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Comparison of surface albedo feedback in climate models and observations

J. A. Crook[1] **and P. M. Forster**[1]

[1]School of Earth and Environment, University of Leeds, Leeds, UK

Abstract Snow and ice albedo feedback plays an important role in the greater warming of the Arctic compared to the tropics. Previous work has estimated the observed Northern Hemisphere cryosphere feedback, but there have been no estimates of surface albedo feedback from observations globally. Here we compare the zonal mean surface albedo feedback from satellite data sets with that from eleven ocean-atmosphere coupled climate models for both climate change and the seasonal cycle. Differences between observed data sets make it difficult to constrain models. Nevertheless, we find that climate change Northern Hemisphere extratropical feedback is considerably higher for observations (potentially $3.1 \pm 1.3\,\mathrm{W\,m^{-2}\,K^{-1}}$) than models ($0.4\text{–}1.2\,\mathrm{W\,m^{-2}\,K^{-1}}$), whereas the seasonal cycle feedback is similar in observations and models, casting doubt on the ability of the seasonal cycle to accurately predict the climate change feedback. Observed Antarctic sea ice feedback is strongly positive in the seasonal cycle and similar to models.

Key Points:

- Models underestimate climate change feedback in the NH extratropics
- Observed Antarctic feedback is strongly positive in the seasonal cycle
- The observed seasonal cycle is unlikley to constrain modeled feedback much

Supporting Information:

- Readme
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Table S1
- Text S1

Correspondence to:
J. A. Crook,
J.A.Crook@leeds.ac.uk

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1. Introduction

Rapid decline of Arctic sea ice in recent years [*Serreze et al*., 2007; *Stroeve et al*., 2007; *Comiso et al*., 2008] has sparked interest in the causes of the greater coincident warming seen in this region compared to the global mean [*Trenberth et al*., 2007]. A number of modeling studies suggest that surface albedo feedback from changes in snow and ice plays an important, although not exclusive, role [*Forster et al*., 2000; *Holland and Bitz*, 2003; *Hall*, 2004; *Vavrus*, 2004; *Alexeev et al*., 2005; *Cai*, 2006; *Winton*, 2006; *Cai and Lu*, 2007; *Lu and Cai*, 2009; *Crook et al*., 2011]. There are few estimates of observed surface albedo feedback. *Flanner et al*. [2011] estimate the observed 1979–2008 Northern Hemisphere snow and ice albedo feedback and suggest that models underestimate this feedback. *Hall and Qu* [2006] estimate the observed spring time Northern Hemisphere snow albedo sensitivity to temperature from the seasonal cycle and show that several models fall outside the estimated range. They suggest that the seasonal cycle can be used to estimate Northern Hemisphere snow albedo sensitivity in the climate change context during spring time. This suggestion comes from analyzing models. In this study we estimate observed surface albedo feedback, extending coverage to the Southern Hemisphere and non-cryosphere regions, and we ascertain whether the seasonal cycle can be used to estimate climate change feedback in regions other than Northern Hemisphere extratropical land.

2. Data and Methods

Surface albedo feedback (Y_α) is commonly defined as the change in the net downward top of atmosphere (TOA) shortwave radiative flux per unit surface temperature change caused by changes in surface albedo (α_s):

$$Y_\alpha = \frac{\partial Q_\alpha}{\partial T} = -I\frac{\partial \alpha_p}{\partial \alpha_s}\frac{\partial \alpha_s}{\partial T} \tag{1}$$

We calculate Y_α for both climate change (Y_{α_cc}) and from the seasonal cycle (Y_{α_sc}) for zonal means and a number of regional means, thereby extending coverage to the Antarctic and non-cryosphere regions. The regional means are for Northern Hemisphere extratropics (poleward of 30°N, hereafter NHext), Southern Hemisphere extratropics (poleward of 30°S, hereafter SHext), both of which are also split into land only and sea only, and Northern Hemisphere sea ice (sea poleward of 60°N, hereafter NH sea ice) and Southern Hemisphere sea ice (sea poleward of 60°S, hereafter SH sea ice). Further details are in the supporting information. To calculate Y_α, we regress estimates of the change in net downward TOA shortwave flux caused by changes in surface albedo against the coincident change in surface temperature for the same region. We estimate the net downward TOA shortwave flux, Q_α, using the Edwards Slingo radiative transfer model (ESRAD) [*Edwards and Slingo*, 1996] set up with temperature, cloud, and water vapor climatological monthly mean profiles based on the International Satellite Cloud Climatology Project (ISCCP) [*Schiffer and Rossow*, 1983] data. For the climate change case, we set the surface albedo from the satellite data set or model in each month in each year of the time series. The changes in temperature and Q_α used in the regressions are the differences from the mean over the whole time period. For the seasonal cycle case, we run ESRAD for a single year, setting the climatological monthly mean surface albedo from the satellite data set or model in each month (referred to as sc), and perform a second radiative transfer run setting all months to the annual mean of the observed/modeled climatological monthly mean surface albedo (referred to as no_sc). We take the difference in Q_α values obtained from the sc and no_sc runs to obtain a measure of the radiative impact of the albedo seasonal cycle, but this difference must also be scaled to remove the effects of different downward TOA shortwave radiation and atmospheric differences between months:

