Radiative Fluxes at Barrow, Alaska: A Satellite View

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ABSTRACT

Satellite estimates of surface shortwave radiation (SWR) at high latitudes agree less with ground observations than at other locations; moreover, ground observations at such latitudes are scarce. The comprehensive observations of radiative fluxes made since 1977 by the Department of Energy Atmospheric Radiation Measurement (ARM) Program at the Barrow North Slope of Alaska (NSA) site are unique. They provide an opportunity to revisit accuracy estimates of remote sensing products at these latitudes, which are problematic because the melting of snow/ice and lower solar elevation make the satellite retrievals more difficult.

A newly developed inference scheme for deriving SWR from the Moderate Resolution Imaging Spectroradiometer (MODIS; Terra and Aqua) that utilizes updated information on surface properties over snow and sea ice will be evaluated against these ground measurements and compared with other satellite and model products. Results show that the MODIS-based estimates are in good agreement with observations, with a bias of $-5.3 \text{ W m}^{-2}$ ($-4\%$ of mean observations) for the downward SWR, a bias of $-5.3 \text{ W m}^{-2}$ ($-7\%$) for upward SWR, a bias of 1 ($1\%$) for net SWR, and a bias of $-0.001$ ($0\%$) for surface albedo. As such, the MODIS estimates of SWR can be useful for numerical model evaluations and for estimating the energy budgets at high latitudes.

1. Introduction

It has been documented that in recent decades the Arctic has warmed and that northern Alaska is one of the most significantly impacted regions from global warming. The evidence of environmental changes in the Arctic regions with a focus on Alaska has been summarized in Hinzman et al. (2005). Studies related to surface shortwave radiation (SWR) in the Alaska region can be traced back to 1880s (Ray 1885) and the first comprehensive measurement of SWR started in the early 1960s (Maykut and Church 1973; Zhang et al. 2003). Several climate-change-related investigations over this region have been undertaken. The studies of Maykut and Church (1973), Dingman et al. (1980), Sturm (2000), Zhang et al. (2003), and Belchansky et al. (2004) emphasize the need to separate various seasons in investigations of the margin areas of the Arctic. The variation patterns of the spectral ultraviolet and visible irradiances at Barrow, Alaska, for the period of 1991–2005 as related to the changes in ozone, cloudiness, and surface albedo were dealt with in Bernhard et al. (2007). In a comprehensive investigation by Dong et al. (2010) using 10 yr of cloud and radiative flux observations collected by the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Program at the North Slope of Alaska (NSA), it is reported that the longwave cloud-radiative forcing (CRF) has a high positive correlations (0.8–0.9) with cloud fraction, liquid water path, and radiating temperature while having negative correlations for shortwave CRF. These Barrow observations provide a baseline for studies of Arctic CRF and serve as a reliable ground truth for validating satellite estimates and model outputs. CloudSat observations that started in 2007 (Stephens et al. 2002) illustrated that the reduced cloud fraction and enhanced downward SWR contributed significantly to the 2007 record minimum sea ice extent (Kay et al. 2008).

This study focuses on Barrow (71.32°N, 156.61°W) located at the northernmost point in the United States, 330 miles north of the Arctic Circle; it is a representative site for evaluating climate change in the western Arctic.
coastal zone (Stone 1997). The monthly mean surface temperature ranges from –25°C during January–February to 4°C during July–August with an annual average of –11°C (based on 10 yr of surface observations; Dong et al. 2010). Studies of the classic synoptic patterns around Barrow using 55 yr of daily sea level pressure data show that the Aleutian low is dominant in southern Alaska and high pressure is dominant over the Beaufort and Chukchi Seas (Cassano et al. 2006). Barrow is found to be at the important latitude where neutral net CRF (negative shortwave CRFs and positive longwave CRFs) nearly cancel each other on an annual average because the net CRFs changes from negative to positive values from Alaska to the Beaufort Sea (Dong et al. 2010). The complexity in the understanding of changes in the Alaskan region is a result of the fact that the region is under the influence of both extratropical and Arctic synoptic activity and because of the many physical feedbacks in that region such as ice–albedo feedback and cloud-radiative feedback (Stone et al. 2002, 2005).

