Clouds and Snowmelt on the North Slope of Alaska

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Introduction

Clouds have a large effect on the radiation field. Consequently, possible changes in cloud properties may have a very substantial impact on climate. Of all natural surfaces, seasonal snow cover has the highest surface albedo, which is one of the most important components of the climatic system. Interactions between clouds and seasonal snow cover are expected to have a significant effect on climate and its change at high latitudes.

The purpose of this paper is to investigate the sensitivity of the surface cloud-radiative forcing during the period of snowmelt at high latitudes. The primary variables investigated are cloud liquid water path (LWP) and droplet equivalent radius (r_e). We will also examine the sensitivity of the surface radiative fluxes to cloud base height and cloud base temperature.

Model Description

A one-dimensional atmospheric radiative transfer model combined with the surface energy balance equation was employed in these investigations. The surface radiation fluxes were calculated using a comprehensive atmospheric radiative transfer model developed by Tsay et al. (1989). The atmospheric radiative transfer model uses a discrete-ordinate approximation to solve the radiative transfer equation (Stamnes et al. 1988) for both solar and terrestrial radiation. The model has detailed routines for including the effects of clouds, arctic haze, CO_2, H_2O, O_3, and snow layers on the atmospheric radiative transfer under arctic conditions.

Sensible and latent heat fluxes are calculated using bulk aerodynamic formulae following Louis (1979) and Ebert and Curry (1993). The ground-soil heat flux is computed using a snow-active layer-permafrost model (Zhang 1993). The lower boundary was set at 1 m below the snow-soil interface, and a constant temperature lower boundary condition was used in this study.

Cloud properties were specified based on the measurements for Arctic stratus by Herman and Curry (1984) and Tsay and Jayaweera (1984). The geometrical thickness is 291.7 m with cloud base at 700 m for low Arctic clouds. Liquid water content ranges from 0.01 g m^3 to 0.40 g m^3 for low Arctic clouds, with the droplet (r_e) ranging from 4 µm to 11 µm. Within the cloud layer, the relative humidity of the atmosphere was set at 100% to calculate the atmospheric water vapor content.

Results and Conclusions

Figures 1A-C show the variations of surface radiation fluxes with LWP and (r_e). Compared with clear sky conditions, clouds reduce the surface net solar radiation significantly, up to 80% (Figure 1A). Clouds increase the incoming longwave radiation from the atmosphere to the snow surface by as much as 30% or more (Figure 1B). The net surface radiation flux (R_N) is greater under cloudy sky conditions than under clear sky conditions (Figure 1C).

As can be seen from Figure 1C, the rapid increase in incoming longwave radiation with LWP dominates for small LWP. As the cloud thickens to the point of high opacity in the thermal infrared so that the incoming longwave flux levels off, the continued decrease in net solar radiation with increasing LWP comes to dominate the net radiation flux, leaving a maximum at moderate LWP.

Plots of shortwave, longwave, and total cloud radiative forcing against LWP simply involve relabeling the axes, and are not shown here. Instead, Figure 1D shows contours of the total cloud radiative forcing as a function of LWP and the droplet (r_e). As can readily be seen, the maximum value of C occurs for (r_e) approximately equal to 9 µm and a LWP of about 29 g m^{-2}.

Figure 2 illustrates the effect of low Arctic clouds on the surface radiative fluxes and snowmelt at high latitudes. The net surface solar irradiance increases with time but decreases significantly with increase of LWP (Figure 2A). The net surface longwave radiation increases rapidly for lower LWP values (Figure 2B). Changes to the net surface longwave radiation are very limited when cloud LWP is higher than about 20 g m^{-2}. Figure 2C shows the net radiative balance as a function of LWP and time. The maximum values of R_N at a given time occur at LWP