$$\Delta Q_{\alpha,\mathrm{sc}}(x,m) = \frac{\left[Q_{\alpha,\mathrm{sc}}(x,m) - Q_{\alpha,\mathrm{no\_sc}}(x,m)\right].\overline{Q_{\alpha,\mathrm{no\_sc}}}(x)}{Q_{\alpha,\mathrm{no\_sc}}(x,m)} \tag{2}$$

where x and m refer, respectively, to space and month dependencies, and $\overline{Q_{\alpha,\mathrm{no\_sc}}}(x)$ is the annual mean of $Q_{\alpha,\mathrm{no\_sc}}(x,m)$. This $\Delta Q_{\alpha,\mathrm{sc}}$ is regressed against the climatological mean surface temperature anomalies (difference from annual mean) in each month.

The impact of the differences between our methods and those of previous studies is discussed in the supporting information. We do not expect the use of regression rather than trends to have a significant effect in the Northern Hemisphere cryosphere. In other regions where the temperature trend in recent climate change is small, our regression method is unaffected by large percentage errors in trends but may be affected if the feedback behaves differently under internal variability. The use of ESRAD rather than the kernel method does impact the absolute value of the feedback but does not affect our comparisons between models and observations.

We use monthly mean surface albedo and temperature data for 11 ocean-atmosphere coupled climate models taking part in the Climate Model Intercomparison Project phase 3 (CMIP3) [*Meehl et al.*, 2007]. We use data from 1983 to 2009 from the 20c3m and sresa1b simulations to cover a similar time period to the observations. Observed surface albedo data are from three sources: monthly surface reflectance data from the ISCCP D2 data set [*Schiffer and Rossow*, 1983], land surface broadband white-sky albedo data (MCD43C3) from the Moderate Resolution Imaging Spectroradiometer (MODIS) data set, and monthly broadband surface albedo data from the Extended Advanced Very High Resolution Radiometer Polar Pathfinder (APP-x) data set [*Wang and Key*, 2005a, 2005b]. The ISCCP D2 data set covers most of the globe for the period July 1983 to June 2008, the MODIS data set covers much of the land area for the period March 2000 to August 2009, and the APP-x data set covers the polar regions for the period January 1982 to December 2004.

We use surface temperature data from the ERA40 [*Uppala et al.*, 2005] and ERA Interim [*Dee et al.*, 2011] data sets to determine Y_{α_cc}. These data sets provide a reanalysis product of absolute surface temperature over the required time period giving full spatial coverage on a 2.5° × 2.5° grid. It would be preferable to use the HadCRUT4 anomaly time series [*Morice et al.*, 2012] data set because it is based entirely on observations with no infilling of missing data and quality controlled for use in climate studies. Unfortunately, its data coverage is poor at high latitudes, particularly in Antarctica, making it impossible to measure surface albedo feedback in this region. In other regions, these two temperature data sets are in good agreement. We use the CRU Absolute [*Jones et al.*, 1999] climatology data set to determine Y_{α_sc} for which the difference between the temperatures in each month is required. This data set is based on the 1961–1990 observed climatology with infilling of missing data.

