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LETTER

Differences in snow-induced radiative forcing estimated from satellite and reanalysis surface albedo datasets over the Northern Hemisphere landmass for the overlapping period of 1982–2012

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Abstract

The snow-induced radiative forcing (SnRF) measures the instantaneous perturbation to Earth’s shortwave radiation at the top of the atmosphere (TOA) caused by the presence of snow cover. Land surface albedo (αs) is a key parameter in estimation of SnRF. Previous studies have focused on using satellite or reanalysis αs data in SnRF quantifications. However, their spatial and temporal differences remain unclear. In this study, SnRF over the Northern Hemisphere (NH) estimates from two satellite and four reanalysis αs datasets were compared for the overlapping period of 1982–2012. The 31-year annual-mean SnRF was estimated at −1.81 to −1.59 W m⁻² from satellite αs datasets, with a peak of −4.01 W m⁻² and Standard Deviation (SD) of 1.54 W m⁻² in April. The comparable SnRF from reanalysis αs was −1.48 to −2.30 W m⁻², with a peak of −4.77 W m⁻² and SD of 0.81 W m⁻² in the same month. In the seasonal cycle, SnRF from satellite αs displayed lower values from October to January, but higher values from February to July, compared with SnRF using reanalysis αs. Moreover, the annual-mean SnRF declined by 0.39–1.25 W m⁻² during 1982–2012 from satellite αs datasets, which is much smaller than the results using reanalysis αs datasets. Furthermore, changes in monthly-mean SnRF from satellite αs displayed an enhance trend in snow accumulation seasons, which are largely different with the comparable changes from reanalysis-based SnRF, indicating that there are large interannual and intra-annual biases between SnRF estimates from satellite and reanalysis αs datasets. Based on above results, we conclude that the large discrepancies between SnRF estimations from satellite and reanalysis αs should be considered in evaluating the response and feedback of snow cover to Earth climate change in future studies, especially in radiation budget anomalies.

1. Introduction

Surface albedo (αs) is defined as the ratio of the solar radiation reflected from the Earth’s surface to the solar radiation incident upon it, is critical in the regulation of Earth’s surface energy budget and characterizing the Earth’s radiative regime (Lofgren 1995, Liang et al 2010, Liang et al 2019). Published studies have proved that snow cover extent (SCE) changes are positively correlated with αs anomalies because of its high reflectance (Qu and Hall 2014, Chen et al 2015, Chen et al 2017, Zhang et al 2019). When the snow cover shrinks, the αs decreases, with less solar radiation reflected back into the space. Meanwhile, the remaining snow generally has a lower αs caused by snow metamorphosis (Qu and Hall 2014). The solar radiation perturbation induced by αs anomalies that are driven by SCE changes is defined as snow-induced radiative forcing (SnRF) (Flanner et al 2011, Chen et al 2015, Chen et al 2016a), which is vital in measuring the feedback of snow cover to Earth radiation budget (Flanner et al 2011, Singh et al 2015) and climate projections (Perket et al 2014, Qu and Hall 2014) under the climate change background.

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To estimate radiative forcing caused by snow cover changes, several studies have estimated the SnRF at different time spans and spatial scales in recent decades (Flanner et al. 2011, Chen et al. 2015, Singh et al. 2015, Chen et al. 2017). For example, Flanner et al. (2011) quantified the radiative forcing from the Northern Hemisphere (NH, the half of the Earth that lies north of the equator) cryosphere during 1979–2008 and reported that the cryospheric cooling declined by 0.45 W m\(^{-2}\) during 1979–2008, with nearly equal contributions from changes in land snow cover and sea ice. Chen et al. (2015) estimated the SnRF induced by snow cover phenology changes over the NH for the period 2001–2014 and found that the contrasting changes in snow cover phenology led to contrasting anomalies of SnRF among the NH middle and high latitudes, which accounted for 51% of the total shortwave flux anomalies at the top of the atmosphere (TOA) during 2001–2014. Singh et al. (2015) quantified the global land shortwave cryosphere radiative effect during 2001–2013 and reported that the NH land SnRF estimates from Moderate Resolution Imaging Spectroradiometer (MODIS) were approximately 18% smaller than previous estimates derived from coarse-resolution advanced very high resolution radiometer (AVHRR) data during the overlap period of 2001–2008. However, being limited by the uncertainty of \(a_s\) datasets and shortage of long-term \(a_s\) datasets, the differences in SnRF evaluated from longterm satellite and reanalysis \(a_s\) datasets are remain unclear.

