Arctic Cloud Fraction and Radiative Fluxes in Atmospheric Reanalyses

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ABSTRACT

Arctic radiative fluxes, cloud fraction, and cloud radiative forcing are evaluated from four currently available reanalysis models using data from the North Slope of Alaska (NSA) Barrow site of the Atmospheric Radiation Measurement Program (ARM). A primary objective of the ARM–NSA program is to provide a high-resolution dataset of direct measurements of Arctic clouds and radiation so that global climate models can better parameterize high-latitude cloud radiative processes. The four reanalysis models used in this study are the 1) NCEP–NCAR global reanalysis, 2) 40-yr ECMWF Re-Analysis (ERA-40), 3) NCEP–NCAR North American Regional Reanalysis (NARR), and 4) Japan Meteorological Agency and Central Research Institute of Electric Power Industry 25-yr Reanalysis (JRA25). The reanalysis models simulate the radiative fluxes well if/when the cloud fraction is simulated correctly. However, the systematic errors of climatological reanalysis cloud fractions are substantial. Cloud fraction and radiation biases show considerable scatter, both in the annual mean and over a seasonal cycle, when compared to those observed at the ARM–NSA. Large seasonal cloud fraction biases have significant impacts on the surface energy budget. Detailed comparisons of ARM and reanalysis products reveal that the persistent low-level cloud fraction in summer is particularly difficult for the reanalysis models to capture creating biases in the shortwave radiation flux that can exceed 160 W m$^{-2}$. ERA-40 is the best performer in both shortwave and longwave flux seasonal representations at Barrow, largely because its simulation of the cloud coverage is the most realistic of the four reanalyses. Only two reanalyses (ERA-40 and NARR) capture the observed transition from positive to negative surface net cloud radiative forcing during a 2–3-month period in summer, while the remaining reanalyses indicate a net warming impact of Arctic clouds on the surface energy budget throughout the entire year. The authors present a variable cloud radiative forcing metric to diagnose the erroneous impact of reanalysis cloud fraction on the surface energy balance. The misrepresentations of cloud radiative forcing in some of the reanalyses are attributable to errors in both simulated cloud amounts and the models’ radiative response to partly cloudy conditions.

1. Introduction

Recent climate modeling has demonstrated significant sensitivity of the Arctic to climate change (Anisimov et al. 2007; Kattsov and Källen 2005). This sensitivity has been verified with observations. According to the Technical Summary of Working Group I (Solomon et al. 2007) for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4), ob-

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of active-layer thickness ranging from 0.04 m yr$^{-1}$ in Alaska to 0.02 m yr$^{-1}$ on the Tibetan Plateau. Observations indicate that sea ice extent, particularly in summer, is experiencing a significant downward trend that could have major implications for the global energy budget (Stroeve et al. 2007). The role of unusually cloud-free conditions and enhanced surface solar absorption on the 2007 record low Northern Hemisphere sea ice minimum is currently being debated. Schweiger et al. (2008) contend that relatively clear conditions did little to enhance surface ice melting during the spring and summer 2007, while Perovich et al. (2008) cite enhanced radiation in areas of open water as a primary source of ocean heat and ice-bottom melting during the historic ice minimum.

Global climate models are one of the most important tools for diagnosis of Arctic climate interactions and projecting Arctic climate change into the future. There is, however, considerable variability in the skill demonstrated by models in their ability to simulate current climate and, presumably, in their projections of change over the next century (Chapman and Walsh 2007). Arctic clouds have long been known to be one of the major sources of uncertainty in simulations of Arctic climate (Randall et al. 1998; Walsh et al. 2005). Arctic clouds modulate abrupt surface albedo changes that by themselves trigger a host of feedback mechanisms (Stamnes et al. 1999). Cloud cover dominates downward longwave radiation that, in turn, strongly influences the initiation and rate of melting (Curry et al. 1993; Curry 1995; Curry et al. 1995; Zhang et al. 1996). Previous research has estimated that clouds in the Arctic are also more prevalent and persistent than clouds elsewhere, with 90% cloud cover in summer (Huschke 1969; Warren et al. 1988; Curry et al. 1996) and as much as 80% in winter (Curry and Ebert 1992). This pervasiveness amplifies their influence in the Arctic climate system. Despite their potentially broad impact on the global climate, the evolution and formation of Arctic clouds and their associated interactions within the Arctic environment is complex and poorly understood. This is due to several factors; for example, high albedo of the snow/ice surface, the lack of solar radiation during the cold season, the extremely cold and dry conditions, and the presence of temperature and humidity inversions. In summer, there is a persistent, multilayered cloud regime in the lowest kilometer of the atmosphere where the upper and lower layers appear to be decoupled from each other (Stamnes et al. 1999). The physical processes involved in forming these ubiquitous and persistent multilayered clouds are not clear. The persistence of these multilayered clouds has been attributed to the lack of cloud dissipative processes in the Arctic: precipitation, radiative heating, convective heating of the boundary layer, large-scale synoptic activity (Herman 1975). Proposed mechanisms for their multilayered stratification have been outlined by Curry et al. (1996), but more observations are needed for verification. These mechanisms involve 1) warming of the intermediate layers of a cloud by solar radiation, but cooling of the bottom and top cloud layers by longwave emission to the colder surface and outer space (Herman and Goody 1976); 2) presence of an advective cloud in the lower layer and an upper-layer cloud formed by very weak updraft/entrainment (Tsay and Jayaweera 1984); 3) the presence of temperature and humidity inversions that lead to strong radiative cooling at the inversion and subsequent mixing (McInnes and Curry 1995a,b). In winter, the Arctic radiation budget is modulated by low-level crystalline clouds and crystalline plumes rising from leads in the ice. The properties of these ice clouds and the radiative transfer processes under such extremely low temperatures and dry conditions are not well known. Observations of these crystalline winter Arctic clouds have been sparse because of the lack of sunlight. More recently, mixed-phase clouds have come to be recognized as a more common occurrence than previously assumed, especially during autumn and spring (Verlinde et al. 2007).

