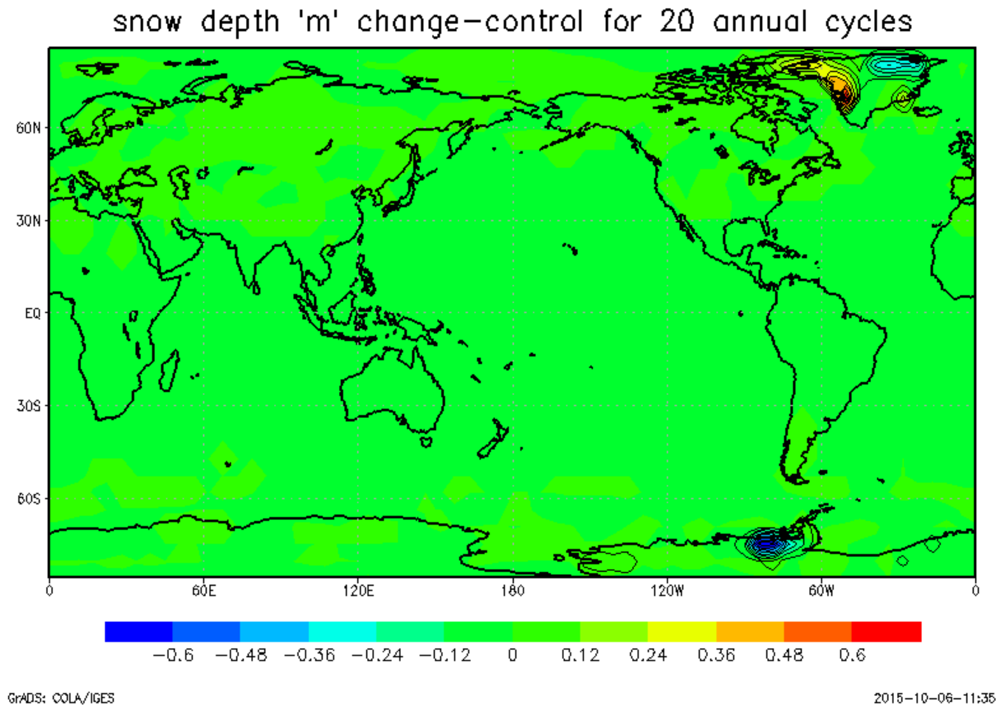

Figure 3: Difference of modified run and control run snow depth (m) averaged over 20 annual cycles (1992-2011). Significant changes are shown in contours.

Discussion

Dependency of snow albedo and snow depth on the variation of temperature range has widely been studied (see e.g. Yan and Gong 2009; Zhou et al., 2014; Koenigk et al., 2014). The extensively adopted incorporation of albedo dependence on temperature is robust (Pirazzini et al., 2006). Albedo decreases when snow ages due to metamorphism which is highly related to temperature history of the region (Pirazzini 2004). During summer-time freeze and thaw process, the presence of melted water between snow grains effect the magnitude of albedo. During winter, sea ice remains generally dry and snow-covered that maintains a rather unvarying magnitude of albedo as long as the near-surface temperatures are well below 0°C. In wintertime, near-surface temperature can occasionally nudge the melting point of snow even in the Central Arctic when cyclones advect warm air and clouds from lower latitudes (Vihma and Pirazzini, 2005). Over sea ice in the Baltic Sea, snow may experience melting also in mid-winter since lower latitudes allow a milder climate in contrast with the Arctic (Granskog et al., 2006). With the advancement of spring season, the increased temperature and shortwave downwelling irradiance accelerate the snow metamorphism – hence galvanizing the melt process. As a result, snow albedo varies as a function of temperature and other atmospheric parameters (Curry et al., 2001). Snow accumulation in the winter season over the Arctic is very low (Wadhams, 2000) thus snow melts over a brief span of time, usually only for a few weeks (Grenfell and Perovich, 2004).

Various snow/ice albedo parameterizations have been established, with several degrees of complexity. The simplest parameterization schemes employ two or more constant values of albedo for miscellaneous surface types (Pirazzini et al., 2002). Other schemes include a dependence on temperature (e.g. in ECHAM5 (Roeckner et al., 2003)) when the surface reaches the melting point, to explain the combined effects of snow metamorphism and snow thinning. The present study has incorporated the temperature range sensitive albedo parameterization which has shown clear spatial differences in albedo, near surface air temperature and snow depth, in post simulated results.

Conclusions

From the analysis and comparison of all the relevant parameters as mentioned above, we may draw the following conclusions:

i. The surface albedo, surface temperature and snow depth are all dependent upon each other; a change in the value of any one of these parameters affects the value of other parameters as well.

ii. The surface albedo is a phenomenon which controls the Earth's heat budget. The value of surface albedo depends upon surface temperature and snow depth. If the greater portion of incoming solar radiation is reflected back, the snow albedo would be higher. However, due to absorption of smaller portion of incoming solar radiation by Earth's surface , the surface temperature would be lower which in turn indicates the larger value of snow depth in case of greater snow albedo. In case of lower value of snow albedo, more solar radiation would be absorbed by Earth's surface than reflected back which would increase the surface temperature thereby enhancing the process of snow melt and therefore, the value of snow depth would decrease in this case. In other words, through the reduced albedo effect, global warming could potentially be exacerbated.

iii. In case of control run, when surface temperature is below -10°C, the surface albedo reaches its maximum value i.e. 0.8 and for surface temperature above -10°C, its value declines and approaches its minimum value i.e. 0.4 at 0°C and above. For temperature range between -10°C and 0°C, its value lies between 0.8 and 0.4 i.e. between maximum and minimum values respectively.

iv. In case of modified run, we have increased the threshold value of surface temperature from -10°C to -1°C so that the maximum value of surface albedo i.e. 0.8 should occur at surface temperature below -1°C instead of -10°C. Now, in case of modified run, the model would incorporate all possible temperature values between -10°C to -1°C as well for execution of maximum value of surface albedo i.e. 0.8. In other words, the range of surface temperature values and in turn the surface area over the entire globe has been increased in order to acquire maximum value of surface albedo i.e. 0.8. Consequently, for larger portion of the globe, especially for northern hemisphere, the value of surface albedo has been increased significantly in case of modified run.

v. In the Northern hemisphere, due to larger landmass and topography, the value of surface albedo is on higher side due to lower heat capacity (absorption) of Earth's surface as compared to water body.

vi. The highest values of surface albedo are observed over the Polar Regions.

vii. Water is much more absorbent and less reflective due to its greater heat capacity. So, if there is a lot of water body, more solar radiation is absorbed by the ocean than reflected back. Therefore, in Southern hemisphere, the value of surface albedo is on lower side due to existence of larger portion of ocean.

viii. During the northern hemisphere spring season, more solar radiations are absorbed by Earth's surface which increases the rate of snow melt during spring season, therefore, snow depth is reduced significantly. Consequently, the value of snow albedo decreases.

ix. For equatorial region, more solar radiations are absorbed by Earth's surface than reflected back. Therefore, surface temperatures are higher and consequently the value of snow albedo falls on the lower side.

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