The \(a_s\) is one of the most important parameters in the calculation of SnRF, which measures the amount of solar radiation reflected back into the space caused by snow cover changes (Groisman et al. 1994, Flanner et al. 2011, Perket et al. 2014, Chen et al. 2015, Singh et al. 2015). However, \(a_s\) is among the main radiative uncertainties in current climate modeling (Liang 2001, Liang et al. 2002), which may bring a cumulative error in the SnRF estimation. For example, Myher and Myher (2003) reported that cropland \(a_s\) values is the most important factor yielding the large range in estimated radiative forcings caused by land use changes. Bright and Kvalevåg (2013) confirmed that through perturbations in \(a_s\), land use activities affected shortwave radiative forcing at the TOA. As one of the most notable component of land cover type over the NH, with large spatial coverage and rapid changes, presence of snow cover are largely related with land use changes over the NH. Published studies have proven that SCE in the NH has experienced a well-documented rapid decrease since late 1960s (Déry and Brown 2007, Brown et al. 2010, Derksen and Brown 2012, Chen et al. 2016a). Moreover, climate projections suggest that the SCE will continue shrinking in the future (Brown and Robinson 2011, IPCC 2013). Thus, to make clear the spatial and temporal differences in SnRF estimation caused by \(a_s\) datasets is necessary to reduce the radiative uncertainties in climate change studies.

Published scholars have reported large differences among current \(a_s\) products, e.g., By analyzing the global \(a_s\) climatology and spatial-temporal variation during 1981–2010, He et al. (2014) showed that at latitudes higher than 50°, the maximum difference in winter zonal albedo ranged from 0.1 to 0.4 among the nine satellite datasets. Assessment of Community Land Model (CLM2) \(a_s\) using MODIS data, Oleson et al. (2003) reported that in regions with extensive snow cover, the CLM2 overestimated white-sky and black-sky \(a_s\) by up to 20%. As the largest single component of the cryosphere in terms of spatial extent, the discrepancy between the satellite-derived and reanalyzed \(a_s\) is evident. Although published studies have estimated SnRF from local to global scales, few of them have provided a comprehensive analysis of the uncertainties in SnRF estimations induced by \(a_s\) datasets.

The objective of the present study is to comprehensively examine the performance of satellite and reanalysis \(a_s\) datasets in representing the large scale spatiotemporal variability and long term change in SnRF over the NH. Additionally, the study aims to understand the differences between reanalysis and satellite \(a_s\) in the context of characterizing radiative forcing within the NH climate system, which is crucial for accurately characterizing NH climate patterns and assessing the underlying evolution of the NH climate system.

2. Methodology and datasets

To calculate SnRF over the NH and cross-compare SnRF results from satellite and reanalysis \(a_s\) datasets, we first introduce the methodology in calculation of SnRF. Then, we give a brief introduction of datasets used in this study.

2.1. Methodology

2.1.1. Estimation of SnRF

To calculate SnRF over the NH, the radiative kernel approach (Shell et al. 2008, Soden et al. 2008) was employed in this study. The radiative kernel approach separates the radiative responses to land surface albedo \(a_s\) induced by snow cover changes with other climate parameters (such as temperature, water vapor, and CO\(_2\)). In this study, the albedo radiative kernels, expressed as the TOA shortwave flux anomalies associated with a 1% change in \(a_s\), were employed to estimate SnRF driven by snow cover changes. The time \(t\) dependence of SnRF (W m\(^{-2}\)), within a region \(R\) (here, the NH) of area \(A\), composed of grid cells \(r\) can be expressed as follows:
(Flanner et al 2011, Chen et al 2015):

\[
S_{nRF}(t, R) = \frac{1}{A(R)} \int_{r} S(t, r) \frac{\partial \alpha_{s}}{\partial S}(t, r) \frac{\partial F}{\partial \alpha_{s}}(t, r) dA(r)
\]

