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Observed albedo decrease related to the spring snow retreat

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Abstract. We study the impact of the spring snow retreat on albedo from 1979 to 1991 using the ultraviolet (UV) reflectivity measured by the Total Ozone Mapping Spectrometer (TOMS). Over the Northern Hemisphere (NH) snowy land area that was snow covered at least once during this period, we find a 1.5% decrease over the 13 years in the springtime UV reflectivity, related to a 5×10^6 km^2 decrease in the satellite derived spring snow cover. About half of the reflectance decrease occurred over regions where snow cover and reflectance correlate at a 99% significance level. The 1.5% UV reflectivity decrease corresponds to a 1% decrease in the visible albedo over the snowy region, and a ~ 2 Wm^{-2} increase in the shortwave heating when averaged over the entire NH land. Based on observed interannual reflectivity changes over the entire NH snowy land area, our study provides a direct constraint on the shortwave forcing of the spring NH snow retreat.

Introduction

Snow strongly affects the surface energy balance (SEB) through its high reflectivity, low thermal conductivity, and the latent heat required for melting. Constraining the SEB feedbacks of snow is important for assessing climate sensitivity.

Satellite observations show that snow cover over Northern Hemisphere (NH) land decreased by $\sim 5 \times 10^6$ km^2 from 1973 to 1992, and that most of the decrease occurred in spring and summer [*Robinson and Dewey,* 1990; *Groisman et al.,* 1994]. Radiative impacts of the decrease in snow cover, especially those related to a decreased albedo during spring, have been inferred and invoked in explaining the observed surface air temperature increase over NH land [*Groisman et al.,* 1994].

In *Groisman et al.* [1994], radiative forcings of the snow cover were inferred from spatial relations between snow cover and components of the heat balance. However, snow cover's radiative effect, in particular, its albedo effect, is known to vary greatly with vegetation, clouds, temperature, age of the snow, and solar zenith angle [*Rosenberg et al.,* 1983; *Robinson and Kukla,* 1985; *Wiscombe and Warren,* 1980; *Groisman et al.,* 1994]. The spatially derived snow cover - albedo relations explained at most 20-30% of the spatial variance in the albedo field within a given temperature range [*Groisman et al.,* 1994]. Large uncertainties may exist in the retrieved snow - albedo relations due to this complexity.

In this work, we seek to quantify albedo changes related to the spring snow retreat using direct reflectivity measurements from the Total Ozone Mapping Spectrometer (TOMS) [*McPeters and Labow,* 1996]. The TOMS reflectivity was measured at two ultraviolet (UV) wavelengths (360 nm and 380 nm) outside the ozone absorption bands. The long term calibration error of the TOMS data is less than 1% per decade [*Herman et al.,* 1991; *Herman and Celarier,* 1997]. We will show that the TOMS UV reflectivity serves as a suitable proxy for visible albedo by correlating it to broad band visible measurement from the Earth Radiation Budget Experiment (ERBE) [*Barkstrom,* 1984].

Data

The Nimbus-7 TOMS monthly reflectivity data (Version 7) are used in this study to monitor albedo changes [*McPeters and Labow,* 1996]. The data are provided in a 1.25° longitude × 1° latitude grid and are available from November, 1978 to April, 1993. Data from 1979 to 1991 are used in this study to avoid effects from the Mount Pinatubo eruption. We note that most of the reported snow retreat occurred over the years when TOMS data are available.

The snow cover information from 1979 to 1991 is obtained from the Northern Hemisphere Weekly Snow Cover and Sea Ice Extent data, provided by the National Snow and Ice Data Center Distributed Active Archive Center (NSIDC DAAC), University of Colorado at Boulder [*National Snow and Ice Data Center,* 1978-1995]. The snow cover is based on weekly National Oceanic and Atmospheric Administration (NOAA) snow charts, derived from manual interpretation of visible-band satellite images [*Matson and Wiesnet,* 1981; *Robinson et al.,* 1993]. The NOAA snow charts are originally in a 89 × 89 Northern Hemisphere grid on a polar stereographic projection, and the cell resolution ranges from 16,000 to 42,000 km^2. The data that we use have been converted into a 25 × 25 km grid on the Lambert equal-area projection (known as the NSIDC EASE-Grid) by the NSIDC. The weekly snow cover data have been averaged into monthly data in this study.

