Comparison of surface albedo feedback in climate models and observations

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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 $3.1 \pm 1.3$ W m$^{-2}$ K$^{-1}$) than models (0.4–1.2 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.

1. Introduction

Rapid decline of Arctic sea ice in recent years [Sereze 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 ($Y_a$) 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 ($\alpha$):

$$Y_a = \frac{\partial Q_{\text{down}}}{\partial T_s} = -\frac{\partial \alpha}{\partial \alpha_s} \frac{\partial T_s}{\partial T}$$

(1)

We calculate $Y_a$ for both climate change ($Y_{a,cc}$) and from the seasonal cycle ($Y_{a,sc}$) 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 NHEx), Southern Hemisphere extratropics (poleward of 30°S, hereafter SHEx), 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 $Y_{a,cc}$ 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, $Q_{sw}$, using the Edwards Slingo radiative transfer model (ESRAD) [Edwards and Slingo, 1996] set up with temperature, cloud, and water vapor climatological monthly mean profiles.
As a preliminary test, we determine whether the satellite era is long enough to give a good measure of the 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

where \( x \) and \( m \) refer, respectively, to space and month dependencies, and \( \bar{Q}_{\text{sc,no,sc}} (x,m) \) is the annual mean of \( Q_{\text{sc,no,sc}} (x,m) \). This \( \Delta Q_{\text{sc,cc}} \) 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 \( Y_{\text{sc,cc}} \). 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 \( Y_{\text{sc,cc}} \) 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 \( Y_{\text{sc,cc}} \) by comparing the modeled \( Y_{\text{sc,cc}} \) in the different satellite periods with that from the 70 year period of increasing CO2 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 \( Y_{\text{sc,cc}} \) 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 \( Y_{\text{sc,cc}} \). We perform correlations between the \( Y_{\text{sc,cc}} \) 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 \( Y_{\text{sc,cc}} \) using only 10 years of observations, such as is available with MODIS. The correlations are good for NHnext for no masking.
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 \( Y_{\alpha,cc} \). However, it should be noted that the errors in the observed feedback are large particularly in the Southern Hemisphere. The range of zonal mean \( Q_\alpha \) 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 \( Y_{\alpha,cc} \).

The APP-x annual mean \( Y_{\alpha,cc} \) is positive in NHext and negative in the Antarctic (Figure 1b), like the ISCCP \( Y_{\alpha,cc} \). The annual mean NHext \( Y_{\alpha,cc} \) for APP-x is \( 3.1 \pm 1.3 \) W m\(^{-2}\) K\(^{-1}\), for ISCCP it is \( 2.0 \pm 1.8 \) W m\(^{-2}\) K\(^{-1}\), whereas modeled NHext 1983–2009 \( Y_{\alpha,cc} \) 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 \( Y_{\alpha,cc} \) from the 1pctto2x simulations. The APP-x estimate is likely higher than the ISCCP estimate due to different missing data; modeled NHext \( Y_{\alpha,cc} \) is generally higher (~1.3 times) with APP-x masking than with no masking. The higher observed NHext \( Y_{\alpha,cc} \) comes from both land and sea. Despite annual mean modeled NHext \( Y_{\alpha,cc} \) being considerably lower than observed NHext \( Y_{\alpha,cc} \), most models have higher Arctic \( Y_{\alpha,cc} \) in summer than observed \( Y_{\alpha,cc} \). 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 \( Y_{\alpha,cc} \) 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 \( Y_{\alpha,cc} \) 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
positive, suggesting that $Y_{\alpha_{cc}}$ 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 $Y_{\alpha_{cc}}$, 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 $Y_{\alpha_{sc}}$ for observations and models are shown in Figure 2. The large negative peaks in the tropical ISCCP $Y_{\alpha_{sc}}$ (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 $Y_{\alpha_{sc}}$ are much more similar. Unlike in the climate change context, both ISCCP and APP-x (Figure 2d) show strong positive SH sea ice $Y_{\alpha_{sc}}$ ($3.2 \pm 1.2 \text{ Wm}^{-2}\text{K}^{-1}$ for ISCCP and $2.2 \pm 1.0 \text{ Wm}^{-2}\text{K}^{-1}$ 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 $Y_{\alpha_{sc}}$, 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 $Y_{\alpha_{sc}}$ than APP-x in Northern Hemisphere high latitudes. With the MODIS mask applied (Figure 2c), $Y_{\alpha_{sc}}$ is large for some models around 50°S and 5°N unlike observations. $Y_{\alpha_{sc}}$ 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. $Y_{\alpha_{sc}}$ around 5°N comes from central Africa and Venezuela, areas in which models may not perform well. The cause of this large $Y_{\alpha_{sc}}$ 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], $Y_{\alpha_{sc}}$ 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.
For the NH next land (Figures 3a, 3d, 3g, and 3j) and NH sea ice (Figures 3b, 3e, and 3h), we find a fairly good correlation between 1pctto2x \( Y^{\alpha}_{cc} \) and \( Y^{\alpha}_{sc} \) although this depends on the observation mask used for \( Y^{\alpha}_{sc} \). This suggests that we might be able to use observed \( Y^{\alpha}_{sc} \) to constrain models and estimate \( Y^{\alpha}_{cc} \) in both these regions. For models, \( Y^{\alpha}_{cc} \) is lower than \( Y^{\alpha}_{sc} \) for NH next land and is comparable or lower than \( Y^{\alpha}_{sc} \) for the NH sea ice region; however, our observed \( Y^{\alpha}_{cc} \) is comparable to or higher than the observed \( Y^{\alpha}_{sc} \) 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 \( Y^{\alpha}_{cc} \) and \( Y^{\alpha}_{sc} \) 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 \( Y^{\alpha}_{cc} \) from \( Y^{\alpha}_{sc} \). There is a good agreement between modeled and observed \( Y^{\alpha}_{sc} \) in this region, although the errors only provide limited constraints on models. These results suggest that using \( Y^{\alpha}_{sc} \) as an estimate of \( Y^{\alpha}_{cc} \) may be possible, but due to the uncertainty in observed \( Y^{\alpha}_{sc} \) it is unlikely to be able to put much constraint on models.

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 \( Y^{\alpha}_{sc} \). Observed \( Y^{\alpha}_{sc} \) 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.
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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