(1)

where \(S(t, r)\) is the domain of SCE over the NH, \(\partial \alpha_{s}/\partial S(t, r)\) is the rate of variation of land surface albedo \(\alpha_{s}\) with snow cover change, and \(\partial F/\partial \alpha_{s}(t, r)\) is the response of the TOA net shortwave radiation anomalies to \(\alpha_{s}\) changes. Following Flanner et al (2011), we assumed that the temporally and spatially varying \(\partial \alpha_{s}/\partial S\) and \(\partial F/\partial \alpha_{s}\) were constant with the snow cover fraction \(S\) and \(\alpha_{s}\), respectively. Therefore, \(\partial \alpha_{s}/\partial S\) could be replaced with the mean albedo contrast \((\Delta \alpha_{s})\) induced by the snow cover anomaly and \(\partial F/\partial \alpha_{s}\) can obtained from the albedo radiative kernels (Flanner et al 2011, Chen et al 2015).

2.2.2.1. CLARA-A2 land surface albedo dataset

The CLARA-A2 dataset provides 5-day black-sky \(\alpha_{s}\) dataset (wavelengths of 0.25–2.5 \(\mu m\)), which is generated based on a homogenized AVHRR radiance time series and is created by using algorithms to separately derive \(\alpha_{s}\) based on a homogenized AVHRR radiance time series and is created by using algorithms to separately derive \(\alpha_{s}\) at weekly intervals for January 1982 through February 2012.

2.2.2.2. Satellite-retrieved land surface albedo datasets

Two longterm satellite \(\alpha_{s}\) datasets were employed to estimate \(S_{nRF}\) over the NH and to cross-compare with \(S_{nRF}\) estimates from reanalysis \(\alpha_{s}\) for the overlapping period of 1982–2012.

2.2.2.2.1. CLARA-A2 land surface albedo dataset

The CLARA-A2 dataset provides 5-day black-sky \(\alpha_{s}\) dataset (wavelengths of 0.25–2.5 \(\mu m\)), which is generated based on a homogenized AVHRR radiance time series and is created by using algorithms to separately derive \(\alpha_{s}\) based on a homogenized AVHRR radiance time series and is created by using algorithms to separately derive \(\alpha_{s}\).
for different land use areas, including snow, sea ice, open water, and vegetation (Karlsson et al 2017). Currently, the CLARA-A2 a<sub>s</sub> dataset is the only available longterm a<sub>s</sub> product derived from AVHRR imagery. In this study, the CLARA-A2 black-sky a<sub>s</sub> over the NH at the spatial resolution of 0.05°, covering from 1982 to 2012 were used to cross-compare S<sub>n</sub>RF estimates from GLASS and reanalysis a<sub>s</sub> datasets. The CLARA-A2 a<sub>s</sub> dataset has been used to estimate sea ice albedo changes (Riihelä et al 2013) and sea ice a<sub>s</sub> comparison (Cao et al 2016) over the Arctic regions.

### 2.2.2.2. GLASS broadband albedo dataset

The GLASS Broadband Albedo Version 40 product is based on the integration of two algorithms through a temporal filter scheme (Liu et al 2013, Zhao et al 2013) using AVHRR and MODIS version 6 radiance data. The GLASS products provide a<sub>v</sub> at total shortwave, visible and near-IR under actual atmospheric conditions spectral ranges. To match black-sky a<sub>s</sub> obtained from CLARA-A2, the 8-day GLASS total shortwave black-sky a<sub>s</sub> at the spatial resolution of 0.05°, covering from 1982 to 2012 were used in this study. The GLASS a<sub>s</sub> dataset has been used to quantify the albedo induced radiative forcing of snow melting over Greenland (He et al 2013), forest disturbances over northeastern China (Zhang and Liang 2014) and snow cover phenology changes over the NH (Chen et al 2015, Chen et al 2016a) with high quality and fine spatial resolution.