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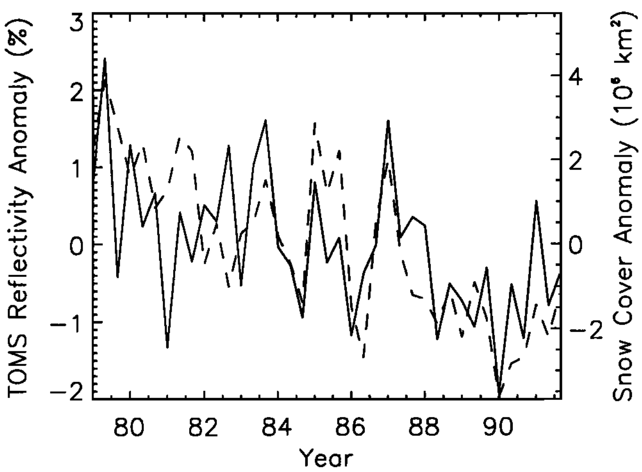

Figure 1. Springtime (March, April, and May) area-averaged TOMS reflectivity (solid line) and snow cover (dashed line) anomalies over the regions that snow covered at least once over the years from 1979 to 1992. The anomalies are formed by removing the mean seasonal cycles. Note that the scale for the TOMS reflectivity is on the left and the scale for the snow cover is on the right.

Results

Figure 1 shows the springtime (March, April, and May) spatially averaged TOMS reflectivity anomalies over the NH land areas that were snow covered for a week for at least once over the period 1979 to 1991. The snowy region is shaded in Figure 2 and encompasses $\sim \frac{3}{5}$ of the NH land area. Over-plotted are the NH spring snow cover anomalies. Note that the scales for the two are labeled separately, with the reflectivity on the left and the snow cover on the right. The anomalies are formed by removing the mean seasonal cycles. We find that TOMS reflectivity decreased by $\sim$ 1.5% from 1979 to 1991. The error in the trend may be characterized by the standard deviation of the time series, which is $\sim$ 0.9%. Therefore, the decrease is significant at 1-σ confidence level. The snow cover has decreased by $\sim 5\times10^6$ km^2 and the standard deviation of the time series is 2×10^6 km^2. Linear correlation of the two time series is 0.6 and remains significant after the linear trends are removed (r=0.44). Although we cannot exclude the effects of other factors (e.g. cloud changes), snow appears to be the most likely cause for the observed albedo decrease because of its significant retreat and its strong albedo effect. We note that a large fraction of the trends in both albedo and snow cover may be attributed to the anomalously high values in 1979 and the anomalously low values in 1990, and do not necessarily imply longer term trends by themselves, even though decreasing NH snow cover has been found over longer terms in other studies [*Groisman et al.*, 1994; *Brown*, 1997].

We carry out linear correlation and linear regression studies for TOMS reflectivity and snow cover variations. For this purpose, both snow cover and the TOMS reflectivity are averaged into a 2.5° longitude × 2° latitude grid. The new grid roughly matches the original resolution of the snow data (16,000 to 42,000 km^2). It is also a denominator of the TOMS grid, and regridding is done with simple averaging. Interpolation, which introduces uncertainties, is avoided. For each grid, anomalies of albedo and snow cover are then formed and linear correlation and regression for each season are computed. Results for spring are shown in Figure 2. Colored regions are where the snow - albedo correlation is of above 99% significance. The colors represent regression coefficients between anomalies of TOMS reflectivity and snow cover. Snow - albedo correlation is significant over $\sim$ 20% of the NH snowy land area ($\sim 11 \times 10^6$ km^2). The 99% significant correlation regions for winter (December, January, February), summer (June, July, August), and autumn (September, October, November), are about 13×10^6 km^2, 2×10^6 km^2, and 7×10^6 km^2, respectively. Variations in the linear regression coefficients would be a consequence of the aforementioned complexity in the albedo impact of snow cover.

