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Actual and insolation-weighted Northern Hemisphere snow cover and sea-ice between 1973–2002

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Abstract Actual and insolation-weighted Northern Hemisphere snow cover and sea ice are binned by latitude bands for the years 1973–2002. Antarctic sea-ice is also analyzed for the years 1980–2002. The use of insolation weighting provides an improved estimate of the radiative feedbacks of snow cover and sea-ice into the atmosphere. One conclusion of our assessment is that while a decrease in both areal and insolation-weighted values have occurred, the data does not show a monotonic decrease of either Arctic sea-ice or Northern Hemisphere snow cover. If Arctic perennial sea-ice is decreasing since the total reduction in areal coverage is relatively small, a large portion of it is being replenished each year such that its radiative feedback to the atmosphere is muted. Antarctic sea-ice areal cover shows no significant long-term trend, while there is a slight decrease in the insolation-weighted values for the period 1980–2002. From the early 1990s to 2001, there was a slight increase in both values. The comparison of general circulation model simulations of changes over the last several decades to observed changes in insolation-weighted sea-ice and snow cover should be a priority research topic.

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1 Introduction

In Pielke et al. (2000), the effects of sea-ice and snow-cover trends on the surface energy budget are assessed by scaling with direct solar insolation. The influence of the radiative feedback to the atmosphere of sea-ice and snow cover is one of several important effects of the cryosphere on the climate system (NRC 2003). The current work extends that study by examining the interannual variability as a function of latitude bands, and by developing an integrated measure of the combined effect of sea-ice and snow cover. The monitoring of the trends in these quantities is an important climate assessment metric (Holloway and Sou 2002; Dye 2002). Comiso (2002), for example, reports on a significant decline in perennial sea-ice coverage in the Arctic. Vinnikov et al. (1999) also show climate change model simulations of Arctic sea-ice decline, which they illustrate in their Fig. 1 as about 0.7 million square km in the GFDL model and around 0.5 million square km in the Hadley Centre model for the period 1973–2002. These represent about 6% and 5% declines in sea-ice coverage, respectively, for the two model results over this time period. The tracking of whether these simulations are skillful predictions is a critical question.

2 Methods

Pielke et al. (2000) introduced a method to assess the influence of temporal changes in sea-ice and snow-cover distributions on solar radiation reflected back into space. This method weights the observed sea-ice and snow-cover distributions by a solar insolation factor that accounts for the seasonal variations in solar elevation angle and day length. While the method ignores cloud and surface albedo variations due to vegetation masking, and patchiness along the snowpack margins, as well as changes in sea-ice albedo during the melt season, it does provide a more useful scaling of atmosphere-cryosphere radiative feedback than areal coverage changes alone.

The advantage of an insolation-weighted assessment is that it more directly relates to the radiative feedback between the Earth's surface and the atmosphere. For example, a decrease in snow cover

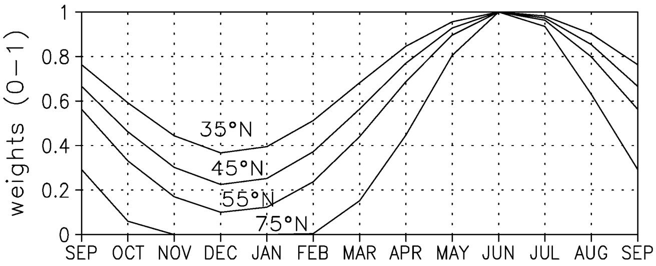

Fig. 1 Weighting function values applied to the snow-cover latitude bands: 35°N for 30–40, 45°N for 40–50, 55°N for 50–60, and 75°N for 60–90°N. The 75°N weights were also used for the sea-ice data

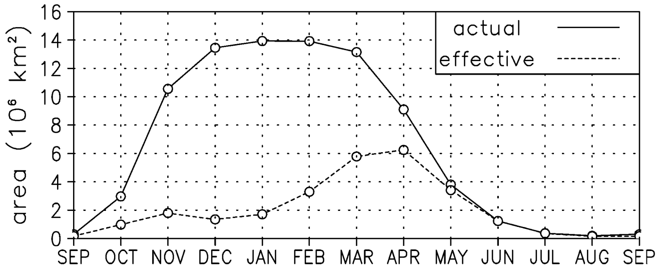

Fig. 2 Example effect of weighting function, 30-year averages, snow cover 50–60°N

for a Northern Hemisphere latitude band in February has a relatively small radiative effect because insolation is low at this time of the year. In contrast, the same snow-cover change in April would be more significant radiatively because insolation is higher.