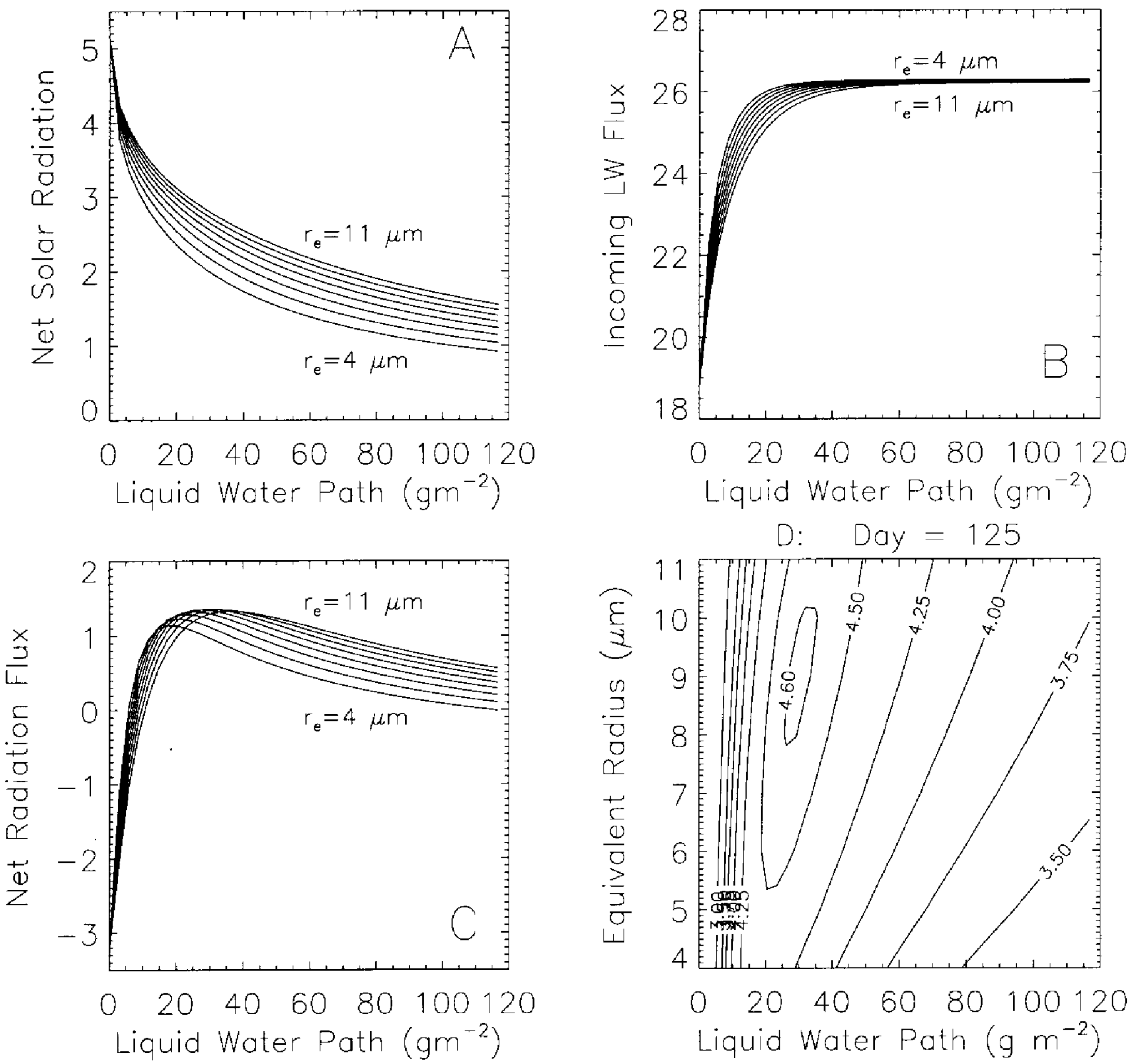

Figure 1. Effect of cloud liquid water path and equivalent radius on the surface radiative fluxes (A: net daily solar radiation; B: net daily incoming longwave radiation; C: net daily radiation balance) and the surface cloud-radiative forcing (D). Units are in MJ m^{-2} day^{-1}.

~25 g m^{-2} during the early period of snowmelt and at LWP ~ 20 g m^{-2} during the late period of snowmelt. As a result, the onset of snowmelt follows a similar pattern (Figure 2D). The onset of snowmelt under cloudy sky conditions happens earlier than under the clear sky conditions (LWP = 0). The timing of the earlier onset of snowmelt due to the effect of low clouds could range from a few days to over a month depending upon the cloud properties (Figure 2D).

This study confirms observational evidence gathered over the last three decades that the net daily radiation balance over a snow surface at high latitudes is larger under cloudy sky conditions than under clear sky conditions. Ambach (1974) suggested that the enhancement of the net surface radiation balance under overcast conditions is due to the significant influence of the incoming longwave radiation and the high albedo of the snow surface. This study supports that suggestion and further indicates that

