Quantifying changes in the Arctic shortwave cloud radiative effects

Doyeon Kim[1], Sarah M. Kang[2], Hanjun Kim[3], Patrick C. Taylor[1]

[1]NASA Langley Research Center, Hampton, Virginia, USA, [2]School of Urban and Environmental Engineering, UNIST, Ulsan, Korea, [3]Department of Earth and Atmospheric Sciences, Cornell University, Ithaca, NY, USA

Research problem

- Compared to CMIP5, the inter-model spread in cloud amount is significantly decreased in CMIP6 (Fig. 1a).
- However, the distinct response of Arctic cloud fraction observed between the CMIP5 and CMIP6 ensembles is not reflected in the SWCRE response (Fig. 1b).

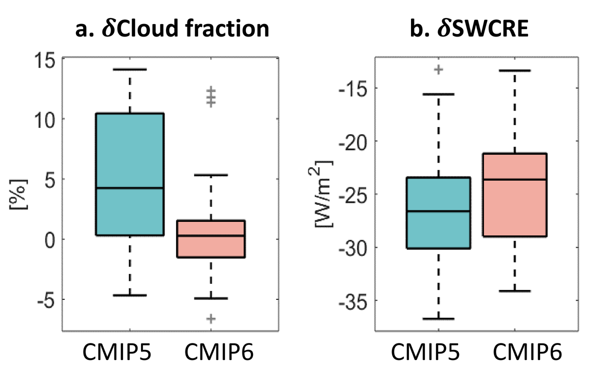

Figure 1. Box-and-whisker plots of the results from 54 CMIP models after an abrupt quadrupling of CO_2 concentrations from the pre-industrial level. The bars indicate the spread of changes in a. surface SWCRE (W/m²) and b. cloud fraction (%) averaged over the Arctic Ocean.

We need to enhance our understanding of the underlying causes contributing to this persistent inter-model uncertainty in SWCRE response.

Method & What is the E-APRP method?

- Approximate PRP (APRP: Atmospheric Radiative Perturbation) method is developed for decomposing the SW fluxes, which uses a simple single-layer radiative transfer model instead of a complex original radiative transfer model (Taylor et al. 2007).
- We extended the conventional APRP (E-APRP) method, adding the absorptivity for the upward beam and considering differences in reflectivity between upward and downward beams, as well as analyzing the cloud masking effect resulting from changes in surface albedo in more detail.

Compared to the PRP-based estimate, the E-APRP significantly outperforms the conventional APRP

Conventional APRP RMS errors in SWCRE response by albedo changes **36%** → E-APRP RMS errors in SWCRE response by albedo changes **10%**

- PRP calculations: Community Earth System Model (CESM) & Parallel Offline Radiative Transfer (PORT) tool in CESM.
- CMIP projections: piControl, abrupt-4xCO_2, historical, RCP4.5, and SSP245 simulations of 23 CMIP5 and 31 CMIP6 models.

Our goal is to use our extended APRP (E-APRP) method to decompose the response of the SWCRE flux at the Arctic surface into contributions from changes in surface albedo, cloud, and non-cloud radiative properties.

How to decompose SWCRE?

$\delta SW = \delta SWCRE + \delta SWCLR$

$\delta SWCRE$

$= \delta SWCRE_{Alb} + \delta SWCRE_{CP}$ [Eq.1]

$= \delta SWCRE_{AlbPM} + \delta SWCRE_{AlbSM} + \delta SWCRE_{CFrac} + \delta SWCRE_{CRef}$