To generate insolation-weighting factors used in scaling the effect of snow and sea-ice extent on surface incident solar radiation, we performed the following calculations. The direct insolation, I, received at a flat portion of Earth's surface can be estimated from

$$I = S_o \frac{a^2}{r^2} (\cos Z)\tau \tag{1}$$

where S_o defines the solar irradiance at the top-of-the-atmosphere striking a surface normal to the solar beam (S_o = 1370 Wm^{-2}) (Kyle et al. 1985). The solar zenith angle, Z, is

$$\cos Z = \sin\delta \sin\varphi + \cos\delta \cos\varphi \cos\omega \tag{2}$$

where φ is latitude and ω is the hour angle. The solar declination angle, δ, can be approximated by

$$\delta = \varphi_T \cos\left(2\pi\left(\frac{d - d_r}{d_y}\right)\right) \tag{3}$$

where φ_T is the latitude of the Tropic of Cancer, d is the day number during the year, d_r is the day of the summer solstice, and d_y is the average number of days in a year. The distance of the Sun from the Earth on a specific day of the year, a, and the average distance of the Earth from the Sun, r, were defined according to a relationship given in Pielke (2002). The net sky transmissivity, τ, accounts for the scattering, absorption, and reflection of shortwave radiation within the atmosphere. The increase in transmissivity as the path length through the atmosphere increases, is approximated by

$$\tau = 0.6 - 0.2\cos Z \tag{4}$$

(Burridge and Gadd 1974).

By choosing appropriate values of d, φ, and ω, the insolation reaching Earth's surface can be calculated using Eqs. 1–4. Using these equations, we calculated average-daily insolation weighting factors and used them to assess the seasonal evolution of the radiative impact of snow-covered area and sea-ice extent. Our data sets consist of monthly Northern Hemisphere sea-ice extent and monthly snow-covered land (including Greenland) area over the latitude bands 30–40, 40–50, 50–60, and 60–90°N. To be compatible with the monthly data, we used d values that correspond to the 15th of each month. Because we used sea-ice data values representing Northern Hemisphere total areas, we used a generally representative latitude of 75°N for the sea-ice weightings. For the snow-cover latitude bands, we used the latitudes of the center of the bands for the weighting calculations, i.e., 35, 45, 55, and 75°N. For our calculations of the average daily insolation, ω was varied over the diurnal cycle. Weighting factors were generated by dividing the monthly insolation values by the June value as shown in Fig. 1. An example of the application of this weighting, as it is used to assess the insolation-weighted coverage is presented in Fig. 2 for snow cover at 50–60°N.

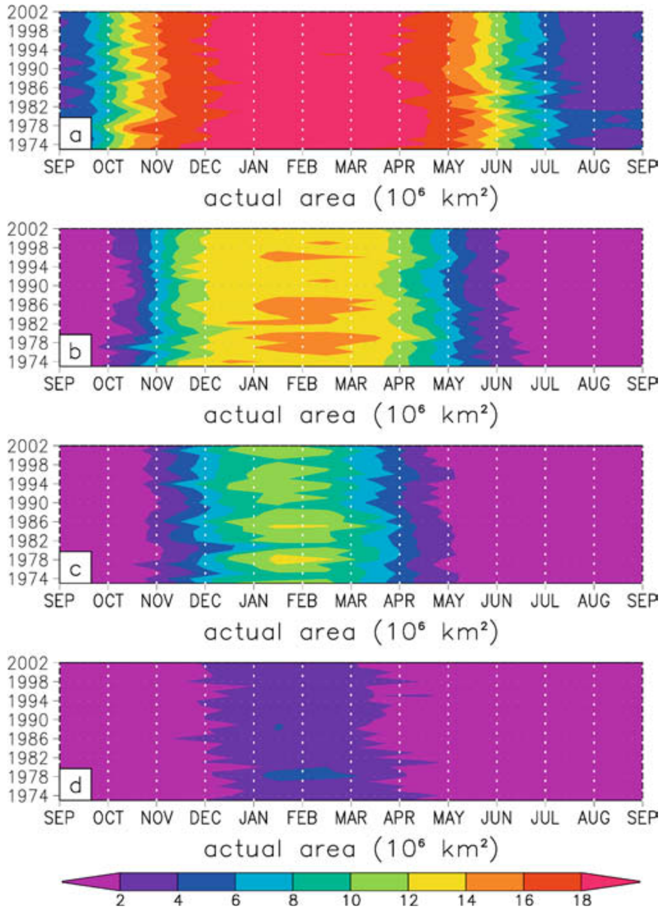

Fig. 3 Actual snow cover by latitude bands **a** 60–90°N; **b** 50–60°N; **c** 40–50°N; and **d** 30–40°N