Figure 3 shows the springtime area-averaged TOMS reflectivity and snow cover anomalies over regions where the two are correlated at a 99% significance level. Over this region, the TOMS reflectivity and snow cover have decreased by 3.4% and 1.6×10^6 km^2, respectively, over the thirteen years. The standard deviations of the time series are 2.1% for TOMS reflectivity and 0.7×10^6 km^2 for the snow cover. Linear correlation of the two time series in Figure 3 is 0.8, and remains high when the trends are removed (r=0.73). Comparison between Figure 1 and Figure 3 shows that the 3.4% reflectivity reduction in the 99% significant correlation region accounts for about half of the reflectivity trend over the entire NH snowy land region (3.4% decrease over 20%

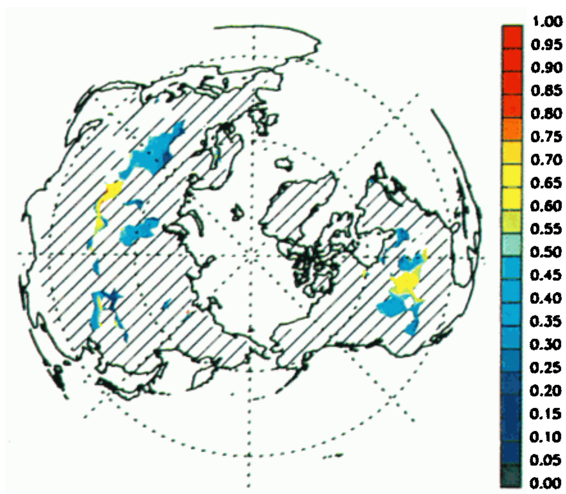

Figure 2. The shaded regions are regions that snow covered at least once over the years from 1979 to 1992. The colored regions are where TOMS reflectivity and the snow cover anomalies are correlated at a 99% significance level. Different colors represent the linear regression coefficients between TOMS reflectivity and the snow cover.

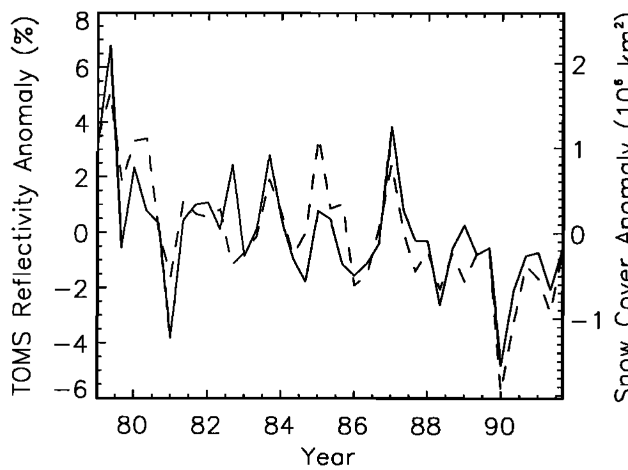

Figure 3. Same as Figure 1, except for averaging over regions where TOMS reflectivity and the snow cover anomalies are correlated at a 99% significance level.

of the NH snowy land area versus 1.5% change over the entire NH snowy land area), and about a third of the snow cover decreases. This half of the reflectivity trend can be quite confidently related to the snow retreat, based on the way that we construct the reflectivity and the snow cover time series, and the high correlation between the two. The other half of the reflectivity trend is likely to be also related to the snow changes, given the significant snow retreat over the area. This may include effects from cloud changes in response to the snow variations. We note that potentially, there could be variations in clouds that are unrelated to the snow changes, yet have played a role in the albedo decrease. With the cloud variations largely unconstrained, one should keep in mind the potential uncertainties that follow.

With the albedo decrease that we have shown, increase in the shortwave heating can be assessed. Since the TOMS reflectivity is taken in the UV, we relate its variation to the broad band visible albedo using monthly ERBE albedo data from February, 1985 to January, 1989. The ERBE data are provided in a 2.5° longitude × 2.5° latitude grid, and the data that we use have been modified by the National Center for Atmospheric Research (NCAR) [*Hurrell and Campbell,* 1992]. Figure 4 shows a comparison between ERBE visible albedo anomalies and the TOMS UV reflectivity anomalies. For the comparison, both data are regridded into a 5° longitude × 5° latitude grid, the least common denominator of the TOMS and ERBE grid. Anomalies are then formed for those grid points over which spring snow cover has changed during the period from 1979 to 1991. A linear relation is retrieved with a regression coefficient of 0.65 ± 0.01% ERBE albedo change per 1% TOMS reflectivity change. The main reason for the non-unity regression coefficient is that the albedo of snow free surfaces is generally greater in the visible (10-30%) [*Hartmann,* 1994] than in the UV (2-4%) [*Herman and Celarier,* 1997] while snow and clouds have similar reflectance in both wavelengths. Almost identical results are obtained for the other seasons. After taking into consideration the empirical relation between UV and visible albedo and the varying incoming solar radiation, we find that the observed spring albedo decrease corresponds to an increase of $\sim 2Wm^{-2}$ in solar heating when averaged over the NH land. Based on directly observed interannual reflectivity changes over the entire NH snowy land area, our study is closely related to the impact on albedo of snow changes on a hemispheric scale, and hence, provides a more direct estimate of the shortwave forcing of the NH snow cover retreat, as compared to previous studies [*Groisman et al.,* 1994].