As a preliminary test, we determine whether the satellite era is long enough to give a good measure of the long-term Y_{α_cc} by comparing the modeled Y_{α_cc} in the different satellite periods with that from the 70 year period of increasing CO_2 in the 1pctto2x model simulations. Ice albedo feedback is not the same in the internal variability context as the climate change context [*Hall*, 2004]. This is likely to have an impact on the 1983–2009 Y_{α_cc} where internal variability plays a larger role, especially in the Antarctic where the 1983–2009 temperature trend, and therefore signal-to-noise ratio, is small. The modeled observation period may also include land use changes which could affect surface albedo, and therefore Y_{α_cc}. We perform correlations between the Y_{α_cc} for 1pctto2x and observational period for several different regions and with the different observational masks (see the supporting information). The correlations are poor in all regions for the MODIS masked results, suggesting that it is not possible to obtain a good measure of the long-term Y_{α_cc} using only 10 years of observations, such as is available with MODIS. The correlations are good for NHext for no masking

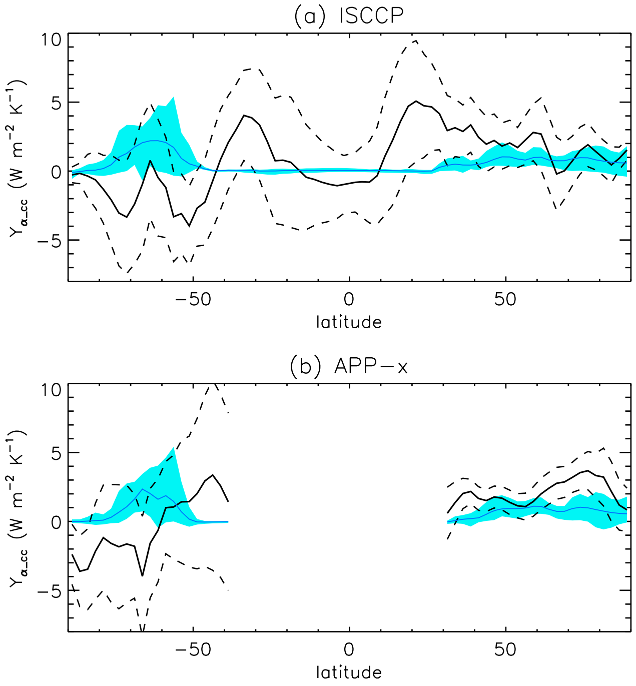

Figure 1. Comparison of observed (black) and model mean (blue) climate change feedback for (a) ISCCP 1983–2008 and (b) APP-x 1982–2004. Models have had the observed albedo missing data mask applied before determining Y_{α_cc}. The dashed lines show the ±2σ uncertainty in the observed Y_{α_cc} determined from the regressions. The light blue shading shows the range of the modeled Y_{α_cc}.

and for ISCCP and APP-x masking. Although SHext has poor correlations, SH sea ice has good correlations for no masking and ISCCP masking. This suggests that it should be possible to obtain a reasonable measure of at least the NHext long-term Y_{α_cc} from 23 or more years of recent observations.

3. Results

3.1. Climate Change Surface Albedo Feedback

The ISCCP annual zonal mean Y_{α_cc} shows distinct features of high positive feedback in midlatitudes in both hemispheres and a negative feedback in the Antarctic unlike models (Figure 1a). A breakdown of the feedback into contributions from all continents and the sea is not able to reveal any particular region being responsible for the midlatitude peaks. It is not clear how much vegetation feedbacks (not represented in the models) or land use change (only in seven of the models) have contributed to changes in albedo. We would not expect the sea to have an influence in regions where there is no sea ice, suggesting that this could be a spurious feature of ISCCP data related to difficulties of measuring albedo under cloudy conditions. Unfortunately, neither APP-x nor MODIS albedo can be used to confirm the midlatitude ISCCP Y_{α_cc}. However, it should be noted that the errors in the observed feedback are large particularly in the Southern Hemisphere. The range of zonal mean Q_α values over the time series in ISCCP and APP-x is an order of magnitude greater than in models although temperature ranges are similar. It appears that there is much greater change in surface albedo that is unrelated to temperature change in observations than models, resulting in much greater errors in observed Y_{α_cc}.