3 Results

Figures 3 and 4 show the actual snow and insolation-weighted coverage for the latitude bands (60–90°N; 50–60°N; 40–50°N; and 30–40°N) where the weighting factors plotted in Fig. 1 were used. Several interesting features are seen in Fig. 3. First, the most significant

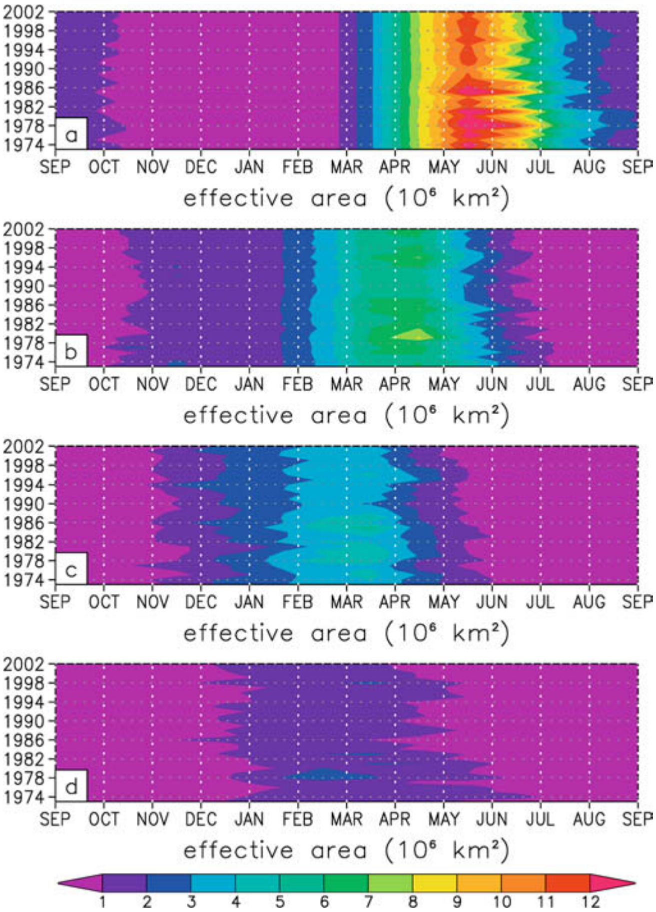

Fig. 4a–d Same as Fig. 3 but for the insolation weighted values

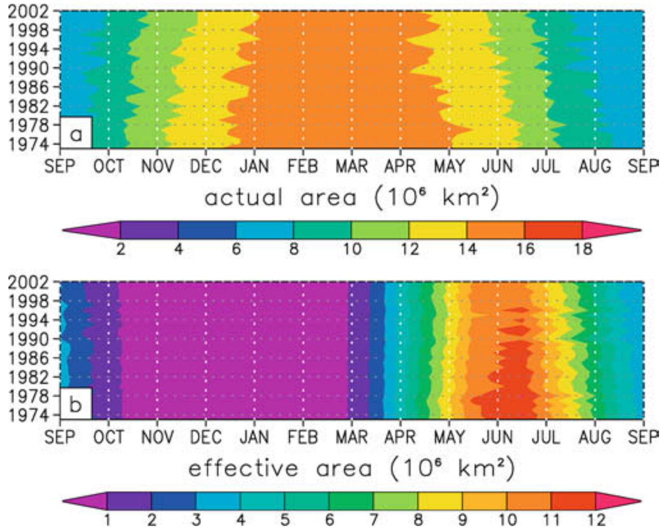

Fig. 5a, b Actual and insolation weighted values for Arctic sea-ice

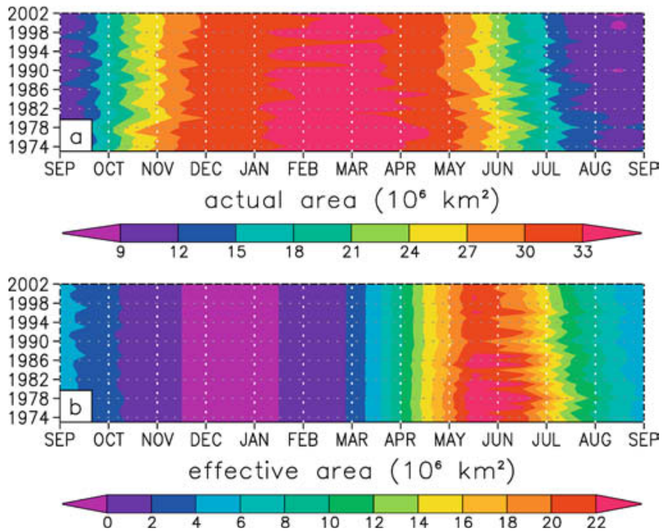

Fig. 6a, b Actual and insolation weighted values with Arctic sea-ice and snow cover (60–90°N) included together

latitudes for actual and weighted snow cover are 60–90°N. In the 30–40°N snow coverage, there was a peak in the late 1970s, and the snow cover lasted longer into the spring than in recent years. This nearly stepwise decline in spring snow cover was first reported in Robinson and Dewey (1990). When the data are weighted by insolation, so as to measure the effective radiative feedback effect of the snow cover, the elevated period of snow cover in the late 1970s for 30–40°N remains prominent, but this time period also has a greater insolation-weighted area at the other latitudes as well.

The actual and weighted sea-ice coverage for 1973–2002 are shown in Fig. 5. In comparison with Fig. 3 for 60–90°N, the areal coverage of sea ice is less than the areal coverage of snow. Because of the earlier melt of snow, however, the weighted values are quite comparable with both peaking in May and June (with sea-ice closer to the solstice).