Recently three major research programs [Surface Heat Budget of the Arctic (SHEBA); Atmospheric Radiation Measurement Program (ARM); First International Satellite Cloud Climatology Program (ISCCP) Regional Experiment (FIRE)] were undertaken to provide comprehensive observational datasets to document the physical processes in the Arctic involving clouds, radiation, the surface energy budget, and the sea ice mass balance (Randall et al. 1998). The focus for the yearlong SHEBA program was the ocean–atmosphere–ice processes. Data were collected from a drifting station on the pack ice of the Arctic Ocean. Data from the SHEBA program have been used in the evaluation of Arctic regional climate modeling studies to elucidate cloud radiative forcing of the Arctic surface (Shupe and Intrieri 2004) and to emulate the clouds and radiation in the Arctic (Wyser et al. 2006). ARM is an ongoing multiyear atmospheric measurement and modeling project directed toward improved understanding of the processes that affect atmospheric radiation with a particular focus on cloud radiative feedback (Stokes and Schwartz 1994). The North Slope of Alaska–Adjacent Arctic Ocean (NSA–AAO) Cloud and Radiation Testbed (CART) site is one of several intensive sites for the ARM project. A primary objective of the NSA–AAO site is to provide high spatial- and temporal-density measurements of Arctic clouds and radiation designed
to elucidate related high-latitude processes and effectively incorporate these processes into global climate models (GCMs). Key processes include radiative transfer in the coupled atmosphere–snow–ice–surface system; radiative effects of mixed-phase and ice-phase clouds; basic cloud microphysical properties; the relative importance of surface versus advective moisture fluxes in the formation of clouds; and the interactions among turbulence, radiation, and cloud microphysics in the evolution of the cloudy atmospheric boundary layer.

While GCMs are the primary tool for projecting global climate change, validations with observed data, such as those produced by ARM, are only possible in a climatological sense. That is, direct day-by-day and hour-by-hour comparisons between GCM output and direct observations are meaningless. Recent atmospheric reanalysis programs, however, use many of the same cloud and radiative formulations as GCMs in their cloud and radiation representations. The reanalysis products are aided by direct assimilations of available primary atmospheric and surface state variables (e.g., air temperature, pressure, moisture), many of which are crucial to accurate depictions of moisture and stability profiles—characteristics critical to producing accurate cloud representations in numerical models. In addition to providing a correspondence of temporal variations, comparisons of ARM cloud radiative measurements to reanalysis output circumvent some of the biases in the cloud radiative parameters resulting from unconstrained GCM errors in the temperature and moisture profiles input into the cloud radiative formulations.

In the following analysis, we use the ARM–NSA data as guidance in evaluating the Arctic cloud radiative interactions for four currently available reanalyses: National Centers for Environmental Prediction (NCEP), 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analysis (ERA-40), North American Regional Reanalysis (NARR), and the Japan Meteorological Agency and Central Research Institute of Electric Power Industry 25-yr Reanalysis (JRA25). Our assessment will seek to identify systematic biases in cloud radiative fields of the reanalyses across seasonal to diurnal time scales, capitalizing upon the time-specific reference frame common to the reanalyses and the ARM measurements. Specifically, we will address three central questions:

1) Do the reanalysis models show any systematic errors in cloud cover and radiative fluxes? If so, how do these errors vary seasonally and across the reanalyses?

2) Are biases in reanalysis radiation variables independent of the cloud fraction biases?

3) Are the characteristics of the reanalyses’ clouds at Barrow, Alaska, representative of reanalyses’ clouds over the Arctic Ocean?

Answers to these questions will prove guidance to future reanalyses that include the Arctic, regardless of whether these future reanalyses are global or Arctic specific.