Most of the studies on SWR at Barrow are based on surface observations. The ARM-NSA site (Stamnes et al. 1999; Ackerman and Stokes 2003) was designed to collect data on clouds and surface radiative processes. A 10-yr (1998–2008) climatology of Arctic radiative fluxes and cloud fraction at Barrow has been generated using the ARM-NSA observations; the cloud fraction has an annual average of 0.76 with seasonal variations between 0.57–0.9 and the radiative fluxes are very close to the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) global reanalysis, the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), the NCEP–NCAR North American Regional Reanalysis (NARR), and the Japan Meteorological Agency and Central Research Institute of Electric Power Industry 20-yr Reanalysis (JRA-25) against the ARM-NSA site for the summers (June–August) of 1999–2006 at a monthly scale, shows that only ERA-40 and NARR can capture the annual cycle of SWR and that the ERA-40 is the best performer with bias of 6 W m\(^{-2}\) while others have a higher bias (i.e., JRA-25 with 16 W m\(^{-2}\), NARR with 25 W m\(^{-2}\), and NCEP with 43 W m\(^{-2}\); Walsh et al. 2009). During the 1-month Mixed-Phase Arctic Clouds Experiment (MPACE), 2 models [the NCEP Eta Model and the Regional Atmospheric Modeling System (RAMS)] have been examined against surface downward SWR and both models overestimated the surface fluxes with a bias of about 30 W m\(^{-2}\) for the Eta Model and about 10 W m\(^{-2}\) for the RAMS model at an hourly time scale (Yamazaki et al. 2009).

Our comprehensive analysis of the satellite SWR estimates (down, up, and net) and surface albedo against ARM-NSA surface observations at a daily time scale can contribute to a better understanding of the satellite products at these latitudes. In this paper, we evaluate various satellite estimates of daily SWR for 2 yr (2003–2004) when all the satellite data are available; the MODIS products are evaluated for the period of July 2002–June 2010.

2. Datasets

2.1. Surface observations

The ARM-NSA Barrow facility has been in operation since July 1997. The focus of the measurements is on solar and thermal infrared radiation at the earth’s surface and relevant atmospheric parameters. Before the start of the ARM observations, many shorter-term campaigns were conducted at high latitudes. One of the most notable programs in the Arctic Ocean was the Surface Heat Budget of the Arctic (SHEBA) experiment led by the National Science Foundation and the Office of Naval Research, for the period of October 1997–October 1998 (Randall et al. 1998; Perovich et al. 1999; Curry et al. 2000).

The SWR at ARM-NSA is collected by rotating shortwave radiometers and pyranometers. The Multifilter Rotating Shadowband Radiometer (MFRSR) takes measurements of direct, diffuse horizontal, and total horizontal
components of the broadband solar irradiance at 6 wavelengths at nominal wavelengths of 415, 500, 615, 673, 870, and 940 nm using a silicon detector. The fundamental measurements are made in millivolts with an accuracy of 0.06% of 250 mV and an uncertainty of 0.06% of 250 mV (Hodges and Michalsky 2011). An Eppley Precision Spectral Pyranometer (PSP) measures the hemispherical downward solar irradiance in the 280–2950-nm range. The downward and upward SWR respond to radiation within a 2π steradian (hemispherical) field of view.

The evaluation of the satellite products will be done against surface measurements of downward, upward, net SWR, and surface albedo. The hourly mean observed SWR fluxes are generated by averaging the 60-min observations corrected to local time; the daily means are obtained by summing the hourly values from sunrise to sunset and dividing by 24. The daily mean net SWR is computed as the difference of the downward and upward components, and the surface albedo is the ratio of upward and downward SWR fluxes.

b. Satellite estimates utilized

1) UMD-MODIS (1°)

The MODIS instrument on board the Terra and Aqua satellites observes at higher spatial and spectral resolution than earlier satellites, thus improving capabilities to detect atmospheric and surface properties. The sensor has 36 spectral bands in a wide spectral range (0.41–14.24 μm), frequent global coverage (up to 7 observations per day at high latitudes), and high spatial resolution (250 m for two bands, 500 m for 5 bands and 1000 m for 29 bands). This permits global monitoring of atmospheric properties and surface conditions at higher accuracy and consistency than previous earth observation imagers (King et al. 1992).

An inference scheme [University of Maryland (UMD) MODIS] was developed (Wang and Pinker 2009) to utilize information based on MODIS observations, to estimate spectral SWR at both 1° (using the MODIS level-3 Atmosphere Daily Global Product) and at 5-km spatial scales (using the MODIS level-2 Swath Product; Su et al. 2008). Information on atmospheric constituents, both water and ice cloud properties (cloud particle effective radius and optical properties), and surface albedo is used. The spectral SWR is retrieved for a multilayered atmosphere that accounts for surface elevation and for the representation of the vertical distribution of atmospheric variables.

