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An Alternative Method to Calculate Cloud Radiative Forcing: Implications for Quantifying Cloud Feedbacks

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Abstract

A modification to the traditional cloud radiative forcing (CRF) formula is presented. This alternative approach uses *incident*--rather than absorbed--solar radiation to calculate shortwave cloud radiative forcing at the surface. By removing the competing influence of surface albedo on CRF, the new formula more effectively isolates the impact of clouds and cloud changes under different climatic regimes. The removal of surface albedo effects makes the change in CRF a more useful measure of cloud feedback, although other factors (such as changes in clear-sky solar absorption) can still muddle the interpretation. I present examples from GCM greenhouse simulations that demonstrate how this new formula can help to differentiate between actual cloud feedbacks versus apparent ones induced by snow and ice meltback using the traditional CRF equation. The results suggest that changes in surface albedo contribute approximately 20 to 40% of the high-latitude CRF anomaly using the standard formula applied to an equilibrium 2 x CO_2 simulation and about 50% to the greater Arctic when used on 21^{st}-century transient greenhouse experiments.

1. Introduction

Cloud feedbacks are considered the largest source of uncertainty in projections of future climate change [*IPCC*, 2001]. Unfortunately, there is also considerable variation in how to determine cloud feedback in climate models. Several methods have been described in the literature, including the use of GCM output to drive simplified climate models [*Hansen et al*., 1984] or offline radiative transfer calculations [*Wetherald and Manabe*, 1988], GCM simulations with fixed clouds [*Vavrus*, 2004], and calculating the change in cloud radiative forcing (CRF) [*Cess et al*., 1990]. As discussed by these authors and others [e.g., *Colman*, 2003], each of these methods has certain advantages and disadvantages, but the simplicity of the CRF approach has given it widespread usage [*Senior*, 1999; *Yao and Del Genio*, 1999; *Tsushima and Manabe*, 2001]. However, this method has been criticized on the grounds that a change in CRF is not equivalent to a cloud feedback [*Soden et al*., 2004] and that such a change can be caused by numerous non-cloud factors, such as a varying solar zenith angle, changes in clear-sky radiative properties, and alterations in surface albedo [*Minnett, 1999*; *Rossow and Zhang*, 1995]. The last of these complicating effects is especially important for assessing cloud feedbacks in polar regions, where major climatic shifts typically involve large changes in surface albedo induced by the response of snow and ice cover.

This paper describes an alternative CRF formulation that removes the contaminating effect of surface albedo changes and thus is particularly well suited to assessing cloud feedbacks in high latitudes, although it can be applied globally. The new formula is designed for quantifying the CRF at the surface and may be used for evaluating the role of clouds in a given climatic regime or in a climate change context. The only other known applications of this type of formula were by *Long and Ackerman* [2000] and Minnett [1999]. The former study calculated “cloud effect”, but the primary interest was in testing automated measurements of clear-sky periods by a broadband pyranometer over short intervals in non-frozen environments, while the latter paper mainly addressed the influence of solar zenith angle on CRF. Here I demonstrate the widespread applicability of this method under greenhouse forcing experiments, utilizing results from several recent GCM simulations.

2. Description of Cloud Radiative Forcing

CRF is defined as the radiative impact of clouds at a reference level of either the top of the atmosphere (TOA) or the surface (SFC). Using the formulation of *Ramanathan et al.* [1989], the total CRF is the sum of the separate shortwave (SW) and longwave (LW) components:

$$CRF_{LW} = F(A_c) - F(0) \quad (1)$$

$$CRF_{SW} = S(A_c) - S(0) \quad (2)$$

$$CRF = CRF_{LW} + CRF_{SW} \quad (3)$$

where A_c is the cloud fraction, F is the net LW flux, and S is traditionally defined as the absorbed SW flux. The first terms on the right hand side of (1) and (2) are the fluxes under all-sky conditions, while the second terms refer to clear-sky fluxes. CRF values greater (less) than 0 imply that clouds have a warming (cooling) effect at the reference level (TOA or SFC).