2. Observed data and reanalysis output

Our comparisons focus on downwelling surface solar and longwave radiative fluxes, cloud fraction, and total net surface radiation. The 60-s mean observed downwelling surface solar and longwave fluxes are obtained from the Sky Radiometers on Stand for Downwelling Radiation (SKYRAD) at the ARM–NSA site at Barrow, Alaska. The corresponding 60-s mean observed upwelling surface solar and longwave fluxes are obtained from the Ground Radiometers on Stand for Upwelling Radiation (GNDRAD) at the Barrow ARM site. Cloud-base heights are obtained via the Vaisala ceilometer also located at the ARM–NSA site at Barrow and temporally integrated to determine a 6-h mean cloud fraction for the Barrow location. The 60-s radiative flux observations are also averaged to 6-h means consistent with the output from the reanalysis products (i.e., ending 0000, 0600, 1200, and 1800 UTC). Downwelling and upwelling solar and longwave fluxes are summed to produce corresponding 6-h average net radiative fluxes at the surface.

The reanalyses provide three-dimensional gridded representations of the atmospheric state by assimilating atmospheric observations (temperature, pressure, wind, humidity) and calculating model-derived fields (e.g., precipitation, radiative fluxes, cloud properties). The atmospheric observations are assimilated into the reanalysis during a 6-h forecast that is initialized with the output from the previous reanalysis cycle. In this manner, the resulting series of outputs represents the evolving atmospheric state that is a synthesis of the available observations and model physics (Uppala et al. 2005; Schlatter 2000). We compare the observed ARM products to the cloud radiative fields of four recent reanalyses listed in Table 1. Each of these reanalyses includes the location of the ARM–NSA site (Barrow, Alaska) in their domain, and each includes all or some of the post-1999 yr of the ARM–NSA archived data. Periods of overlap of the four reanalysis products with the ARM observations are provided in Table 1. Except when noted, our comparisons use monthly climatologies for an 8-yr span (1999–2006). These averages are obtained from the 6-h average ARM observations and reanalysis clouds and radiative fluxes.
The four reanalysis models have different approaches in simulating and representing the cloud cover, an important input into their radiation parameterizations. The NCEP reanalysis (Kalnay et al. 1996), based on the oldest frozen model of the four reanalyses, uses a diagnostic approach to estimate cloud cover. Estimates of stratiform cloud cover are derived from empirical relationships between relative humidity and the U.S. Air Force (USAF) real-time nephanalyses (Campana et al. 1994). According to Kanamitsu et al. (2002), this relationship is assumed to be a function of latitude band, surface type (land or water), and location of clouds in the Eastern or Western Hemisphere. Convective cloud cover is derived from the model convective precipitation rate (Campana et al. 1994; Slingo 1987). The other three reanalyses utilize a prognostic approach in their cloud scheme, whereby the cloud water content is explicitly calculated from the rates of formation and dissipation of clouds droplets. This explicit calculation of cloud water (ice) content provides for better depiction of the thermodynamic effects of subgrid-scale condensation processes and a more direct linkage among the radiative, dynamical, and hydrological processes (Slingo 1987). The JRA25 uses a prognostic approach similar to the one proposed by Smith (1990), where a probability distribution function is assumed between two predictors: total water mixing ratio and liquid water potential temperature (Japan Meteorological Society 2002; Xu and Randall 1996), but the advection of cloud water is not taken into account (Onogi et al. 2007). The cloud fraction is estimated diagnostically from the total water mixing ratio and the saturation specific humidity. The NARR also combines a prognostic and diagnostic approach in their cloud scheme. A cloud water/ice mixing ratio is explicitly calculated (Mesinger et al. 2006) after Zhao et al. (1997). According to Zhao et al. (1997), the inclusion of cloud ice, horizontal advection of cloud water, and microphysical processes such as evaporation and condensation allow for improved cloud forecasts. Cloud fractions are estimated diagnostically, with stratiform fractions computed from relative humidity fields (after Sundqvist et al. 1989) and convective fractions computed from convective precipitation rates (after Slingo 1987). A disadvantage of this cloud prediction scheme is the potential for inconsistencies between the cloud water/ice mixing ratio and the cloud fraction since there is not a constrained linkage between the cloud water and cloud fraction within this scheme. (Wilson and Gregory 2003). ERA-40 is the only reanalysis of the four in this study that also explicitly calculates cloud amount along with cloud water–ice content. These prognostic formulations follow from the mass balance equations for cloud water–ice content and cloud air (Tiedtke 1993; Gregory et al. 2000; Uppala et al. 2005). The ERA-40 scheme has also been shown to simulate realistically the observed behavior of fog as a function of temperature and wind speed (Teixeira 1997). In view of the similarities between fog and low stratus clouds (Houze 1993), together with the pervasiveness of low stratus clouds at Barrow during summer, ERA-40 likely brings advantages to the intercomparison described here.