Since the publication of the Wang and Pinker (2009) manuscript, improved information on surface properties at high latitudes became available. To be able to utilize such information, modifications were introduced to the inference scheme, in particular, on the spectral surface reflectance in the presence of snow or sea ice. In the original scheme the spectral reflectance for snow is assumed to be 0.9 for visible band and 0.6 for the near-infrared (NIR) part of the spectrum; for sea ice it is assumed to be 0.73 for the visible and 0.33 for the NIR part of the spectrum. The MODIS daily global snow cover data at 0.25° were utilized (see online at http://modis-snow. gsfc.nasa.gov/). In the updated version, higher-resolution snow cover at 0.05° at a daily time scale (MOD10C1 from Terra, MYD10C1 from Aqua) and at monthly time scale (MOD10CM from Terra, MYD10CM from Aqua) are utilized. It is based on a snow mapping algorithm that employs additional criteria such as the normalized difference snow index (Hall et al. 2006). This information is available from the National Snow and Ice Data Center (NSIDC; available online at http://nsidc.org/data/modis/ data_summaries/index.html). The MODIS surface reflectance products provide a 5-yr (2000–04) climatological statistics of spectral reflectance when the surface is covered by snow (the underlying surface types are aggregated according to the International Geosphere-Biosphere Program (IGBP) classification (Moody et al. 2007). For instance, the white-sky reflectance at wavelength of 0.55 μm for snow-covered grassland, desert, and permanent snow are 0.72, 0.87, and 0.94, respectively (Moody et al. 2007). In the original scheme used the monthly mean sea ice extent is at 1° grid cells based on the Special Sensor Microwave Imager (SSM/I) of the National Oceanic and Atmospheric Administration/National Environmental Satellite, Data, and Information Service (NOAA/NESDIS) National Climate Data Center (NCDC). In the updated version, higher-resolution (25 km) sea ice concentrations at both daily and monthly time scales as derived from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SSMR) and the Defense Meteorological Satellite Program (DMSP) SSM/I radiances are used [based on a National Aeronautics and Space Administration (NASA) algorithm; Cavalieri et al. 2008; see online at http://nsidc.org/data/nsidc-0051.html]. The fixed values of spectral reflectance of sea ice in the original scheme have been updated for four distinct phases in the margin areas of the Arctic (winter stationary, spring melt season, summer stationary, and autumn freeze up) according to Zhang et al. (2003) and Belchansky et al. (2004). Since the daily snow cover has many missing values at high latitudes, they have been replaced with monthly mean values. In the present study results from implementation at 1° resolution are presented. An example of daily mean SWR distributions from UMD-MODIS estimates over the Arctic regions (60°–90°N) for 1 May 2007 are shown in Fig. 1 (the downward and upward SWR, the net SWR, and the surface albedo).
Extensive evaluations of the 1° UMD-MODIS products against ground measurements over oceans and land sites both at monthly and daily time scales have been performed (Pinker et al. 2009; Niu et al. 2010). Evaluation of daily mean UMD-MODIS surface downward SWR estimates against buoy observations at low latitudes has shown that the correlation coefficient is 0.90, with a bias within 3 W m\(^{-2}\) (1%), and a root-mean-square error (RMSE) within 36 W m\(^{-2}\) (17%); against buoy observations at high latitudes the corresponding values were 0.94, −7 W m\(^{-2}\) (−6%), and 38 W m\(^{-2}\) (21%), respectively. The evaluation of daily mean UMD-MODIS surface downward SWR estimates against land observations at low latitudes has shown a correlation coefficient of 0.98, a bias of −3 W m\(^{-2}\) (−2%), and an RMSE of 21 W m\(^{-2}\) (11%); against land observations at high latitudes the corresponding values were 0.97, −7 W m\(^{-2}\) (−5%), and 28 W m\(^{-2}\) (21%), respectively.

At high latitudes the UMD-MODIS approach can be implemented at higher spatial resolution (5 km) and higher temporal resolution (up to 7 overpasses per day) in order to improve the representation of variability in ice extent and snow cover and to better represent the diurnal variability of SWR. Evaluation of the 5-km products is in progress.