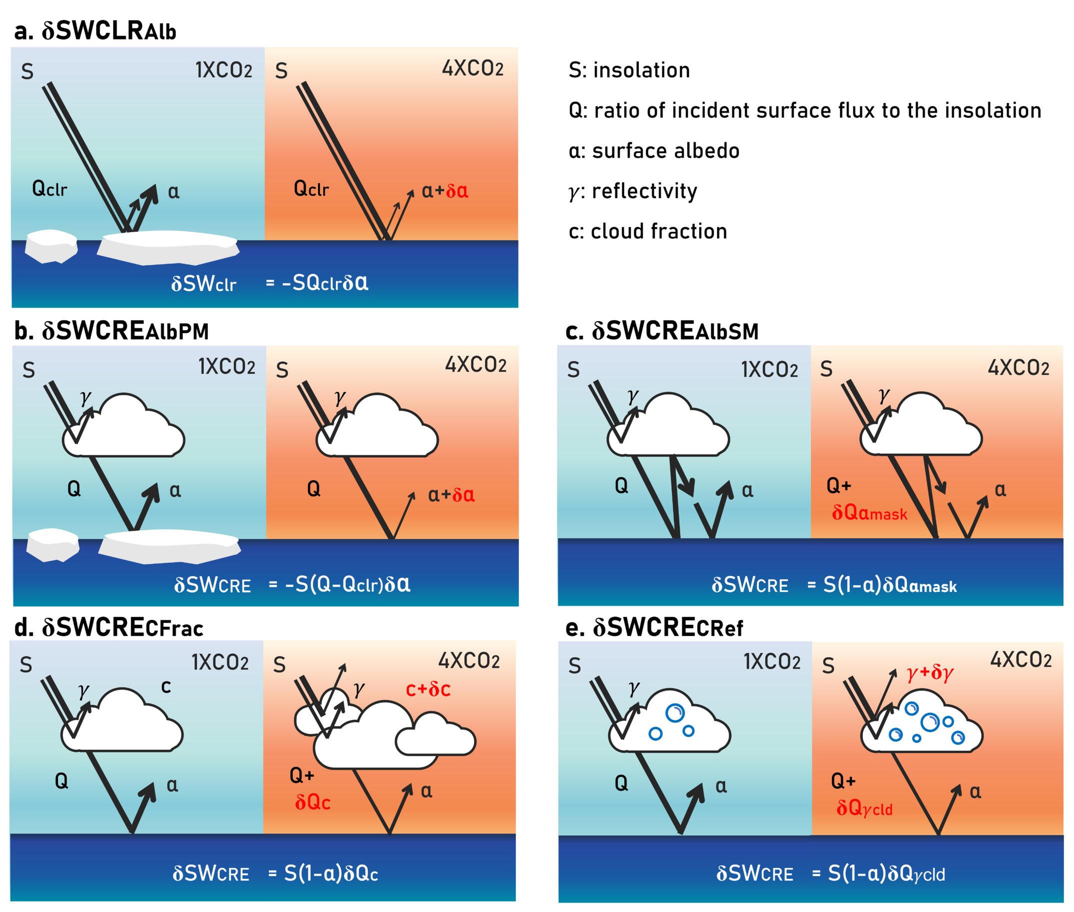

Figure 2. Schematic illustration of changes in surface SW fluxes in response to CO_2-induced global warming

Arctic clouds can hinder the positive albedo feedback (Fig. 2a)

- by changing the albedo in two ways:

  (1) decreasing incoming SW fluxes due to cloud reflection (Fig 2b, $\delta SWCRE_{AlbPM}$: primary albedo cloud masking effect)

  and

  (2) decreasing SW fluxes reaching the surface after being reflected by clouds (Fig 2c, $\delta SWCRE_{AlbSM}$: secondary albedo cloud masking effect).
- by changing the cloud properties in two ways:

  less incoming SW fluxes by increased

  (1) cloud amount (Fig. 2d) and (2) cloud liquid water (Fig. 2e).