An additional factor potentially contributing to differences in the cloud representations is the method of cloud overlap assumption being implemented in each reanalysis. ERA-40, JRA25, and NARR use similar formulations of the maximum–random overlap where there is maximum overlap in adjacent clouds but random overlap in separate cloud layers (Räisänen 1998). ERA-40 uses the formulation outlined in Jakob and Klein (2000), the JRA25 uses the formulation from Geleyn and Hollingsworth (1979), and the NARR uses the formulation in Zhao et al. (1997). According to Campana et al. (1994), the NCEP reanalysis, the oldest of the reanalyses, made a significant improvement on the original formulation (Lacis and Hansen 1974) in the vertical structure of clouds by allowing groups of contiguous layers where cloud fraction is greater than zero define clouds, rather than constraining the clouds to the traditional high, middle, and low cloud typing. Another improvement with the NCEP reanalysis scheme is that stratiform clouds are able to coexist above and below the

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convection. While the differences among the model’s overlap assumptions are not necessarily large, the assumptions used by all models were not tailored specifically to Arctic applications, and thus may contribute significantly to the biases and across-model differences in both cloud fraction and surface radiative fluxes.

The archived reanalysis variables we are comparing to ARM–NSA observations include 1) total cloud cover, 2) downwelling shortwave solar radiative flux, 3) downwelling longwave flux, and 4) net surface radiative flux defined as the net surface shortwave flux plus the net surface longwave flux. With the exception of the NARR, the reanalyses provide 6-h average cloud fractions for each grid cell and are thus directly comparable to the 6-h average ARM-derived cloud fractions. The NARR, however, provides gridded cloud fractions at specific times (every 3 h, 8 times daily) that we average into 6-h means. Therefore, we only include the NARR results in our comparisons of climatological means. These climatologies are composed of 8 yr (over 23 200 3-h snapshots) of observations. While radiative fluxes are archived in the reanalyses regardless of cloud coverage, the accompanying cloud information permits the stratification of the fluxes according to cloud coverage, thereby permitting evaluation of the cloud radiative forcing in the subsequent results.

3. Results

Comparison of observations at the North Slope ARM site near Barrow, Alaska, with the four reanalyses is presented in section 3a. In section 3b, we discuss the impacts of cloud fraction on the surface energy budget by presenting depictions of observed and reanalysis-derived surface cloud radiative forcing for Barrow.

The Barrow–North Slope ARM site (Fig. 1) is situated in a geographically diverse location. The true-color Moderate Resolution Imaging Spectroradiometer (MODIS) image shown in Fig. 2 for early summer 2001 shows the extreme surface variability at and near Barrow. This coastal region is influenced by a mix of open ocean and sea ice cover in late spring, and the land has considerable vegetative diversity with variable snow cover at this time. These spatial and temporal variations in surface type have strong influences on the surface heat and moisture fluxes to the atmosphere that, in turn, influence the regional cloud cover via local stability and moisture availability. In the 8 June 2007 example (Fig. 2), the relatively narrow, ice-free ocean along the north coast of Alaska appears partially obscured by an optically thin cloud cover.

Given the geographic diversity of the ARM Barrow site, we provide as background an intercomparison among the reanalyses of climatological mean cloud fraction segregated by land, ocean and land–ocean combined (Fig. 3). The area-averaged seasonal variations of reanalysis-derived cloud fractions are for the “Arctic-wide” domain, 70°–90°N, outlined in Fig. 1. Since the NARR is a regional reanalysis covering only a North American domain, we include only a subdomain of points from the NARR domain including the North American half of 70°–90°N. For each of the reanalyses and seasons, the simulated cloud fractions over land are less than those simulated over maritime environments and the Arctic-wide averages most closely match the ocean-only values. There are marked differences in the seasonal ranges and magnitudes of the mean cloud fractions output by the reanalyses. The NCEP reanalysis has a narrow seasonal range hovering near 50%, while ERA-40 has a broader seasonal range of significantly higher values (60%–90%). Also, in two of the reanalyses (ERA-40 and JRA25) the differences between land and ocean cloud fraction averages show large increases during the summer months.

a. ARM observations and reanalysis products at Barrow, Alaska

As an example of the variability of cloud cover at the Barrow ARM site, Fig. 4 shows the cloud-base heights at 20-s temporal resolution (black) plotted with corresponding 6-h average cloud fraction derived from these data (red) for June 2001. This example illustrates the cloud regime typical of late spring and summertime.
conditions in the Arctic when skies at Barrow are cloud covered 70%–95% of the time. During days 10–18 and 22–28 of June 2001, Barrow experienced variable cloud coverage typical of synoptic systems. For much of the rest of the month, the sky appears obscured by a persistent low-lying cloud layer on what might otherwise be clear-sky days (e.g., days 4–9, 19–22, and 30). These clouds have low-level cloud-base heights reported from 0 to 1000 m, most often in the 100–400-m vertical range. The MODIS image shown in Fig. 2 is taken from the middle of one of these periods, 8 June 2001.