2) NASA LARC (1°)

The Global Energy and Water Cycle Experiment (GEWEX) Shortwave Radiation Budget (SRB) daily mean surface fluxes (release-3.0, at 1° grid) are generated at the NASA Langley Research Center (LaRC; these are available online at http://eosweb.larc.nasa.gov/PRODOCS/srb/table_srb.html#daily).

The data are derived with the shortwave algorithm of the NASA World Climate Research Programme (WCRP/GEWEX) SRB model (Hinkelman et al. 2009). The daily
average values representative of local time are used since the surface observations are obtained at local time.

3) AVHRR (25 km)

Information on SWR as generated from the AVHRR on board NOAA polar-orbiting satellites is available. The specific datasets are the Extended AVHRR Polar Pathfinder (APP-x) project. The data are twice-daily composites for north and south polar regions (Key and Schweiger 1998; Key 2001; Wang and Key 2003, 2005a,b). The data cover the period 1982–2004 and as such, are of interest for long-term needs. They are at a spatial resolution of 25 km for both Arctic and Antarctic (available online at ftp://stratus.ssec.wisc.edu/pub/appx/). The local solar times are 1400 and 0400 (Arctic). The SWR are computed by using the FluxNet model (Key and Schweiger 1998). Evaluation of the hourly mean SWR against the Surface Heat Budget of the Arctic Ocean (SHEBA) field experiment data has shown a bias of 12.5 W m$^{-2}$, a standard deviation of 136.2 W m$^{-2}$, and a correlation of 0.95 for all seasons (Liu et al. 2005).

4) UMD-D1 (2.5°)

The UMD-D1 radiative flux estimates are based on International Satellite Cloud Climatology Project (ISCCP) D1 data (Rossow et al. 1996) as implemented with the University of Maryland Surface Radiation Budget model (UMD/SRB; Pinker and Laszlo 1992; Liu and Pinker 2008). It utilizes shortwave radiances as observed from satellites at the top of the atmosphere (TOA), transforms them into broadband fluxes, corrects for bidirectionality, estimates average optical properties of aerosols (from the clear-sky radiances) and of clouds (from cloudy-sky radiances) to be used in inferring the surface fluxes. It can be driven with satellite data from various sources such as the ISCCP D1 data, the Geostationary Operational Environmental Satellite (GOES), or Meteosat. The UMD-D1 radiative estimates are provided globally at 2.5° spatial resolution, at 3-hourly, daily, and monthly time steps. [An early version of the data can be found online at http://www.atmos.umd.edu/~srb/pathfinder/webpath.htm (to be updated with the version used in this study).]

c. Reanalysis products

The NCEP/DOE Atmospheric Model Intercomparison Project (AMIP-II) reanalysis (NCEP) products [provided by the NOAA/Office of Oceanic and Atmospheric Research/Earth System Research Laboratory (NOAA/OAR/ESRL) Physical Sciences Division (PSD), Boulder, Colorado, from the Web site online at http://www.esrl.noaa.gov/psd/] are based on the NCEP–NCAR reanalysis by removing some errors and by updating the parameterizations of several physical processes. The products are global (T62 Gaussian grid) at temporal coverage of
4 times per day, daily mean, and monthly mean for the period of 1979–2010 (Kanamitsu et al. 2002). (The surface downward and upward SWR is available online at http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.gaussian.html.)

3. Results

a. Evaluation of 8 yr of UMD-MODIS estimates

Eight years (July 2002–June 2010) of daily means MODIS-based SWR (down, up, and net) and surface albedo have been generated at 1° resolution and evaluated against the ground measurements at the ARM-NSA site (Aqua started observations from 2002). The daily averaged values are generated by using 2 observations per day (Terra at 1030 and Aqua at 1330 local time; Wang and Pinker 2009).

After eliminating cases outside of three standard deviations (indicated in the figures as percentage of data eliminated) results are presented in Fig. 2. As evident, the bias is $-5.3 \text{ W m}^{-2}$ (about $-4\%$ of mean values), $-5.3 \text{ W m}^{-2}$ ($-7\%$), $1.0 \text{ W m}^{-2}$ ($1\%$), $-0.001$ ($0\%$) for surface downward SWR, upward SWR, net SWR, and surface albedo, respectively. The values of the standard deviations are $22.9 \text{ W m}^{-2}$ (16%), 17.2 (24%), 15.8 $\text{ W m}^{-2}$ (23%), and 0.077 (15%) for the four parameters. The correlations are 0.97. The UMD-MODIS values underestimate both the downward SWR and upward SWR, which reduces the bias of the net SWR.