### 2.2.3. Reanalysis land surface albedo datasets

Four longterm reanalysis a<sub>s</sub> datasets were selected to quantify S<sub>n</sub>RF over the NH and to cross-compare with S<sub>n</sub>RF estimates from satellite a<sub>s</sub> from 1982 to 2012, including JRA-55, CFSR, MERRA-2, and ERA-5.

#### 2.2.3.1. ERA-5 reanalysis land surface albedo datasets

The ERA-5 product is the latest global atmospheric reanalysis dataset produced by the ECMWF (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5) (C3S 2017). ERA-5 has important changes relative to the former ERA-Interim atmospheric reanalysis, including higher spatial and temporal resolutions with a latest model and data assimilation system (Albergel et al 2018).

The monthly ERA-5 a<sub>s</sub> was calculated with clear sky surface downward and upward shortwave fluxes at a 0.125 spatial resolution from 1979 to present. By using eight independent observations including evapotranspiration, gross primary production, soil moisture, and leaf area index from remote sensing observations and soil moisture, turbulent heat fluxes, river discharges and snow depth from in situ observations, Albergel et al (2018) reported that the ERA-5 showed a consistent improvement over ERA-Interim. To cross-compare S<sub>n</sub>RF results from satellite and other reanalysis datasets, the monthly ERA-5 a<sub>s</sub> at the spatial resolution of 0.125°, covering NH from 1982 to 2012 were employed in this study.

#### 2.2.3.2. JRA-55 reanalysis land surface albedo datasets

The JRA-55 is the longest reanalysis dataset that uses the full observing system (in contrast, products like ERA-20C and NOAA 20CR assimilate a very limited set of observations while NCEP R1 uses an antiquated model and assimilation scheme) spanning 1958 to present (https://climatedataguide.ucar.edu/climate-data/jra-55). The monthly JRA-55 a<sub>s</sub> product is parameterized as functions of solar zenith angle and surface skin temperature
In this study, the monthly JRA-55 $a_s$ at the spatial resolution of 0.5°, covering NH from 1982 to 2012 were used in quantification of $S_a$RF over the NH.

2.2.3.3. MERRA-2 reanalysis land surface albedo datasets
The MERRA-2 is a global atmospheric reanalysis derived from the Goddard Earth Observing System atmospheric general circulation model, version 5 (GEOS-5) (Guemard et al 2019) (https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/). The MERRA-2 is the first satellite-era global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system spans from 1980 to 2017. To cross-compare $S_a$RF results from satellite and other reanalysis datasets, the monthly MERRA-2 $a_s$ at the spatial resolution of 0.5°, covering NH from 1982 to 2012 were used in this study.

2.2.3.4. CFSR reanalysis land surface albedo datasets
The NCEP CFSR is a global, high resolution, atmosphere–ocean–land surface–sea ice coupled system over the period January 1979 to November 2017 (Saha et al 2010) (https://climatedataguide.ucar.edu/climate-data/climate-forecast-system-reanalysis-cfsr). The CFSR was designed to provide the best estimate of the state of these coupled domains over this period. The monthly NCEP CFSR $a_s$ was calculated using the land model Noah described by Rai et al (2019). To cross-compare $S_a$RF results from satellite and other reanalysis datasets, the monthly CFSR $a_s$ at the spatial resolution of 0.5°, covering NH from 1982 to 2012 were used in this study.

2.2.4. MCD43GF snow-free land surface albedo dataset
To obtain climatology of monthly-mean snow-free surface albedo $\alpha_{sf}$ needed in $S_a$RF calculation, the gap-filled daily MCD43GF $\alpha_{sf}$ at spatial resolution of 1 km (Schaaf 2019) was used in this study, which representing the $a_s$ after removing the presence of snow cover. The MCD43GF$\alpha_{sf}$ product are computed for MODIS spectral bands 1 through 7 as well as shortwave-infrared, visible and near-infrared bands from 2001 to 2017. To compare with white-sky $a_s$ from CLARA-A2 and GLASS datasets, the daily shortwave broadband white-sky $\alpha_{sd}$ from 2001 to 2012 was used in this study.