One of the shortcomings of this traditional approach is the strong influence that the surface albedo exerts on the net SW fluxes and thus CRF_{SW} in (2). The surface reflectivity thus complicates the goal of isolating the radiative influence of clouds. One way to avoid this problem is simply to use the *incident* rather than the net SW fluxes in (2) when calculating CRF (this modification can not apply to TOA CRF). Intuitively, this alternative approach is appealing, because the goal of calculating CRF is to evaluate the impact of clouds, not surface characteristics. This modification has little effect in regions where surface albedo is low but can significantly change CRF_{SW} in high latitudes, where large solar zenith angles and prevalent snow and ice cover cause pronounced surface reflectivity during most of the year. In these areas, using incident instead of net SW in (2) causes a decrease in CRF_{SW} (more negative), because surface albedo no longer smears the difference between the clear-sky and all-sky solar fluxes. This alternative CRF formula ignores any analogous differences between incident and absorbed LW in calculating CRF_{LW}, an assumption justified by the fact that surface emissivity and thus absorptivity is typically near the maximum of 1. Thus, the amount of incident or absorbed longwave radiation at the surface between cloudy and clear conditions is already dictated by the downwelling impact of clouds in (1), rather than by surface properties.

Using incident solar radiation (in the modified formula) instead of absorbed SW flux (in the traditional formula) provides improvements in identifying the radiative impact of clouds under current climatic conditions as well as altered climates. *Intrieri et al*. [2002] and *Shupe and Intrieri* [2004] used data from the SHEBA ice camp in the Arctic Ocean to show that observed CRF depends strongly on the surface albedo. Observations demonstrate that the net effect of Arctic clouds is to warm the surface during winter (when positive CRF_{LW} dominates) and to cool during summer (when negative CRF_{SW} dictates) [*Schweiger and Key*, 1994]. However, because surface albedo is still sizeable even during Arctic summer, the cooling effect of summertime clouds may be underestimated by the traditional CRF formula. In greenhouse warming simulations, the large drop in polar surface albedo favors the typically negative changes in CRF_{SW} [*Senior*, 1999; *Yao and Del Genio*, 1999; *Vavrus*, 2004], regardless of cloud behavior.

Recent satellite-derived time series from the Arctic show increasingly negative CRF_{SW} [*Wang and Key*, 2003], a trend that agrees with the significant increases in warm-season clouds but also consistent with the decrease in surface albedo during the past decades.

3. Applications of modified CRF formula

Climate model simulations with greenhouse forcing are used to demonstrate the effect of the altered CRF equation (i.e., using incident rather than net SW flux in (2)). 2 x CO_2 experiments using fixed and interactive clouds in the GENESIS2 atmosphere/mixed-layer GCM help to separate the role of changes in clouds versus surface conditions on CRF_{SW}, while a set of transient greenhouse runs using the recently released IPCC model archive illustrates the utility of the new formula across a collection of state-of-the-art, fully coupled atmosphere-ocean climate models. The GENESIS2 model and its 2 x CO_2 simulations are fully described in *Vavrus* [2004], a study that focused on clouds and Arctic climate. The standard greenhouse run with prognostic cloud changes (2CO2) is compared with a companion run in which 3-dimensional cloud fields were fixed at their modern control values (2CO2F). Figure 1 shows for each case the zonally averaged changes between the 2 x CO_2 and modern control runs for CRF_{SW}, cloud fraction, and surface albedo. The surface CRF_{SW} is calculated using both the traditional formula and the modified equation for CRF_{SW}. In 2CO2 (Fig. 1a), the general pattern of CRF_{SW} increases (decreases) in lower and middle (high) latitudes using either formula bears a strong negative correlation with the distribution of cloud cover anomalies (Fig 1c). This agreement suggests that the calculated CRF_{SW} is capturing the cloud feedback, such that greater (less) cloudiness causes less (greater) solar radiation and heating at the surface and thus a negative feedback poleward of about 45° and a positive feedback in lower latitudes. Closer inspection, however, reveals a complication in high latitudes, where reduced surface albedo (Fig. 1d), due mostly to sea ice melt, strongly favors CRF_{SW} decreases in regions of large ice loss. This superimposed effect from altered surface characteristics is especially pronounced in the region with maximum sea ice reduction in the Southern Ocean (around 60ºS), where the CRF_{SW} falls by 16 W m^{-2} using the traditional formula. This negative CRF_{SW} spike is nearly halved, however, when applying the modified formula. Such a difference suggests that only about half of the standard CRF_{SW} anomaly in this region is caused by the large increase in cloudiness, while the remainder is due to the decrease in surface albedo from the loss of sea ice. Areally averaged over the high southern latitudes (50º-90ºS), the CRF_{SW} decrease is 2.5 W m^{-2} less (36% less) using the modified formula and 0.9 W m^{-2} less (20%) over the greater Arctic region (50º-90ºN) (Table 1). Over regions of maximum sea ice reduction, the local differences between the formulas are much larger: up to 10 W m^{-2} in the Bering Sea and 12 W m^{-2} in the Southern Ocean (not shown).