The time series of 8-yr daily averaged downward SWR, upward SWR, and net SWR and surface albedo estimated from UMD-MODIS and as observed at the Barrow are shown in Fig. 3. The start day is 21 February and the end day is 19 October (the MODIS products are constrained to daily mean solar zenith angle less than 85°). There are no retrievals if the sun elevation is too low. The polar night is during January and December; during early February and all of November, the sunrise hour is around 1000 local time and the sunset is around 1400. The UMD-MODIS estimates fit well with the observations and have the capability of capturing the seasonal variation of surface properties in the margin areas of Arctic, which are generally considered as winter consistent (surface albedo of $\sim 0.8$), spring melt onset, summer consistent (surface albedo of $\sim 0.2$), and autumn freeze up. At Barrow, the downward SWR reaches a maximum during June (around the summer solstice);

<table>
<thead>
<tr>
<th>Name of datasets</th>
<th>Organization</th>
<th>Spatial resolution</th>
<th>Temporal resolution</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>UMD-MODIS</td>
<td>University of Maryland</td>
<td>1°</td>
<td>Twice per day; daily</td>
<td>2002–10</td>
</tr>
<tr>
<td>NASA/LaRC</td>
<td>NASA/Langley</td>
<td>1°</td>
<td>3-hourly; daily; monthly</td>
<td>1983–2007</td>
</tr>
<tr>
<td>AVHRR</td>
<td>CIMSS/Polar Remote Sensing and Climatology Group</td>
<td>25 km</td>
<td>Twice per day; monthly</td>
<td>1982–2004</td>
</tr>
<tr>
<td>UMD-D1</td>
<td>University of Maryland</td>
<td>2.5°</td>
<td>3-hourly; daily; monthly</td>
<td>1983–2006/07</td>
</tr>
<tr>
<td>NCEP</td>
<td>NOAA/NCEP-DOE reanalysis</td>
<td>Global T62 grid</td>
<td>Daily; monthly</td>
<td>1979–2010</td>
</tr>
</tbody>
</table>
the upward SWR peaks about one month before the summer solstice when the surface albedo starts to fall as associated with the surface snowmelt onset, which result in the increase of the net SWR that reaches a peak around the summer solstice when the sun is higher and the albedo is lower than during the rest of the year; the surface albedo remains stable during the summer and starts to increase around the autumnal equinox when the snow freezes up.

b. Evaluation of 2 yr of satellite and reanalysis products

Four satellite estimates (UMD-MODIS, NASA/LaRC, AVHRR, and UMD-D1) and NCEP/DOE II reanalysis (NCEP) of SWR (down, up, and net) and surface albedo are evaluated against surface observations collected at the ARM-NSA site for 2 yr (2003–04) at a daily scale when data from all sources are available. The spatial and temporal resolution and the time period for all these products are shown in Table 1.

The evaluations of the daily averaged downward SWR from the satellites and from reanalysis products against surface observations are presented in Fig. 4. The results show that the bias is $-3.6$ W m$^{-2}$ ($-2\%$ of mean value), $7.0$ W m$^{-2}$ ($5\%$), $9.5$ W m$^{-2}$ ($6\%$), $10.9$ W m$^{-2}$ ($7\%$), and $51.8$ W m$^{-2}$ ($34\%$), respectively, for UMD-MODIS, NASA/LaRC, AVHRR, UMD-D1, and NCEP. The

![Fig. 4. Evaluations of daily averaged surface downward SWR (W m$^{-2}$) from satellite estimates (a) UMD-MODIS, (b) NASA/LaRC, (c) AVHRR, (d) UMD-D1, and from (e) NCEP reanalysis against surface measurements at the ARM-NSA site for 2 yr (2003–04).](image-url)
values of the standard deviations are 22.6 W m\(^{-2}\) (15%), 46.8 W m\(^{-2}\) (31%), 51.0 W m\(^{-2}\) (34%), 42.2 W m\(^{-2}\) (28%), and 51.4 W m\(^{-2}\) (34%) and the correlations are 0.97, 0.88, 0.84, 0.89, and 0.87, for UMD-MODIS, NASA/LaRC, AVHRR, UMD-D1, and NCEP, respectively. Compared with the other satellite and reanalysis products, the UMD-MODIS product has a lower bias and standard deviation and higher correlation.