Atmospheric reanalyses do not explicitly assimilate cloud parameters. This will likely remain the case in the Arctic for the near future, as Arctic clouds are especially difficult to detect and archive using remote sensing platforms. As summarized in section 2, cloud processes are numerically simulated and/or parameterized in the reanalysis atmospheric models using vertical temperature and moisture profiles, some of which are directly assimilated into the reanalysis system. An evaluation of the skill of the different reanalysis models in their representation of Arctic cloud fraction can, therefore, give a good sense of the current “state of the art” of numerical models with respect to simulating clouds and cloud–radiation interactions in the Arctic.

To illustrate the biases of the reanalysis-derived cloud coverage, Fig. 5 shows the observed monthly mean cloud fraction at the Barrow ARM site together with corresponding cloud fractions simulated by the four atmospheric reanalyses for the ARM-observation period of record (1999–2006). ERA-40 monthly means are limited to 1999–2002. Monthly mean values for each reanalysis were linearly interpolated from the four nearest grid points to the ARM Barrow location.

In this analysis, we compare gridecell mean cloud fractions provided by the reanalyses with observed cloud fractions obtained by time-averaged lidar returns at a single point. Values for the former are representative of an area of several thousand square kilometers and the latter of only a single vertical point or transect in the case of a wind-driven cloud field. Retrieval differences between the point-source and gridecell averaging techniques need to be reconciled before one can make direct comparisons between the observed and reanalysis data. Astin et al. (2001) outline a method to quantify confidence intervals on the estimated cloud fractions obtained from point-source transects, and we apply the method here to the lidar observations at Barrow. Confidence intervals for the means are estimated by applying Bayes’ theorem to observed probability distributions obtained from the numbers and lengths of noncontiguous gaps in the point-source cloud-observation series or transect. We utilize the high-temporal-resolution (20 s) lidar returns to compile distributions of
cloud-gap numbers and lengths for each 6-h period in the 1999–2006 record. Error bars are then estimated according to Eq. (9) in Astin et al. (2001) for each 6-h period. The errors are averaged over all years (1999–2006) for each calendar month and illustrated in Fig. 5 as a shaded region. Using this technique, 50% coverage cloud fields composed of cumulus-type clouds will have the largest error bars. Since stratus clouds are more typical of the Arctic marine environment, the error bars derived for the 6-h means at Barrow are only from $\pm 1\%$ to $3\%$ in the winter months and grow to $\pm 5\%$–7\% in June and July. In summary, the uncertainty imposed by the differences in point-source versus gridcell averaging is much smaller than the differences among reanalysis sources and the observed versus reanalysis intercomparison.

The shapes of the seasonal cycles in the JRA25 and NCEP reanalyses are well simulated, but their amplitudes are muted when compared to the observed climatology. Biases in these reanalyses throughout the year, however, are very large, ranging from $-10\%$ (winter) to $-29\%$ (summer) for the NCEP reanalysis. ERA-40 summer cloud fractions are very well simulated but the smallest cloud fractions observed in winter are not simulated by ERA-40 as illustrated by a bias of $+11\%$ in winter. Winter cloud fraction biases for the NARR are similar to ERA-40 ($+11\%$) and the NARR is too clear in summer with a bias of $-16\%$ relative to the ARM–NSA measurements. A comparison of the simulated cloud fractions at Barrow (Fig. 5) with the simulated cloud fractions over the Arctic Ocean (Fig. 3) shows that they are similar to one another (biases and all). To the extent that the observed cloud fractions at Barrow and over the Arctic basin are similar, the reanalyses’ cloud fraction biases for the Arctic basin will be similar to those shown for Barrow in Fig. 5.

The relatively large seasonal cloud fraction biases have significant impacts on the reanalyses’ surface energy budgets, given the unique seasonal radiative flux characteristics of the Arctic. For example, the negative summer cloud fraction biases seen in all the reanalyses contribute to positive biases of downwelling shortwave radiation flux at the surface in the reanalyses (Fig. 6).
Shortwave flux biases averaged over June–August for ERA-40 are +16 W m$^{-2}$ but are much more significant for the JRA25 (+16 W m$^{-2}$), NARR (+25 W m$^{-2}$), and NCEP (+43 W m$^{-2}$) reanalyses corresponding directly to undersimulated summertime cloud fraction biases.

One detail of the observed seasonal cycle of shortwave flux is the apparent skew of the seasonal downwelling flux maximum toward springtime (away from the summer solstice). While clear-sky solar fluxes reach a maximum near the end of June (summer solstice), the
observed surface solar fluxes show a maximum closer to May than July.