The APP-x annual mean Y_{α_cc} is positive in NHext and negative in the Antarctic (Figure 1b), like the ISCCP Y_{α_cc}. The annual mean NHext Y_{α_cc} for APP-x is 3.1 (±1.3) W m^{-2} K^{-1}, for ISCCP it is 2.0 (±1.8) W m^{-2} K^{-1}, whereas modeled NHext 1983–2009 Y_{α_cc} ranges from −0.2 to 1.6 W m^{-2} K^{-1}, depending on the model and observation mask applied. This model range extends from 0.4 to 1.0 W m^{-2} K^{-1} for Y_{α_cc} from the 1pctto2x simulations. The APP-x estimate is likely higher than the ISCCP estimate due to different missing data; modeled NHext Y_{α_cc} is generally higher (~1.3 times) with APP-x masking than with no masking. The higher observed NHext Y_{α_cc} comes from both land and sea. Despite annual mean modeled NHext Y_{α_cc} being considerably lower than observed NHext Y_{α_cc}, most models have higher Arctic Y_{α_cc} in summer than observed Y_{α_cc}. It is likely that this is due to difficulties of measuring surface albedo of sea ice under cloudy conditions, rather than models overpredicting the melting of Arctic sea ice [*Stroeve et al.*, 2007]. This implies that observed Y_{α_cc} could be even higher than our estimates. *Flanner et al.* [2011] also found the observed annual mean Northern Hemisphere snow and sea ice albedo feedback to be considerably higher than models, and *Winton* [2011] showed that climate models underestimate the recent sensitivity of annual mean Arctic sea ice coverage to temperature. Unlike the Northern Hemisphere, there is little temperature change in the Antarctic compared to internal variability over 1983–2008. The Y_{α_cc} measured here is more dependent on internal variability than forced change and can be influenced strongly by 1 or 2 years with extreme values. It may also be more influenced by changes in snow fall rather than melting ice. Poleward of 65°S, the linear trend in both ISCCP and APP-x albedo is negative, and the linear trend in ERA40/Interim temperature is

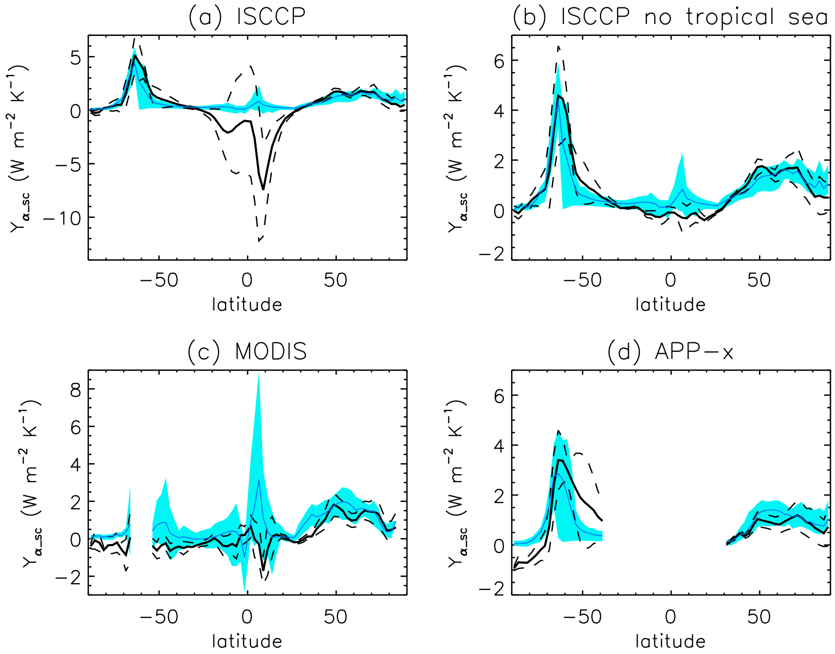

Figure 2. Comparison of observed (black) and model mean (blue) seasonal cycle feedback. Models have had the equivalent observed albedo missing data mask applied before determining Y_{α_sc}. The dashed lines show the ±2σ uncertainty in the observed Y_{α_sc} determined from the regressions. The light blue shading shows the model range with the exception that one model has been removed around 50S in Figure 2c as it had exceptionally high (~12 W m^{-2} K^{-1}) Y_{α_sc}.

positive, suggesting that Y_{α_cc} due to forced change is likely positive here. Between 30°S and 65°S, the temperature trend is negative. Observations of Antarctic sea ice extent show a small positive linear trend [*Turner et al.*, 2013] consistent with a positive Y_{α_cc}, but neither APP-x nor ISCCP albedo observations show the expected increase in albedo in the sea ice region.