Figure 6 shows the 60–90°N total actual and effective areas when sea-ice and snow cover are included together. The elevated coverage of late 1970s period also is evident with the late May and early June time period clearly seen as the most sensitive with respect to the effective area.

Figure 7 summarizes the interannual variability on an annual basis. While there is a reduction compared to the 1970s, the trends are mostly near zero since 1990. Arctic sea-ice has decreased slightly while snow cover in the same latitudes showed a slight increase. The sea-ice decline from 1973 is about 6% while from 1980 the decrease to 2002 is about 3%. The observed 1973–2002 decline is in close agreement with the model-projected values reported in Vinnikov et al. (1999). However, the 1980–2002 observed decrease is less than the simulated decrease of actual sea ice areal coverage reported in that paper.

The decrease in actual area of both Arctic sea-ice and snow cover since the beginning of the record in 1973 is about 5%, while the insolation-weighted value has decreased by 11%. The insolation-weighted value provides a more appropriate measure of the decrease with respect

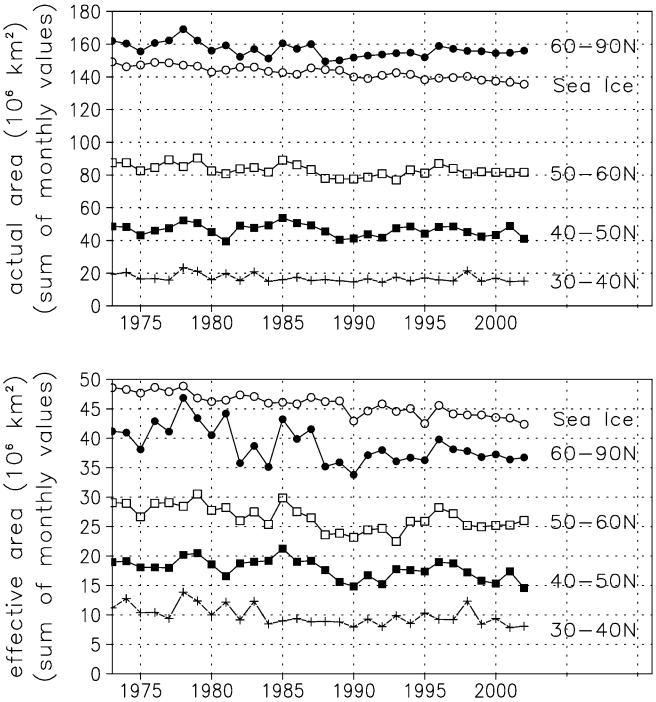

Fig. 7 The sum of monthly values of actual area and insolation weighted areas for the period 1973–2002