Another way to isolate the impact of clouds is by examining the CRF_{SW} anomaly in the run with fixed clouds (2CO2F) in Fig. 1b. Ideally, there would be no change in CRF_{SW} with clouds fixed, and this expectation basically holds over most of the world (equatorward of 60º), where CRF_{SW} is under 0.5 W m^{-2} calculated with either method. However, the traditional formula still produces substantial negative anomalies where large sea ice reductions occur, including approximately 2 W m^{-2} decreases in the central Arctic and a nearly 8 W m^{-2} decrease over the Southern Ocean. The modified formula ameliorates the superimposed sea ice influence, such that the CRF_{SW} anomaly is close to zero throughout the Arctic and peaks at a much smaller –2.6 W m^{-2} value in the Southern Ocean (this local deviation from zero appears to be caused by increased in-cloud solar absorption as the cloud phase shifts toward liquid in the warmer climate). The difference in CRF_{SW} between the two formulas (2.1 W m^{-2} area averaged poleward of 50ºS, and 1.4 W m^{-2} averaged north of 50ºN) gives an estimate of the contribution by surface changes in the traditional CRF_{SW} calculation (Table 1). This measure should and does approximate the difference in CRF_{SW} between the two formulas in the unconstrained 2CO2 experiment, which would be the practical metric for assessing non-cloud impacts on CRF_{SW} changes in most model simulations. By this reasoning, the surface changes (lower albedo) contribute 2.1-2.5 W m^{-2} to the CRF_{SW} anomaly in the greater Antarctic region and 0.9-1.4 W m^{-2} in the greater Arctic (Table 1). For comparison, the cloud changes account residually for only about 4.4 W m^{-2} (64%) and 3.4 W m^{-2} (80%) of the total change in the traditional CRF_{SW} in 2CO2 across the high southern and northern latitudes respectively. If one equates cloud feedback as the change in CRF, then between one-fifth to more than one-third of the shortwave cloud feedback would be incorrectly attributed to clouds rather than to independent changes in surface conditions.