The diurnal variations in climatological shortwave flux summarized in Fig. 7 show that the springtime skewness in observed shortwave flux is primarily seen in the high sun angle periods around midday. The maximum solar flux observed during the overnight hours (0600–1200 UTC) in Barrow occurs in June (bottom panel, blue line) while the maximum solar flux observed during the afternoon hours occurs in May (bottom panel, red line). While Barrow cloud fractions are at least as large in May as in June (Fig. 5), the springtime clouds are evidently of a different character than the more optically dense clouds characteristic of the mid-summer Arctic Ocean. During June, the likelihood of sea ice retreat from the north coast of Alaska increases and vertical moisture fluxes into the lowest atmospheric levels also increase, resulting in the formation of more

FIG. 7. Diurnal cycle of shortwave flux at Barrow: (top) NCEP, ERA-40; (middle) NARR, JRA25; (bottom) ARM observations.
optically thick marine stratus-type clouds characteristic of the summer Arctic Ocean. In contrast, the cloudiness in May is typical of continental landmasses in spring (i.e., scattered “fair weather” cumulus clouds that form on an otherwise clear day). In a low-solar-zenith-angle environment such as the Alaskan North Slope, scattered cumulus clouds sideways scatter a significant fraction of the downwelling solar flux to the surface, thereby increasing the solar flux incident on the surface beyond the otherwise clear-sky amounts. It is clear that cloud formulation details such as cloud overlap assumptions can play a key role in the potential success of a model in capturing the subtleties of cloud radiative interactions in a complex cloud/low-sun-angle environment like the Arctic springtime. In this regard, ERA-40 and JRA25 clearly outperform the other reanalyses in capturing the springtime skewness feature.

The impact of Arctic summertime cloud fraction on the downwelling longwave flux are opposite in sign to that of the downwelling shortwave flux. Negative cloud fraction biases result in less downwelling longwave flux at the surface in the reanalyses than in the ARM observations (Fig. 8). Negative downwelling longwave flux biases range from −15 to −21 W m⁻² for the NARR, JRA25, and NCEP reanalyses. ERA-40 has a small positive summertime bias of +4 W m⁻². In winter, reanalyses with positive winter cloud fraction biases (ERA-40 and NARR) oversimulate the downwelling longwave flux, while reanalyses with negative winter cloud fraction biases (NCEP and JRA25) undersimulate the downwelling longwave flux by −9 to −18 W m⁻². Winter downwelling longwave flux simulations by ERA-40 are quite reasonable given that the winter cloud fractions are oversimulated by at least 10%. In fact, ERA-40 is a notably good performer in both its surface shortwave and longwave downwelling flux seasonal representations at Barrow, even though the simulated winter cloud fractions are somewhat oversimulated.

Comparisons of cloud fraction and radiative flux biases are shown in more detail for each June for which ARM observations and corresponding reanalysis-derived output exist in Figs. 9, 10 for the NCEP reanalysis and Figs. 11, 12 for ERA-40. Time series of 6-hourly observed (ARM–Barrow) and NCEP reanalysis average cloud fraction and downwelling surface shortwave flux for eight Junes (1999–2006) are displayed in Fig. 9. The characteristics of summertime observed Barrow cloudiness (black) are clearly missed in the NCEP reanalysis (blue). The observed 6-h average cloud fraction distribution appears bimodal with a majority of the 6-h periods characterized as 100% cloud covered. Less frequently, clear or nearly clear skies are recorded and, only rarely, are partly cloudy conditions observed.

In contrast, the 6-h average cloud fractions simulated by the NCEP reanalysis are very rarely 100% and are most often in the partly cloudy range. The impacts of the erroneous cloud cover are seen clearly on the NCEP-simulated downwelling shortwave flux (red). In the rare 6-h periods that the NCEP cloud fractions match the observed, the NCEP downwelling shortwave fluxes are well simulated when compared to observations. The large negative cloud fraction biases, however, result in simulated downwelling fluxes that are almost always too large, in some cases by as much as 500 W m⁻² at midday.

Impacts of simulated cloud fraction biases on the surface downwelling longwave flux are illustrated in Fig. 10. Periods when the NCEP reanalysis cloud fractions closely match the observed cloud fractions (e.g., first half of June, 2006) show that NCEP-simulated downwelling longwave flux values closely match the ARM observations. More often, however, the simulated cloud fractions are much too low and corresponding simulated downwelling longwave fluxes are more than 50 W m⁻² too low (e.g., first half of June, 2001).

By comparison, plots of 6-h average cloud fraction and downwelling shortwave flux from ERA-40 are plotted with corresponding ARM–Barrow-observed cloud fraction and surface downwelling shortwave flux for four Junes (1999–2002) in Fig. 11. When cloud fractions are undersimulated by ERA-40, corresponding downwelling shortwave flux values are overestimated by an amount similar to errors from the NCEP reanalysis (200–400 W m⁻²). The key to the relative success of ERA-40 in correctly simulating summer downwelling shortwave flux is the frequency with which cloud fractions are correctly
FIG. 9. The 6-h mean June 1999–2006 surface downwelling shortwave flux at Barrow, AK, for ARM observations (black, thin) and NCEP reanalysis (red) plotted with corresponding 6-h mean cloud fractions for ARM observations (black, thick) and NCEP reanalysis (blue).
Fig. 10. The 6-h mean June 1999–2006 surface downwelling longwave flux at Barrow, AK, for ARM observations (black, thin) and NCEP reanalysis (red) plotted with corresponding 6-h mean cloud fractions for ARM observations (black, thick) and NCEP reanalysis (blue).
represented. While there are still periods ERA-40 does not correctly capture the cloud fraction characteristics seen in the ARM–Barrow observations (e.g., middle of June 2002), the bimodal character of the observed frequency distribution is more apparent in ERA-40 than in NCEP, with ERA-40's simulated summertime cloud fractions at 100% for extended periods.