2.2.5. Albedo radiative kernels datasets
To reduce radiative uncertainty in $S_a$RF estimation caused by albedo radiative kernels, three monthly albedo radiative kernels: CAM3 gridded at 2.81° horizontal resolution from Shell et al (2008), AM2 gridded at 2.50° horizontal resolution from Soden et al (2008), and ECHAM6 gridded at 1.875° horizontal resolution from Mauritsen et al (2013) were used in this study. The seasonal cycle of albedo radiative kernels from CAM3, AM2 and ECHAM6 over the NH are shown in figure 1.

2.2.6. Data preparation
Considering the time span and spatial resolution of individual datasets, this study was carried out among the overlapping period of 1982–2012 in 0.5° spatial resolution. Because of missing AVHRR surface reflectance data in 1994, the satellite $a_s$ datasets from CLARA-A2 and GLASS were incomplete in this year. Thus, we excluded 1994 in this study. Due to difficulties in discriminating snow from ice over Greenland, this region was excluded from the analysis.

Before calculation, datasets used in this study in table 1 were regridded and remapped at a spatial resolution of 0.5° with geographic latitude/longitude projection with the help of gdalwarp (http://www.gdal.org/gdalwarp.html).
For datasets with spatial resolution greater than 0.5°, we used ‘average’ in the resampling process, which computed the average of all non-NODATA contributing pixels in the domain of our study. For datasets with spatial resolution lower than 0.5°, we used ‘cubic-spline’ in the resampling process.

To match the temporal interval of albedo radiative kernels, the weekly NHSCE snow cover dataset, 8-day GLASS, 5-day CLARA-A2, and daily MCD43GF datasets were temporally aggregated to produce a monthly-averaged series in the calculation. To make sure the quality of datasets, the quality control flags of ‘00’ and ‘01’ of the 8-day GLASS as, indicating uncertainties of <5% and <10%, were used to generate the monthly mean as series. Quality assurance values between ‘0’ and ‘1’ of daily MCD43GF, representing the majority of high-quality and good quality full inversion values, were used to generate the monthly mean snow-free surface albedo and climatology snow-free surface albedo over the NH.

3. Climatology of $S_n$RF over NH

The annual-mean and monthly-mean of $S_n$RF over the NH for the period 1982–2012 were used to explore the climatology differences between 31-year averaged $S_n$RF derived from satellite and reanalysis as datasets. For $S_n$RF estimates using a given as dataset, we first calculated the monthly $S_n$RF using CAM3, AM2, and ECHAM6 albedo radiative kernels, respectively. Then, we obtained the annual-mean $S_n$RF by averaging the monthly-mean $S_n$RF from January to December. The numbers in parenthesis indicate the SD of averaged annual-mean $S_n$RF between three $S_n$RF results.

3.1. Annual-mean $S_n$RF

The spatial distributions of the 31-year annual-mean $S_n$RF estimates from two satellite and four reanalysis as datasets during 1982–2012 are presented in figure 2. As shown in figure 2(a), $S_n$RF estimates from both satellite and reanalysis as datasets displayed similar spatial distribution over the NH during 1982–2012, with generally larger values in the high latitude areas of Eurasia and North America, and the high elevation Rocky Mountains, Tibetan Plateau, and Stanovoy Range, but smaller values in the low latitude and low elevation regions.

The annual mean $S_n$RF over the NH during 1982–2012 was estimated at $-1.81 \pm 0.06$ W m$^{-2}$, $-1.59 \pm 0.10$ W m$^{-2}$, $-2.30 \pm 0.15$ W m$^{-2}$, $-1.48 \pm 0.16$ W m$^{-2}$, $-1.74 \pm 0.07$ W m$^{-2}$, and $1.49 \pm 0.06$ W m$^{-2}$ using the GLASS, CLARA-A2, ERA-5, CFSR, JRA-55, and MERRA-2 as datasets, respectively.