The time series of daily mean SWR (downward, upward, and net) and surface albedo for the year 2003 are illustrated in Fig. 5. The UMD-MODIS estimates are in good agreement with observations while the NCEP reanalysis results seem to have some problems, particularly during the snowmelt season. The statistics for the surface downward SWR, upward SWR, net SWR, and surface albedo are summarized in Table 2.

4. Issues in satellite estimates of SWR over a coastline at high latitudes

The Barrow site is located around the coastline where melting of snow and ice during the spring and freezing during autumn take place, and as such, of interest in climate research. From the information provided by the National Snow and Ice Data Center (NSIDC), the monthly mean of snow/ice coverage around the Barrow sites are illustrated in Fig. 6. The sea ice concentrations are derived from the Nimbus-7 SMMR and the DMSP
SSM/I radiances at a gridcell size of 25 × 25 km² (Cavalieri et al. 2008; the data are available online at http://nsidc.org/data/nsidc-0051.html). The snow coverage is based on MODIS monthly mean global snow cover data at 0.05° from Terra. The snow–ice starts melting from May (from 100% to 70%), keeps melting during June (from 70% to 10%), reaches an almost snow–ice-free period during summer (July–September), and starts freezing from October (going up to 100%). The variations of snow/ice coverage make it difficult to retrieve SWR from satellites over the coastline of the Arctic because of the difficulty to account correctly for surface type. The relatively lower solar elevation at high latitudes adds to the challenge. Utilizing the 8 yr (July 2002–June 2010) of UMD-MODIS estimates, the bias and RMSE against the ARM-NSA observations are calculated at a monthly scale as shown in Fig. 7. The monthly mean snow–ice coverage and solar zenith angles (SZA) are also shown. More solar energy is available during June (around the summer solstice) when the SZA reaches a minimum (~68°), so that the bias of satellite estimates is smaller. However, the snow–ice is in the melting phase during June (from snow-covered to an almost snow-free situation), which increases the RMSE. During the summer months (July–September), the surface is almost snow free and the bias and RMSE are relatively stable and smaller. After September, the snow–ice starts freezing and the SZA is relatively larger, the bias and RMSE begin to increase. Correlations of the relative bias (ratio of bias and mean observations, as $R_{\text{bias}}$) and relative RMSE (ratio of RMSE and mean observations, as $R_{\text{RMSE}}$) to snow–ice percentage ($C_{\text{snow}}$) and cosine of SZA ($\cos \theta$) show a strong negative correlation ($-0.97$) for $R_{\text{bias}}$ and $C_{\text{snow}}$ and a smaller positive correlation (0.13) for $R_{\text{bias}}$ and $\cos \theta$; a negative correlation ($-0.73$) for $R_{\text{RMSE}}$ and $\cos \theta$ and a positive correlation (0.25) for $R_{\text{RMSE}}$ and $C_{\text{snow}}$.

5. Conclusions

Eight years of SWR estimates based on the UMD-MODIS model have been evaluated against daily-averaged surface observations at Barrow, Alaska. Ground observations obtained under the ARM project at the ARM-NSA site were used. The UMD-MODIS estimates of surface downward, upward, and net SWR and the surface albedo are in good agreement with observations. Two years (2003–04) of independent daily satellite and reanalysis products have been also evaluated against ground measurements. The UMD-MODIS products are in best agreement with both surface downward and upward SWR. The NASA/LaRC and AVHRR products are in good agreement with the surface observations of the downward SWR, while they are in lesser agreement with the upward SWR. The UMD-D1 estimates perform relatively well for the downward and upward components, except for the summer months. The NCEP reanalysis products overestimate SWR at high latitudes, for both downward and upward components of the SWR, especially during the snowmelt seasons. The variations