3.2. Seasonal Cycle Surface Albedo Feedback

Zonal mean Y_{α_sc} for observations and models are shown in Figure 2. The large negative peaks in the tropical ISCCP Y_{α_sc} (Figure 2a) are entirely due to sea and are very likely to be spurious features caused by cloud (tropical cloud-like patterns are visible in maps of the seasonal cycle of ISCCP albedo). With the tropical sea contribution removed (Figure 2b), ISCCP and modeled tropical Y_{α_sc} are much more similar. Unlike in the climate change context, both ISCCP and APP-x (Figure 2d) show strong positive SH sea ice Y_{α_sc} (3.2 ± 1.2 W m^{-2} K^{-1} for ISCCP and 2.2 ± 1.0 W m^{-2} K^{-1} for APP-x). Although models show little change in albedo in the Antarctic continent in the seasonal cycle, both MODIS (Figure 2c) and APP-x do have a significant change resulting in a negative Y_{α_sc}, but this is not backed up by ISCCP. In this region, the temperature does not rise above freezing point. Therefore, either this is an artefact in both MODIS and APP-x, or the albedo changes are due to changes in snow accumulation and deposition of dirt which may well be modeled poorly. Several models have a higher Y_{α_sc} than APP-x in Northern Hemisphere high latitudes. With the MODIS mask applied (Figure 2c), Y_{α_sc} is large for some models around 50°S and 5°N unlike observations. Y_{α_sc} around 50°S is due to snow albedo in Patagonia where some models have a much greater seasonal cycle in the albedo than MODIS and ISCCP data suggest is the case. This may be due to difficulties of representing mountainous regions in models or of observing albedo in mountainous regions. Y_{α_sc} around 5°N comes from central Africa and Venezuela, areas in which models may not perform well. The cause of this large Y_{α_sc} in some models is not immediately obvious and is beyond the scope of this study.

3.3. Comparison of Climate Change and Seasonal Cycle Surface Albedo Feedback

We now compare the feedback in the seasonal cycle and climate change contexts (Figure 3) to test whether the seasonal cycle can be used to estimate annual mean climate change surface albedo feedback in all regions. See also the supporting information. As in *Hall and Qu* [2006], Y_{α_sc} for several models fall outside the observed estimates, but it should be noted that the shading only indicates the error estimate from the regressions and does not include estimates of errors in the measurements themselves.