Although the cloud fractions are simulated relatively well in ERA-40, the downwelling longwave flux does not always reflect the accuracy of the cloud cover. Simulated and observed surface downwelling longwave fluxes (Fig. 12) agree quite well during June 1999. However, while the ERA-40 cloud fractions are similar to and often exceed the ARM observations in mid-June 2000, the ERA-40 downwelling longwave fluxes during this period are less than the ARM observations. The optical properties, vertical profiles, cloud-base heights, and associated temperatures of the simulated clouds may be very different than those of the observed clouds to result in these counterintuitive biases during this period.

b. Cloud cover impacts on Barrow's surface energy budget

Summaries of the impacts of cloud cover biases for each reanalysis on individual components of the surface energy budgets are shown in Fig. 13 (shortwave flux) and Fig. 14 (longwave flux). In these figures, downwelling surface flux biases are shown as functions of both cloud fraction bias and calendar month. For cases in which the models accurately reproduce the observed cloud fractions, surface shortwave flux biases are generally less than $\pm 20 \text{ W m}^{-2}$. However, when simulated cloud fractions are more than 50%–100% different than observed, absolute errors in the downwelling surface shortwave radiation fluxes can exceed 160 W m$^{-2}$ during the summer months at Barrow. The relatively small biases of downwelling surface shortwave flux at 0% cloud fraction errors contrast with those at higher cloud fraction errors, demonstrating the importance of accurate cloud cover simulations for the modeled surface energy budget.

Cloud fraction biases have the opposite effect on surface longwave flux biases (Fig. 14). When cloud fraction is undersimulated by the reanalyses, downwelling longwave flux at the surface is negatively biased compared to ARM observations by $-50$ to $-80 \text{ W m}^{-2}$. Alternatively, oversimulation of cloud fraction in the reanalyses produces positive longwave flux biases of similar magnitudes. However, when cloud fractions are correctly simulated, the net surface longwave biases are
very near zero. While the gross characteristics of the cloud fraction–longwave bias profiles are similar from model to model, there are seasonal differences. For example, maximum positive longwave flux biases for over-simulated cloud fractions occur in summer for ERA-40 but are near zero during the summer and maximum during the winter months for the NARR. Also, the magnitudes of the longwave flux biases are larger for negative cloud fraction biases in the JRA25 than they are for positive cloud fraction biases in all months.

The impact of cloud cover on a surface energy budget can be summarized by the total surface cloud forcing. We define total surface cloud forcing as the average net (shortwave + longwave) radiation at the surface averaged over 6-h periods for all cloud conditions (0%–100% cloud fraction) minus the average net surface radiation for 6-h periods with only clear-sky conditions, for corresponding dates and times. We define clear-sky conditions here as 6-h periods with less than 10% cloud fraction to ensure enough clear-sky reference values throughout the annual cycle. Figure 15 shows the total surface cloud radiative forcing at Barrow, Alaska, derived from ARM data and the four reanalyses. The observed cloud forcing (black) illustrate that cloud cover at Barrow cools the surface for 3.5 months of the year (May through mid-August). ERA-40 simulates a similar seasonal pattern of cloud radiative forcing with the length and timing of the cooling period nearly identical to observed. The NARR also shows a net cooling effect of cloud cover in summer but the period of cooling is only two months (June and July). The impact of cloud cover in the JRA25 and NCEP models is to warm the surface for the entire year, including the summer months. Clearly these two models are not adequately capturing the first-order effects of cloud cover on the surface energy budget at Barrow throughout the year. During nonsummer months, ERA-40 and NARR are also notably good performers. The exception would be a positive net radiation bias of +10 to +15 W m$^{-2}$ for the NARR in late winter and spring. The maximum in the observed net cloud radiative forcing occurs in autumn when the sun has set for the winter and the local air (and low cloud) temperatures are still relatively warm. Again, ERA-40 and NARR are closest to capturing this subtle feature, although the magnitudes are muted, while the NCEP and JRA25 models show nearly opposite cloud forcing signals.