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean obs</th>
<th>Correlation</th>
<th>Std dev (%)</th>
<th>Bias (%)</th>
<th>No. of cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>SWR₂ (W m⁻²)</td>
<td>MODIS</td>
<td>151</td>
<td>0.97</td>
<td>22.6 (15)</td>
<td>-3.6 (-2)</td>
</tr>
<tr>
<td></td>
<td>NASA/LaRC</td>
<td>151</td>
<td>0.88</td>
<td>46.8 (31)</td>
<td>7.0 (5)</td>
</tr>
<tr>
<td></td>
<td>AVHRR</td>
<td>151</td>
<td>0.84</td>
<td>51.0 (34)</td>
<td>9.5 (6)</td>
</tr>
<tr>
<td></td>
<td>UMD-D1</td>
<td>152</td>
<td>0.89</td>
<td>42.2 (28)</td>
<td>10.9 (7)</td>
</tr>
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<td></td>
<td>NCEP</td>
<td>152</td>
<td>0.87</td>
<td>51.4 (34)</td>
<td>51.8 (34)</td>
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<tr>
<td>SWR₁ (W m⁻²)</td>
<td>MODIS</td>
<td>77</td>
<td>0.98</td>
<td>16.1 (21)</td>
<td>-5.2 (-7)</td>
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<td></td>
<td>NASA/LaRC</td>
<td>78</td>
<td>0.78</td>
<td>45.0 (58)</td>
<td>-14.6 (-19)</td>
</tr>
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<td></td>
<td>AVHRR</td>
<td>77</td>
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<td>42.7 (55)</td>
<td>-19.9 (-26)</td>
</tr>
<tr>
<td></td>
<td>UMD-D1</td>
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<td>0.88</td>
<td>35.2 (45)</td>
<td>4.9 (6)</td>
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<tr>
<td></td>
<td>NCEP</td>
<td>78</td>
<td>0.76</td>
<td>63.9 (82)</td>
<td>44.3 (56)</td>
</tr>
<tr>
<td>Net SWR (W m⁻²)</td>
<td>MODIS</td>
<td>72</td>
<td>0.97</td>
<td>16.0 (22)</td>
<td>2.5 (3)</td>
</tr>
<tr>
<td></td>
<td>NASA/LaRC</td>
<td>69</td>
<td>0.92</td>
<td>25.0 (36)</td>
<td>24.7 (36)</td>
</tr>
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<td></td>
<td>AVHRR</td>
<td>73</td>
<td>0.88</td>
<td>36.5 (50)</td>
<td>30.7 (42)</td>
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<tr>
<td></td>
<td>UMD-D1</td>
<td>70</td>
<td>0.90</td>
<td>27.2 (39)</td>
<td>8.1 (12)</td>
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<tr>
<td></td>
<td>NCEP</td>
<td>70</td>
<td>0.75</td>
<td>44.4 (63)</td>
<td>9.5 (13)</td>
</tr>
<tr>
<td>Surface albedo</td>
<td>MODIS</td>
<td>0.5</td>
<td>0.98</td>
<td>0.07 (14)</td>
<td>-0.01 (-2)</td>
</tr>
<tr>
<td></td>
<td>NASA/LaRC</td>
<td>0.5</td>
<td>0.76</td>
<td>0.20 (41)</td>
<td>-0.13 (-27)</td>
</tr>
<tr>
<td></td>
<td>AVHRR</td>
<td>0.5</td>
<td>0.84</td>
<td>0.17 (35)</td>
<td>-0.12 (-24)</td>
</tr>
<tr>
<td></td>
<td>UMD-D1</td>
<td>0.5</td>
<td>0.90</td>
<td>0.14 (29)</td>
<td>-0.0 (-0)</td>
</tr>
<tr>
<td></td>
<td>NCEP</td>
<td>0.5</td>
<td>0.66</td>
<td>0.26 (53)</td>
<td>0.05 (10)</td>
</tr>
</tbody>
</table>
of snow–ice coverage and lower solar elevation along coastlines of high latitudes call for the need to utilize higher-resolution satellite observations in order to improve the representation of the variability in surface properties.

It is believed that the high-resolution 5-km products that can be generated using the UMD-MODIS approach have the potential to improve estimation of the surface radiant energy budget because the specification of the underlying surface can be improved and up to 7 observations per day can be used to represent the diurnal cycle. There is a need to utilize more accurate information on both surface and atmospheric conditions for high latitudes. High-quality ground observations at high latitudes

![Fig. 6. Monthly mean of snow–ice coverage around Barrow site (marked as a black triangle) for May, June, July, August, September, and October 2007. The information is from the NSIDC.](image-url)
collected during the International Polar Year (IPY 2007–08) and observations from CloudSat could be useful for evaluation and improvements.

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REFERENCES


Key, J., 2001: The Cloud and Surface Parameter Retrieval (CASPR) system for polar AVHRR data user’s guide. Space