Compared with $S_n$RF estimates from GLASS as (figure 2(a)), the results from CLARA-A2 (figure 2(b)) was minor at high latitudes, especially in regions of Eurasia near the Arctic Ocean. However, compared with $S_n$RF derived from GLASS and CLARA-A2, most of the $S_n$RF estimates from reanalysis as displayed minor values in high latitude and high elevation regions, especially JRA-55 (figure 2(d)) and MERRA-2 (figure 2(e)). Moreover, as shown in figure 2(c), the $S_n$RF estimates from ERA-5 as displayed higher values in mountainous regions, such as the Rocky Mountains, Tibetan Plateau, and Stanovoy Range. In contrast, $S_n$RF estimates from CFSR as was minor in the high elevation Rocky Mountains, Tibetan Plateau, and Stanovoy Range, which indicate that there are large differences exist between $S_n$RF results from individual as dataset, even among reanalysis as datasets.
3.2. Seasonal cycle of the SnRF

The climatology of monthly-mean SnRF in each month for a given dataset was calculated by averaging the three SnRF estimates using CAM3, AM2, and ECHAM6 albedo radiative kernels. The climatology of seasonal SnRF over the NH for the period 1982–2012 derived from two satellite and four reanalysis datasets are displayed in Figure 3. The satellite-based SnRF in Figure 3 were calculated by averaging SnRFs estimate from GLASS and CLARA-A2 datasets. The reanalysis-based SnRF in Figure 3 were calculated by averaging SnRFs estimate from JRA-55, CFSR, MERRA-2, and ERA-5 datasets.

As shown in the seasonal cycle of SnRF over the NH estimates from six individual datasets during 1982–2012 (Figure 3(a)), the SnRF from both satellite and reanalysis datasets captured the seasonal cycle of SnRF over the NH. The SnRF broadly peaked at approximately $-5.97 \pm 0.07$ W m$^{-2}$ to $-4.22 \pm 0.05$ W m$^{-2}$ in April because of the high solar radiation and large SCE over the NH in April. Meanwhile, the SnRF valleys were broad at $-0.33 \pm 0.003$ W m$^{-2}$ to $-0.08 \pm 0.001$ W m$^{-2}$ in August because of low SCE and albedo radiative kernels values in August caused by higher cloud optical thickness over the NH.

However, there were large differences between seasonal cycles of SnRF derived from satellite and reanalysis datasets. Compared with the SnRF estimates from GLASS and CLARA-A2 datasets, SnRF calculated from the ERA-5 dataset displayed higher values in snow accumulation seasons from October to January, but lower values in snow melting seasons from February to July, which indicated that the reanalysis-based SnRF could not capture the actual seasonal cycle of SnRF over the NH during 1982–2012.

Figure 3. Seasonal cycle of SnRF over the NH from 1982 to 2012. (a) The climatology of monthly-mean SnRF calculated from six individual datasets, (b) the monthly-averaged SnRF and associated error range between SnRFs derived from six individual datasets, and (c) error ranges between SnRFs derived from satellite and reanalysis products. Error Range indicates differences between the maximum and minimum value of SnRF for a given month.
4. Changes in SnRF over the NH

Changes in annual-mean and monthly-mean SnRF were used to explore the ability of SnRF derived from satellite and reanalysis datasets in capturing the radiative feedback of snow cover to Earth climate system for the period 1982–2012. Changes were calculated as linear trends multiplied by the time interval.

4.1. Changes in annual-mean SnRF

4.1.1. Spatial distribution of changes in annual-mean SnRF

The spatial distribution of 31-year changes in annual-mean SnRF estimates from six individual datasets during 1982–2012 are displayed in Figure 4.