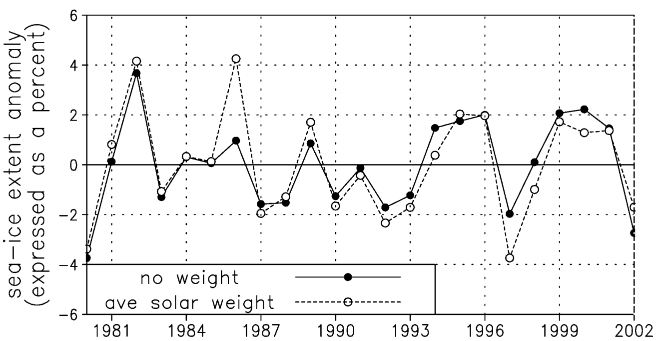

Fig. 8 Antarctic annual-averaged sea-ice extent anomaly, 1980–2002, for the cases of no weighting and average daily solar weighting

to the albedo radiative feedback to the atmosphere. The greater percentage decrease in the insolation-weighted value is a result of an earlier spring decrease in areal coverage.

Figures 8 and 9 show the analysis for Antarctic sea-ice using the insolation-weighted assessment. In contrast to the Arctic sea ice, there is no clear trend during the period of record in areal coverage, with significant interannual variability. In another study, Vyas et al. (2003) does show a slight increase in areal coverage between the years 1978–2001. The insolation-based values do show a negative trend but this interpretation is a direct result of one larger value in 1986 as contrasted with the areal coverage. During the period from

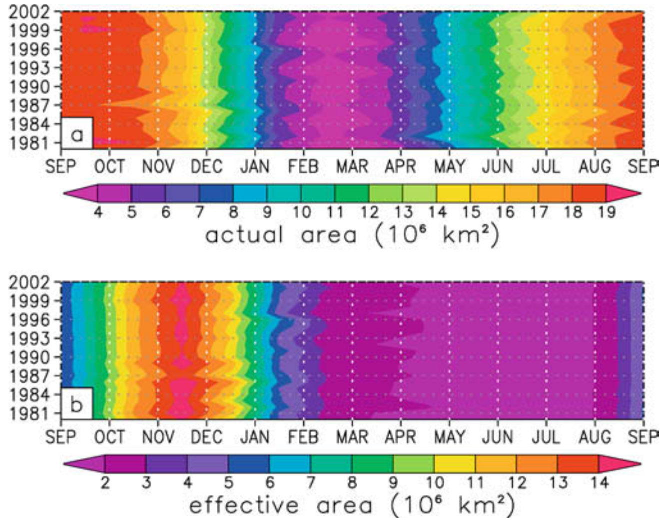

Fig. 9 **a** Actual and **b** insolation-weighted monthly Antarctic sea-ice extent for 1980–2002

the early 1990s to 2001, there was a slight increase in coverage.

4 Conclusions

The use of latitude bands and insolation effective areas provide a more detailed assessment of snow-cover and sea-ice trends than can be obtained using just total area by itself. One of the conclusions of our assessment is that while a decrease in both areal coverage and the insolation-weighted values have occurred, the data does not show a monotonic decrease of either Arctic sea-ice or Northern Hemisphere snow cover. If Arctic perennial sea-ice is decreasing, since the total areal reduction is relatively small, a large portion of it is being replenished each year such that its radiative feedback to the atmosphere is muted. Antarctic sea-ice shows no significant trend during the period of record analyzed although there is a small insolation-weighted decrease using a linear trend across the entire period of record.

The comparison of general circulation model simulations of changes over the last several decades in insolation-weighted sea-ice and snow cover should be a priority research topic in order to test the predictive skill of these models.

Our analysis approach should be generalized to include cloud cover and surface albedo effects on the insolation at the surface. The insolation received and reflection from snow cover and sea-ice are influenced by the cloud cover, which varies diurnally and monthly. The surface snow albedo is affected by vegetation masking, as well as its patchiness, while the albedo of sea-ice changes as it ages during the melt season.

Our analysis of snow cover and sea-ice uses a specific set of data. Other data sets, with different thresholds of areal coverage, should be applied to determine if our insolation-based assessment is robust. Our work, however, clearly demonstrates the value-added in climate studies of the cryosphere using this assessment approach.

Acknowledgements The snow data was obtained from NOAA weekly snow maps, which are produced by a visual interpretation of visible satellite imagery. The information is standardized, converted to monthly values, and archived at Rutgers University (http://climate.rutgers.edu/snowcover). The DMSP SSM/I sea-ice data were obtained from the National Snow and Ice Data Center. The Referees provided specific suggestions which significantly improved the study. Support for this work was provided by National Science Foundation Grants 0229973-001 and ATM-9905924, and by National Oceanic and Atmospheric Administration Grant NA06GPO566.

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