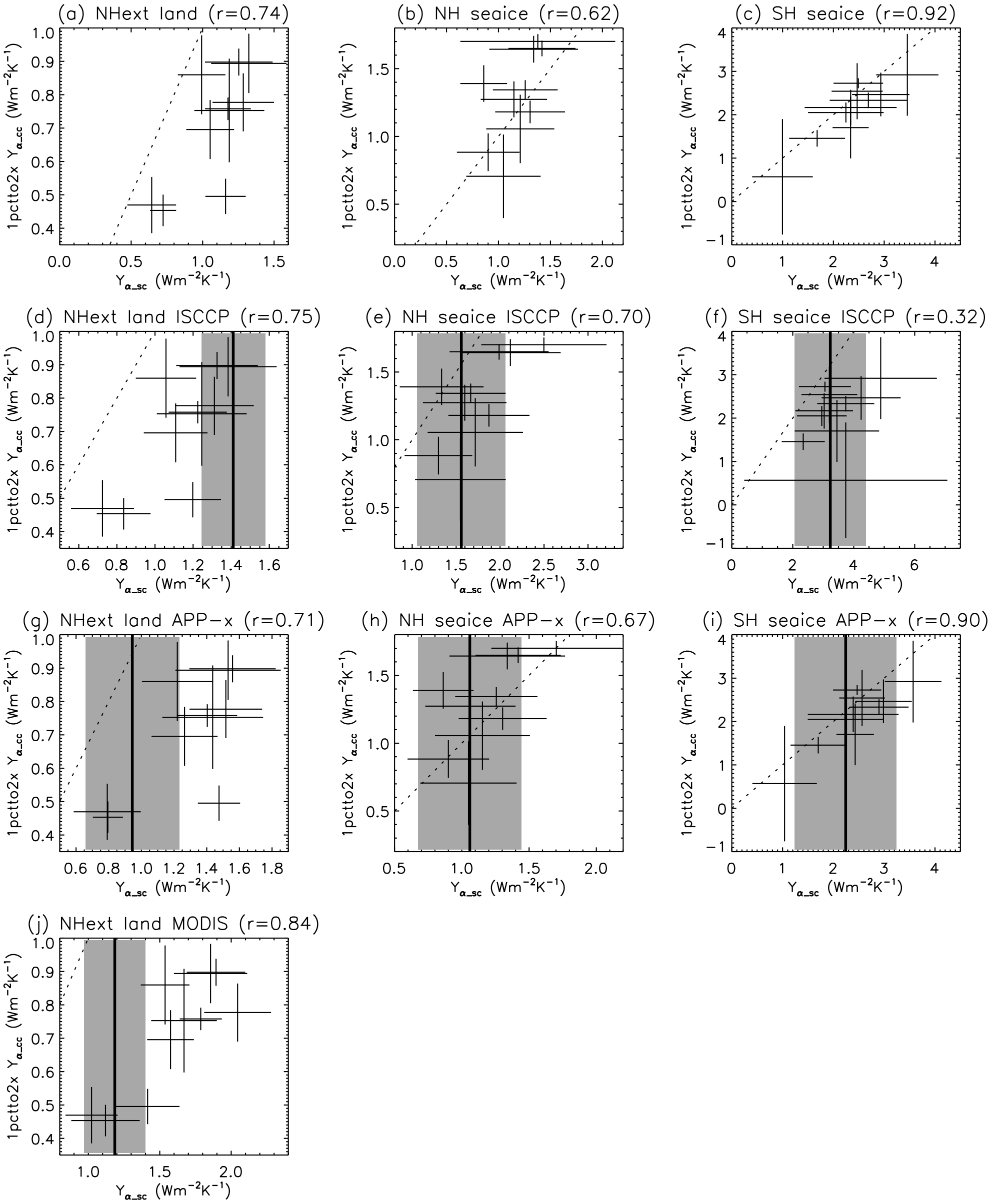

Figure 3. Scatterplot of the 1pctto2x climate change feedback vs. the seasonal cycle feedback from all models (horizontal and vertical bars indicate the ±2σ error determined from the regressions) for no masking and different observation masks on Y_{α_sc}. Observed Y_{α_sc} for the indicated satellite data set is shown as a vertical line with shading showing the ±2σ uncertainty. The dashed line shows the 1:1 line and correlations are provided.

For the NHext land (Figures 3a, 3d, 3g, and 3j) and NH sea ice (Figures 3b, 3e, and 3h), we find a fairly good correlation between 1pctto2x Y_{α_cc} and Y_{α_sc} although this depends on the observation mask used for Y_{α_sc}. This suggests that we might be able to use observed Y_{α_sc} to constrain models and estimate Y_{α_cc} in both these regions. For models, Y_{α_cc} is lower than Y_{α_sc} for NHext land and is comparable or lower than Y_{α_sc} for the NH sea ice region; however, our observed Y_{α_cc} is comparable to or higher than the observed Y_{α_sc} in both these regions, suggesting that the relationship may not hold so well in the real world. For SH sea ice, we find a good correlation between 1pctto2x Y_{α_cc} and Y_{α_sc} and a good fit to the 1:1 line for no masking (Figure 3c) and APP-x masking (Figure 3i), suggesting that it may be possible to estimate Y_{α_cc} from Y_{α_sc}. There is a good agreement between modeled and observed Y_{α_sc} in this region, although the errors only provide limited constraints on models. These results suggest that using Y_{α_sc} as an estimate of Y_{α_cc} may be possible, but due to the uncertainty in observed Y_{α_sc} it is unlikely to be able to put much constraint on models.

4. Conclusions

Looking at zonal means has allowed us to highlight some issues with the satellite data. APP-x and ISCCP show some significant disagreements, highlighting the need for accurate measures of surface albedo in order to constrain the feedback. Nevertheless, our results show that models underestimate the NH extratropical climate change feedback, although they capture the seasonal cycle feedback here much better. It is very likely that APP-x and MODIS data have better quality than ISCCP, since ISCCP reflectance is determined from only two visible channels. Although in Antarctica the climate change feedback is negative in observations and positive in models, the seasonal cycle feedback is strongly positive in both. We may simply need a larger temperature change in Antarctica to be able to measure the climate change feedback here. Although the Antarctic sea ice region is small and does not contribute largely to the global mean feedback, the fact that the local feedback here is strong causes strong meridional heating responses [*Crook et al*., 2011]. The seasonal cycle feedback may provide an estimate of the long-term climate change feedback, but whether this can be used to constrain models is questionable. There are uncertainties in measuring surface albedo feedback due to differences in methodologies, and these differences also affect the robustness of the seasonal cycle climate change feedback relationship. However, our study shows that this relationship is also affected by whether there are missing data, as there is in observations, which was not taken into account in previous studies. We also find that the observed NH extratropical seasonal cycle and climate change feedbacks are quite different. Our analysis has used the CMIP3 climate models, but *Qu and Hall* [2013] find very similar NH snow albedo feedback behavior in the CMIP5 generation of climate models to the CMIP3 generation. This is strongly suggestive that our findings are equally applicable in the CMIP5 generation of models. Understanding reasons for the low NH extratropical climate change feedback for both land and sea in the current generation of climate models should be a priority.

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