As shown in Figures 4(a) and (b), the NH experienced weakened cooling effects with a smaller magnitude of SnRF changes in high latitudes near the Arctic Ocean, but strengthened cooling effects with a larger magnitude of SnRF changes in the mid-latitudes, including the central United States and Tibetan Plateau during 1982–2012. Compared with SnRF changes based on satellite datasets, the comparable changes using ERA-5 (Figure 4(c)) and JRA-55 (Figure 4(d)) displayed general positive anomalies over the NH, except for the TP regions. Moreover, the large scale negative SnRF changes in the United States and Northern China from satellite-based SnRF results were not captured in SnRF estimates from ERA-5 (Figure 4(c)), JRA-55 (Figure 4(d)), and MERRA-2 (Figure 4(e)). Moreover, the CFSR-based SnRF displayed significant negative changes among most of the NH landmass, except for the high latitudes of Eurasia, which is in conflict with the published findings of rapid snow cover extent reduction in recent decades (Brown et al. 2007, Déry and Brown 2007, Chen et al. 2016a).

4.1.2. Interannual variability of annual-mean SnRF over the NH

Detailed comparisons of 31-year annual-mean SnRF variabilities over the NH calculated from six individual a_s datasets during 1982–2012 are provided in Figure 5. The large discrepancies between SnRFs estimate from two satellites and four reanalysis a_s datasets are clearly displayed in Figure 6.

Both satellite and reanalysis-based SnRF present generally positive changes with the shrinking of the SCE over the NH during 1982–2012 (figure 5). The peak of annual-mean SnRF ($-$1.67 ± 0.03 W m$^{-2}$) occurred in 2012, whereas in the valley, the peak at $-$1.92 (±0.05) W m$^{-2}$ occurred in 2004 in GLASS-based SnRF estimations. Compared with GLASS-based SnRF, the magnitude of SnRF from CLARA-A2 was much smaller, with the peak and valley being $-$1.38 ± 0.08 W m$^{-2}$ in 2000 and $-$1.83 ± 0.11 W m$^{-2}$ in 1992, respectively. For SnRF estimates from reanalysis a_s datasets, the ERA-5 and JRA-55-based SnRF series presented peak values in 2007 with $-$1.99 ± 0.14 W m$^{-2}$ and $-$1.59 ± 0.12 W m$^{-2}$, respectively. Moreover, the valleys of the ERA-5 and JRA-55-based SnRF series occurred in 1985, with $-$2.60 ± 0.19 W m$^{-2}$ and $-$1.94 ± 0.15 W m$^{-2}$.

The SnRF over the NH declined by 0.39 W m$^{-2}$ to 1.25 W m$^{-2}$ during 1982–2012 based on series from satellite a_s datasets, which was much smaller than the comparable results calculated from the reanalysis-based SnRF (2.02 W m$^{-2}$ to 2.65 W m$^{-2}$), which may have overestimated the role of snow cover in climate change.
studies and future climate projections. Thus, the discrepancies between $S_{\text{RF}}$ estimations from satellite and reanalysis datasets should be considered when evaluating the snow-induced energy budget and climate system anomalies in future studies.
4.2. Changes in seasonal $S_n$RF

The 31-year linear changes of $S_n$RF over the NH in each month derived from two satellites and four reanalysis datasets from 1982–2012 are shown in figure 7. Changes in $S_n$RF in a given month from 1982 to 2012 were calculated as linear trends multiplied by the time interval.

Driven by the decreased SCE over the NH in spring and summer seasons (Chen et al. 2016a), the $S_n$RF calculated from both GLASS and CLARA-A2 datasets displayed positive changes from April to August, which coincided with the $S_n$RF changes derived from reanalysis datasets. However, the negative $S_n$RF changes calculated from GLASS and CLARA-A2 in the snow accumulation seasons from November to February were largely different from the $S_n$RF changes derived from reanalysis datasets, except for CFSR, especially in January. The changes in $S_n$RF calculated from GLASS ($-0.10 \pm 0.010\ W\ m^{-2}$) and CLARA-A2 ($-0.41 \pm 0.06\ W\ m^{-2}$) datasets were negative in January, which indicated an enhanced cooling effect caused by snow cover. However, this phenomenon could not be adequately represented by a reanalysis-based $S_n$RF.