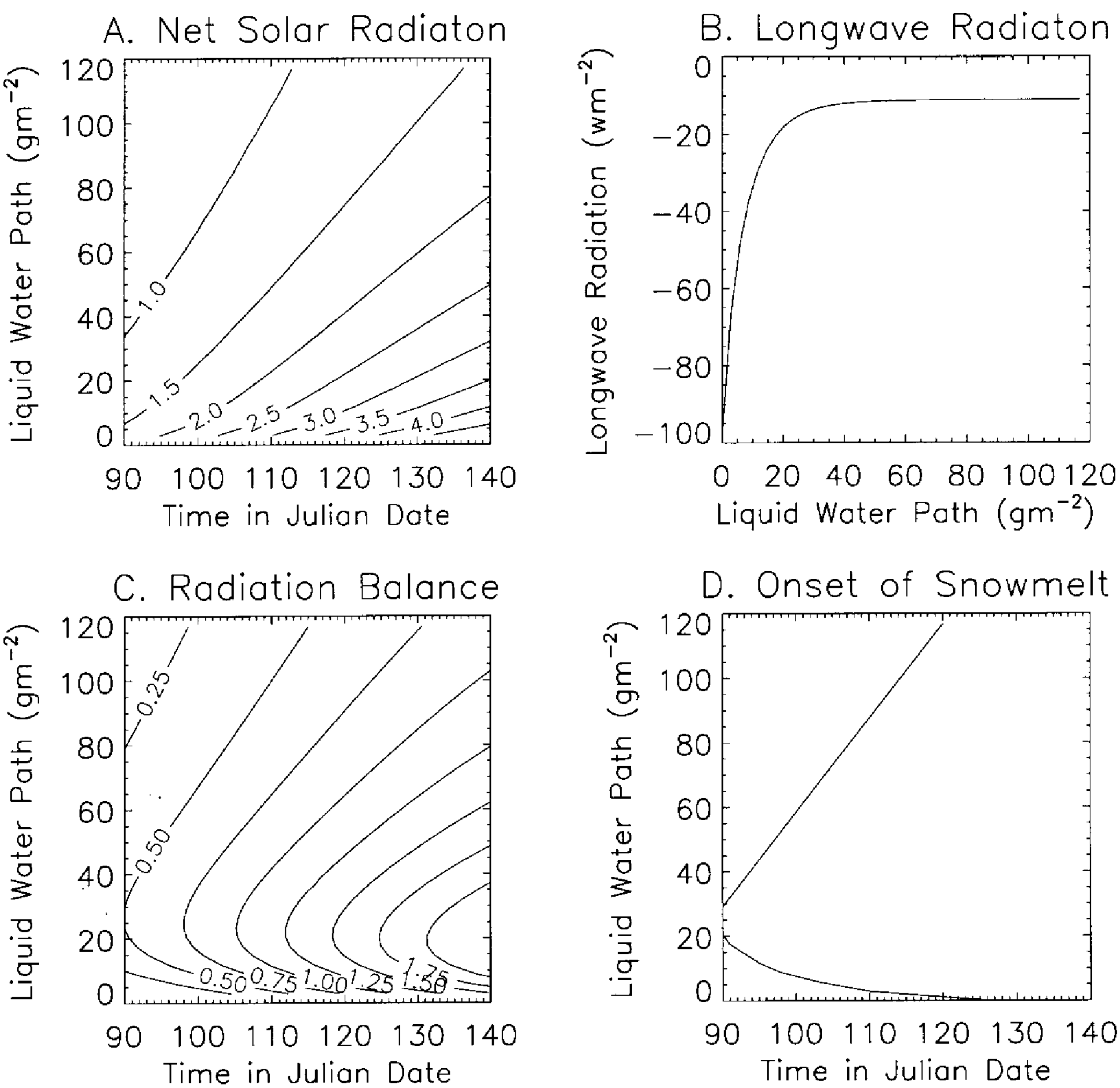

Figure 2. Effect of low clouds on the surface radiative fluxes and the onset of snowmelt at high latitudes. Units for the contours in (A) and (C) are in MJ m^{-2} day^{-1}.

clouds exert a strong control on the surface radiation balance by reducing the incident solar radiation and increasing the incoming longwave radiation. However, the warming effect due to surface longwave cloud-radiative forcing is indeed greater than the cooling effect due to surface shortwave cloud-radiative forcing, which results in an enhancement of the net radiation balance under cloudy sky conditions that warms the snow surface and the lower atmosphere. The magnitude of this enhancement under overcast conditions depends strongly upon cloud microphysical properties, cloud base height, cloud base temperature, and cloud thickness.

This study shows that the impact of changes in cloud conditions, such as cloud microphysical properties (r_e and LWP), cloud base height and temperature, on the onset of snowmelt could range from a few days to over a month, which is sufficient to account for the observed inter-annual variations in the timing of snowmelt at high latitudes.

This study also illustrates that clouds have a positive feedback on the climate system at high latitudes, at least during the period of snowmelt. This feedback is caused by positive surface cloud-radiative forcing leading to earlier snowmelt. Some general circulation models predict that temperature and thereby evaporation would increase due to elevation of the CO_2 content in the atmosphere. A warmer atmosphere has a greater moisture-bearing capacity, and enhanced evaporation implies an increase in cloudiness unless the precipitation is significantly changed. In the Arctic, the abundance of cloud condensation nuclei may prevent clouds from precipitating more in a warming climate. Thus the end result may be an enhanced moisture-cloud radiative warming and a positive feedback loop. Earlier snowmelt would reduce the surface albedo and allow the surface to absorb more solar radiation and warm the atmosphere. The coupling between these two positive feedback loops (moisture-cloud radiative warming and earlier snowmelt) could result in an amplified feedback to the climate system in the Arctic.

Finally, this study suggests that comprehensive field measurements of cloud physical properties (including cloud liquid or ice water content, cloud particle size and shape, cloud height and morphology), atmospheric temperature and moisture conditions, surface and near surface radiation, wind, humidity, and surface optical properties are required to improve our physical understanding of the transfer of energy, momentum, and mass between the atmosphere and the surface. Better knowledge of these interactions over land as well as over the ocean in the Arctic is a prerequisite for improved comprehension of the Arctic climate system.

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