These basic conclusions are not unique to a single model that lacks full ocean-atmosphere coupling under idealized 2 x CO_2 equilibrium conditions, but instead apply to a set of representative GCMs recently run for the IPCC Fourth Assessment Report (AR4) under transient greenhouse forcing. The models analyzed are NCAR's CCSM3, Hadley Centre's HadCM3, Institut Pierre Simon Laplace's IPSL, and JAMSTEC's MIROC, all of which provided output from the end of a transient greenhouse simulation using the SRES A1B emissions scenario [*IPCC*, 2001]. The climate changes are defined as the means averaged over the last 20 years of the 21st century minus the 1980-1999 control run values, which used observed radiative forcings. The zonal anomalies averaged over the four models are given in Figure 2 for CRF_{SW} (traditional and modified formulas), cloud fraction, and surface albedo. These plots are very similar in their basic features to those from GENESIS2, except that the Southern Ocean response is tempered due to the thermal inertia from the much deeper mixed-layer with a dynamical ocean. The IPCC models produce the same meridional pattern of cloud changes: increased (decreased) cloudiness in high (low-middle) latitudes, consistent with the sign of the CRF anomalies. In addition, the regions with maximum reductions in surface albedo—60ºS and the central Arctic—again show the largest negative spikes in CRF. Given the frequent disagreement among cloud simulations in climate models [*Cess et al.*, 1990; *IPCC*, 2001], the similarity of these GCMs with GENESIS2 is encouraging, especially since GENESIS2 contains a cloud parameterization that is rather dated [*Smith*, 1990] compared with the state-of-the-art climate models used for the IPCC analysis.

4. Conclusions

The modified CRF formula using incident solar rather than absorbed solar radiation has a number of advantages over the traditional method, but also important limitations. The modification can be adopted simply into the existing conceptual framework of cloud radiative forcing and can be applied to observational data or models. By more effectively isolating the portion of CRF anomalies due to cloud changes rather than surface albedo influences, the altered CRF formula provides a more reliable measure of cloud feedback if one equates the feedback as the change in CRF. Although this paper is mainly concerned with climate change, the altered formula can also be applied to modern conditions, in which case the summertime minimum in CRF (large negative) over polar regions would be more extreme due to the elimination of surface albedo dependence. While the new formula can be used over any region, it will only have a significant effect where surface albedos are high, either in the modern climate or in a climate change scenario. Another caveat is that this modification only applies to the shortwave component of CRF, while leaving the longwave portion unchanged. Furthermore, the modification does not consider the adverse effect of other non-cloud factors, such as atmospheric solar absorption under clear skies or the known influence of solar zenith angle [Minnett, 1999], which affect the calculated CRF using either formula. Finally, this suggested variant applies to the *surface* CRF rather than the TOA value, for which no analogous distinction can be made between incident and net solar radiation. In the context of identifying cloud impacts, however, this constraint does not seem to be serious, based on the high correlations between CRF values computed at the surface and the TOA using the traditional formula. For example, observed shortwave cloud forcings over the frozen Arctic Ocean surface are nearly identical to those at the top of the atmosphere [*Schweiger and Key*, 1994], and the spatial anomalies in the GENESIS2 2CO2 simulation correlate at 0.96 between surface and TOA CRF_{SW} (0.85 for CRF_{NET}). As long as users are aware of how it should be applied, this modified approach to cloud radiative forcing may enhance our understanding of clouds in the climate system.

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Figure Captions

Figure 1. (a) Change in shortwave CRF (W m-2) using the traditional formula (open circles) and the modified formula (closed circles) in the GENESIS2 $2CO_2$ experiment, (b) As in (a) but for the $2CO_2F$ fixed-cloud experiment, (c) Change in cloud fraction in $2CO_2$, and (d) Change in surface albedo in $2CO_2$ (open circles) and $2CO_2F$ (X marks).

Figure 2. As in Figure 1 but for the composite of 4 GCMs in the IPCC model archive. Also shown in (b) and (c) is the inter-model standard deviation of the change in total cloud fraction and surface albedo (crosses; multiplied by -1 in (d) for plotting purposes).

Table 1. Changes in mean annual CRF_{SW} (W m^{-2}) over the greater Arctic (50-90ºN) and Antarctic (50-90ºS) in the 2CO2 and 2CO2F simulations using the traditional and modified CRF_{SW} formulas.