Analysis of changes in Arctic surface SWCRE using the E-APRP method

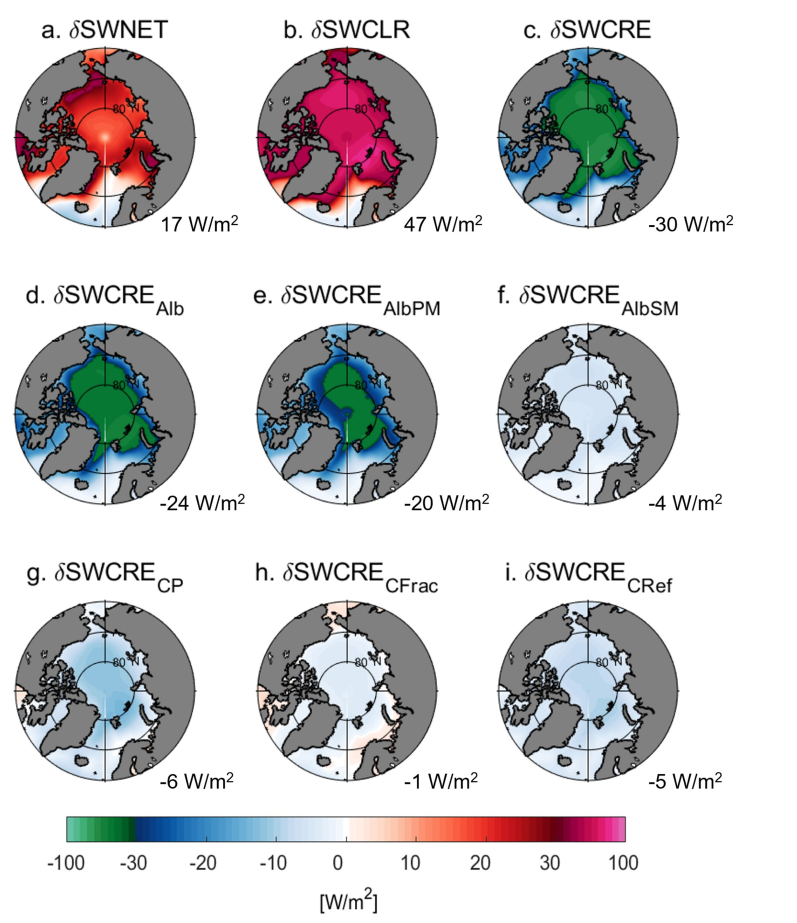

Figure 3. The ensemble mean SW change for the sunlit season (i.e., Mar to Sep) from CMIP models after an abrupt quadrupling of CO_2 concentrations from the pre-industrial level. Each panel includes denoted Arctic Ocean averaged values below.

- $\delta SWCRE_{AlbPM}$ counteracts the effect of the clear-sky surface albedo feedback $\delta SWCLR$ by 43% (Fig. 3d).
- In contrast, the cloud property-driven changes in SWCRE contributes only a quarter of the albedo-driven changes (Fig. 3g).
- This is because cloud amount and reflectivity remain fairly constant in response to global warming (Figs. 4c,d) while the surface albedo clearly decreases over time (Fig. 4b).
- The temporal evolution of SWCRE changes closely follows that of surface albedo changes, again pointing to the dominant role of surface albedo changes in driving the SWCRE changes (Fig. 4a,b).