To compare with previous results, the albedo decrease is recomputed for April and May, following *Groisman et al.* [1994]. From the TOMS data, we estimate an increase of $\sim 2.7Wm^{-2}$ in the absorbed shortwave radiation over the 13 years. Using a shortwave impact of -11.6 Wm^{-2} for a spring mean snow cover of $\sim 22 \times 10^6$ km^2, as derived by *Groisman et al.* [1994], a snow cover decrease of 5×10^6 km^2 would increase the absorbed solar energy by $2.6Wm^{-2}$. The two agree well with each other.

Discussion

Besides its impact on shortwave radiation, snow cover changes also affect other components of the heat budget (for instance, the longwave radiation and the latent heat to melt snow). Model studies have shown that effects of snow cover on the longwave radiation and the latent heat for snow melt are small compared to the albedo effect [*Cohen and Rind,* 1991]. The former has been confirmed by satellite observations, where a longwave forcing of $\sim$ 3 Wm^{-2} and a shortwave forcing of $\sim$ -12 Wm^{-2} was found for the spring snow cover [*Groisman et al.,* 1994]. Here, we make a crude estimate of latent

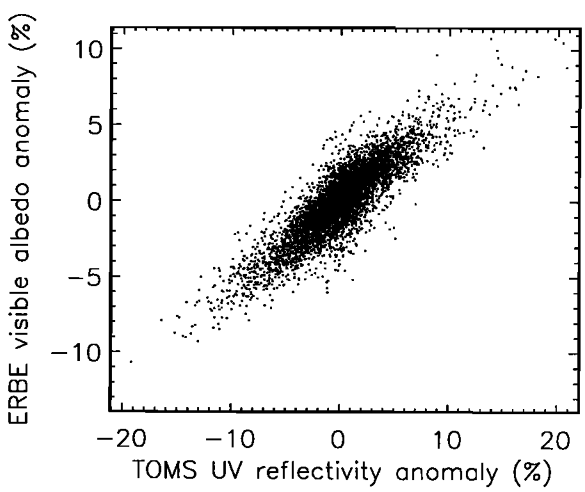

Figure 4. Comparison of the TOMS UV reflectivity anomalies and the ERBE visible albedo anomalies. The linear correlation is 0.87. The linear regression coefficient is 0.65 ± 0.01% ERBE albedo change per 1% TOMS reflectivity change. See text for more details.

heat change related to the snow retreat. Taking climatological values of snow cover and snow mass [*Foster and Chang,* 1993], we estimate that 1×10^6 km^2 of snow cover roughly corresponds to $\sim 7\times10^{16}$ g of snow mass. Since the snow cover in winter did not show a significant decrease, a retreat of 5×10^6 km^2 in the spring snow cover corresponds to an increase of $\sim 3.5\times10^{17}$ g in the snow melt for a period of 3 months. 1×10^{20} J is needed to melt this amount of snow, which is roughly a 0.1 Wm^{-2} change for 3 months when averaged over the NH land and is insignificant compared to changes in the shortwave heating.

Based on the above discussion, the spring snow retreat did increase the net heating over NH land by 1-2 Wm^{-2}. This would have significant effects on the climate system based on studies of climate sensitivity [*Hansen et al.,* 1997], and feedback to the climate system. However, we emphasize that snow is only one of the many variables that affect the SEB, and without further constraining the variability of other important climate components (e.g. cloud changes, heat advection), the radiative effect of the spring snow retreat does not necessarily explain the larger increase in spring temperature compared to the other seasons, as suggested by *Groisman et al.* [1994].

Conclusion

Using the TOMS reflectivity measurements, we find a 1.5% decrease in the spring UV reflectivity over the NH snowy land area from 1979 to 1991, most likely a consequence of the spring snow retreat. Based on direct observations of interannual reflectivity changes that are integrated over the whole NH snowy land area, our results provide direct estimates of the shortwave forcing of the snow cover decrease. We find a ~ 2 Wm^{-2} increase in the absorbed solar energy over the NH land, related to the 5×10^6 km^2 spring NH snow retreat. Our results agree with previous estimates by *Groisman et al.* [1994].

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