	Traditional	Modified	Modified - Traditional
2CO2 Arctic	-4.30	-3.44	0.86
2CO2 Antarctic	-6.88	-4.40	2.48
2CO2F Arctic	-1.04	+0.37	1.41
2CO2F Antarctic	-2.60	-0.55	2.05

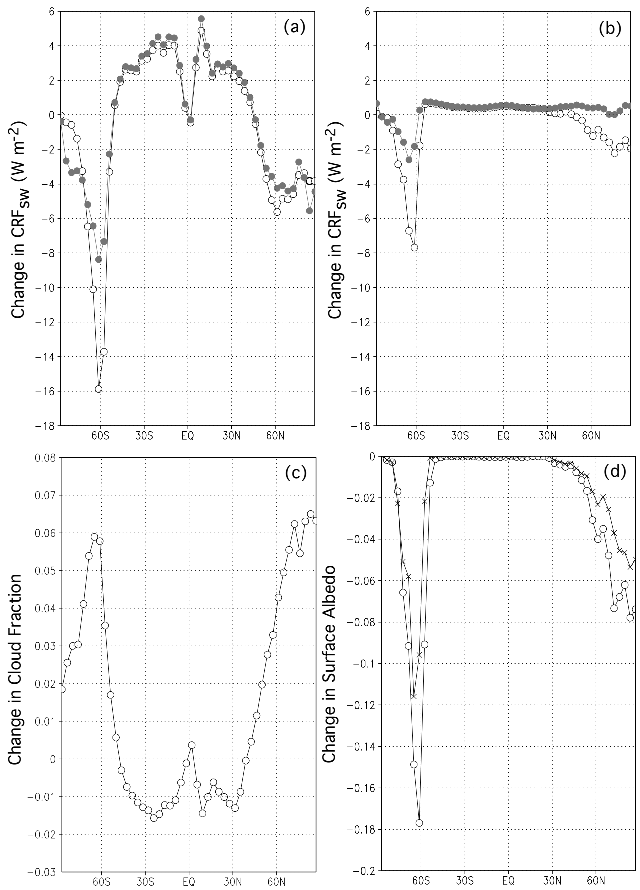
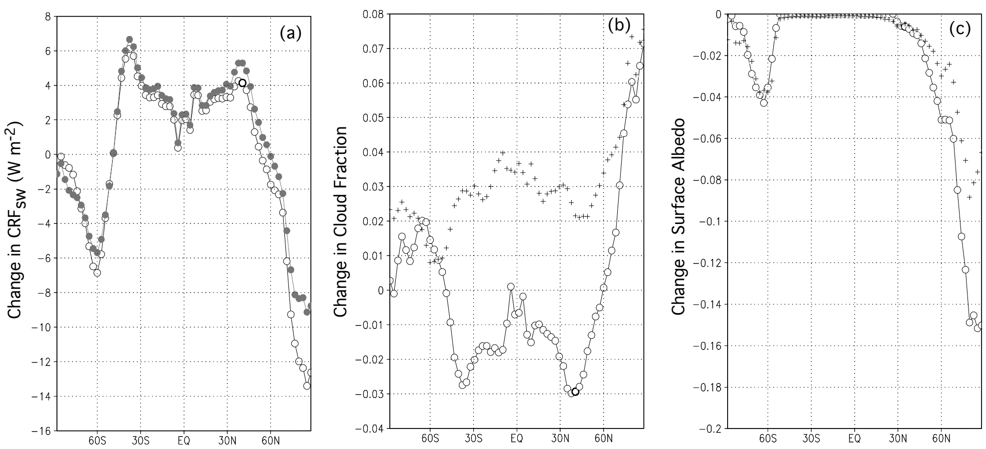


Figure 1. (a) Change in shortwave CRF (W m^{-2}) using the traditional formula (open circles) and the modified formula (closed circles) in the GENESIS2 2CO2 experiment, (b) As in (a) but for the 2CO2F fixed-cloud experiment, (c) Change in cloud fraction in 2CO2, and (d) Change in surface albedo in 2CO2 (open circles) and 2CO2F (X marks).



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