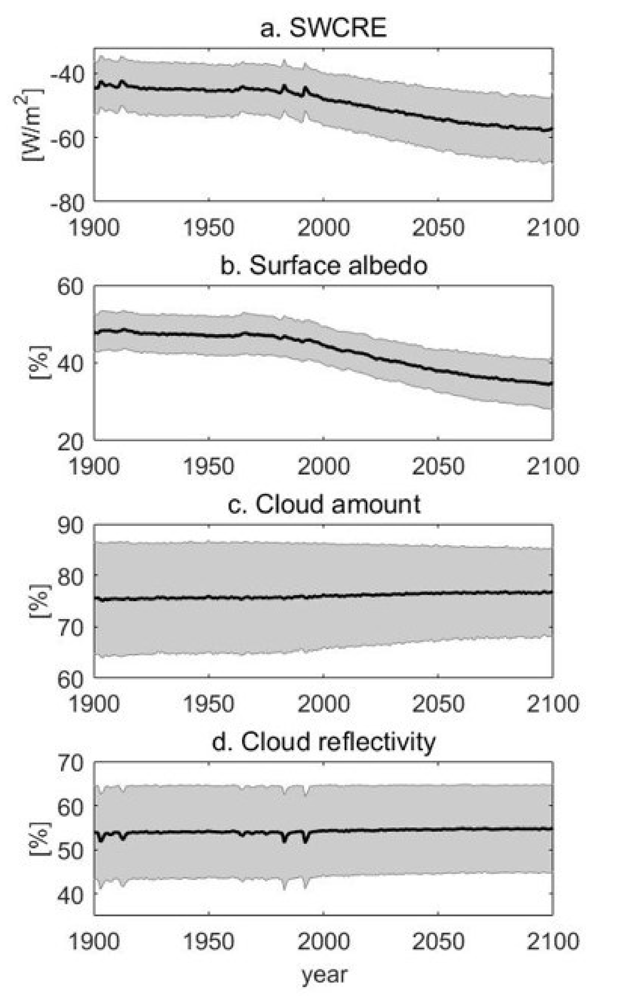

Figure 4. Time series of the a. SWCRE (W/m²), b. surface albedo (%), c. cloud amount (fraction %), and d. cloud reflectivity (%) in CMIP5 (CMIP6) historical and RCP4.5 (SSP245) simulations. The solid line shows the multi-model mean; the envelope represents +/- one inter-model standard deviation bounds for CMIP5/6 models.

- The inter-model spread of SWCRE changes primarily originates from the inter-model differences in the albedo-driven components, especially (Fig. 5).

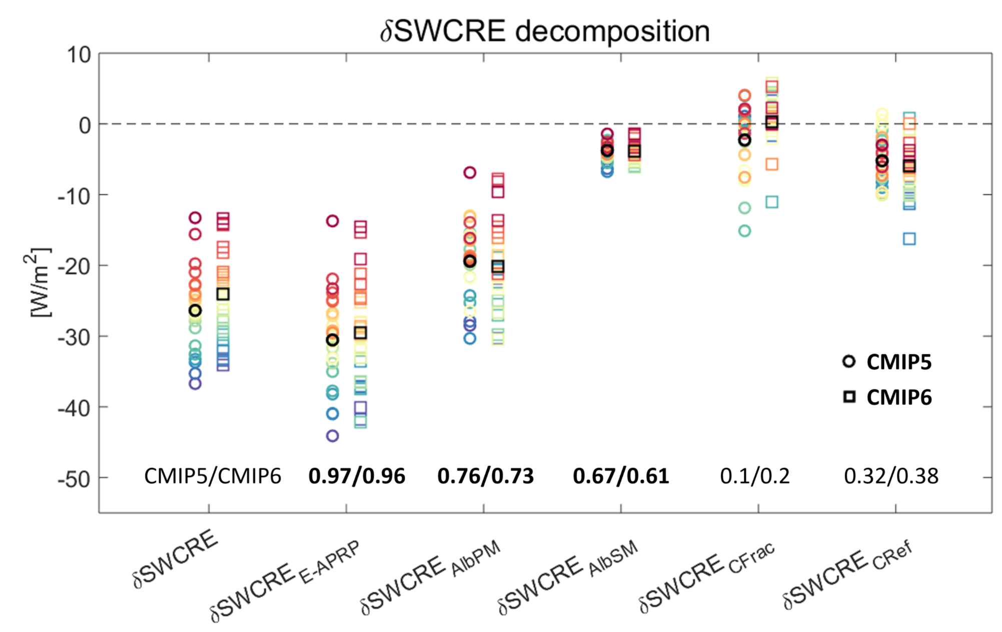

Figure 5. Attribution of inter-model spread of changes in surface SWCRE (W/m²) in response to a quadrupling of CO_2 concentrations from the pre-industrial level, averaged over the Arctic Ocean during the sunlight season, to differences in the E-APRP (Eq.1) components. The results from 54 CMIP models are color-coded according to the changes in surface SWCRE.

Conclusion

- A shortwave radiative decomposition using a one-layer radiation model estimates how surface albedo, cloud fraction, and cloud reflectivity drive responses in shortwave cloud radiative effect to increases in CO_2.
- Changes in surface albedo mostly determine the magnitude and the inter-model spread of shortwave cloud radiative effect changes observed in the CMIP models.
- Changes in cloud fraction and reflectivity in CMIP models show minimal impact on the changes in shortwave cloud radiative effect.

Kim, Doyeon, NASA Postdoctoral Program Fellow, Langley Research Center, Hampton, Virginia, USA
doyeon.kim@nasa.gov

Taylor, K., and Coauthors, 2007: Estimating shortwave radiative forcing and response in climate models. *Journal of Climate*, 20, 2530–2543