As reported by Chen et al. (2016a) and Cohen et al. (2012), driven by Arctic Amplification, increasing snow cover and widespread boreal winter cooling occurred from the 1990s onward. With increased snow cover extent and greater albedo contrast, additional solar radiation was reflected to space, which resulted in a strengthened cooling effect of snow cover and negative changes in $S_n$RF. In contrast, with the rapid decline of spring and summer SCE over the NH (Brown and Robinson 2011, Derksen and Brown 2012, Chen et al. 2016a), obviously weakened cooling effects should have been detected from $S_n$RF. Compared with satellite observations, the reanalysis field captured the $S_n$RF changes.

5. Discussion and conclusions

The $S_n$RF is a vital indicator to evaluate the contribution of snow cover to Earth radiation budget under the background of global warming and rapid SCE reduction over the NH in the past few decades. As a key parameter in $S_n$RF estimation with large bias between satellite and reanalysis products, a comprehensively examine the performance of satellite and reanalysis $a_s$ datasets in representing the large scale spatiotemporal variability and long term change in $S_n$RF over the NH are necessary. Using two satellite and four reanalysis $a_s$ datasets coupled with several ancillary datasets, this study explored the differences between satellite- and reanalysis-based $S_n$RFs over the NH for the overlapping period of 1982–2012.

Although both satellite- and reanalysis-based $S_n$RFs captured the climatology of the annual-mean and seasonal cycle of $S_n$RF over the NH during 1982–2012, large differences still exist between them. For climatology of annual-mean $S_n$RF, the reanalysis-based $S_n$RF displayed lower values in high latitude and high elevation regions compared with satellite-based $S_n$RF, which may underestimate the radiative forcing and feedback of snow cover to climate change in those regions. For the seasonal cycle, the reanalysis-based $S_n$RF displayed higher values in snow accumulation seasons from October to January, but a lower value from February to July, compared with satellite-based $S_n$RF over the NH from 1982 to 2012.

Changes in $S_n$RF over the NH during 1982–2012 derived from satellite and reanalysis $a_s$ datasets were also cross-compared in this study. The annual-mean $S_n$RF over the NH declined by $0.39\ W\ m^{-2}$ to $1.25\ W\ m^{-2}$ during 1982–2012 from satellite-based $S_n$RF, which is much smaller than the results calculated from the reanalysis-based $S_n$RF. In addition, changes in monthly-mean $S_n$RF from satellite-based $S_n$RF series displayed an
enhance trend in snow accumulation season over the NH from 1982 to 2012, which are largely different with the comparable changes from reanalysis-based S<sub>r</sub>RF, indicating that the reanalysis-based S<sub>r</sub>RF results cannot capture the actual inter-annual and intra-annual changes of S<sub>r</sub>RF over the NH.

Compared with previous research, the present study investigated the spatial and temporal differences between S<sub>r</sub>RF over the NH using satellite and reanalysis a<sub>s</sub> datasets for the overlapping period of 1982–2012, which is important for current climate change studies and future climate projections. However, several unresolved issues remain in our study. Subjected to the coarse resolution of NHSCE snow range and reanalysis a<sub>s</sub> datasets, this study was carried out at 0.5 spatial resolution, which may mixed the radiative forcing induced by snow cover and other land cover types, especially vegetation and permafrost (Johansson et al 2013). As an integral component of the global climate system with rapid changes, more detailed evaluation and analysis of radiative forcing and feedback induced by snow cover changes with fine resolution is necessary in future studies. Since CLARA-A2 only provides white-sky surface albedo products, this study used white-sky surface albedo products from satellite observations in the cross-comparisons with reanalysis-based annual-mean and monthly-mean S<sub>r</sub>RF results. However, previous studies have reported that the differences between S<sub>r</sub>RF with white-sky albedo and black-sky albedo are slightly (Flanner et al 2011, Qu and Hall 2014, Chen et al 2016b), which will not influence the results of this study. Considering the large discrepancies in S<sub>r</sub>RF results from different surface albedo datasets, the uncertainties in S<sub>r</sub>RF estimations should be considered in future studies.

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