In an attempt to isolate the cloud cover conditions responsible for contributing to the errors in total net cloud radiative forcing above, we include a variable...
cloud radiative forcing (VCRF) defined as the net surface radiative flux under varying cloudiness conditions minus the corresponding clear-sky net radiative flux as a function of cloud fraction and calendar month (Fig. 16). For these calculations, we binned the surface flux data into 5% cloud fraction bins. In Fig. 16, both the VCRF derived from ARM observations (top panel) and those from the reanalyses are positive throughout most of the year, indicating that cloud cover has a net warming influence on the Arctic surface during the cold months. For 2–3 months during the summer, the sign of the VCRF changes to negative, (i.e., cloud cover has a net cooling effect on the surface energy budget). These first-order characterizations of the ARM-observed VCRF are captured by the reanalyses. However, the details of the VCRF profiles vary among observations and the four reanalyses. For example, the negative summertime VCRF values approximate the ARM values in ERA-40 and the NCEP reanalysis for 100% cloudy skies, but the negative VCRF values do not persist at cloud fractions less than 100%, indicating that the models’ radiative flux and/or cloud optical depth parameterizations may need refinement. The same cannot be said for wintertime partly cloudy conditions in which some reanalyses (NCEP and NARR) respond with net radiative fluxes that are too high, while JRA25 and ERA-40 simulate too little net surface radiative flux for partly cloudy conditions.

4. Conclusions

The ARM–NSA Barrow site is characterized by large cloud fractions, especially in summer when there is persistent low-level cloud cover that often obscures an otherwise clear sky. Cloud fraction climatologies illustrate that all of the reanalyses, with the exception of ERA-40, have a difficult time capturing this cloud cover distribution and undersimulate cloud fractions in summer. However, the radiative flux climatologies indicate that, when the reanalysis models correctly simulate the cloud fraction at Barrow, the radiative fluxes are generally well simulated. When cloud fraction is undersimulated, positive biases in monthly surface downwelling shortwave flux range from +4 to +43 W m⁻² and
the negative downwelling longwave flux biases range from $-15$ to $-21$ W m$^{-2}$. Our intercomparison of 6-hourly time series of cloud fractions and radiative fluxes during June at Barrow for NCEP–ARM and ERA-40–ARM confirms that radiative flux biases in the reanalyses can be traced to the inability of models to accurately simulate the summertime cloudiness. Impacts of these 6-hourly cloud fraction biases can range from $+200$ to $+400$ W m$^{-2}$ in the surface downwelling shortwave flux at midday when insolation is greatest and more than $-50$ W m$^{-2}$ in the surface downwelling longwave flux. Intercomparison of the 6-hourly data also indicates that ERA-40, relative to the NCEP and other reanalyses, simulates more accurately the frequency distribution of summertime cloud fractions and downwelling radiative fluxes. The ERA-40 cloud formulations are the most detailed of the four global reanalyses included here, and our validation results suggest the additional complexity is paying dividends in both better Arctic cloud fraction and surface radiation representations.

For the winter months, cloud fraction climatologies show that the NARR and ERA-40 oversimulate cloud fractions at Barrow, while the JRA25 and NCEP reanalyses undersimulate cloud fractions. This is reflected in positive longwave biases of $+22$ W m$^{-2}$ for the NARR and negative longwave biases of $-9$ to $-18$ W m$^{-2}$ for the JRA25 and NCEP, respectively. Cloud fraction

![Fig. 14. Same as Fig. 13, but for surface downwelling longwave flux.](image)

![Fig. 15. Total surface cloud radiative forcing derived from ARM observations (black), ERA-40 (red), NCEP (blue), JRA25 (green), and NARR (orange) reanalyses at the Barrow–ARM location.](image)
biases in ERA-40 are not reflected in the summer/winter longwave or the summer shortwave fluxes.

Seasonal summary plots of the impacts of cloud fraction biases on downwelling surface fluxes for each reanalysis show that

- when the cloud fraction is well simulated by the reanalysis models there are minimal biases in the radiative fluxes;
- when summer cloud fractions are more than 50%–100% less than observed, monthly mean net surface shortwave flux biases can exceed $+160 \text{ W m}^{-2}$;
- when cloud fractions are undersimulated (oversimulated), the monthly mean net surface longwave flux are negatively (positively) biased by 50–80 W m$^{-2}$.

The impacts of cloud fraction biases on the surface radiation budget share common characteristics among the reanalyses, but there are some seasonal differences. For example, maxima in positive longwave flux bias occur in winter for the NARR and in summer for ERA-40.

Cloud radiative forcing calculations made for the ARM data at Barrow show that cloud cover has a net warming effect throughout the year except for 2–3 months in the summer. This annual cycle of cloud forcing at Barrow is captured only by ERA-40 and the NARR reanalysis. Observational studies from other locations in the Arctic (Walsh and Chapman 1998; Schweiger and Key 1994; Intrieri et al. 2002) also reflect this net warming throughout the year except for at least part of the summer. Walsh and Chapman (1998) used Russian drifting stations during 1950–90 and Schweiger and Key (1994) used a monthly cloud product from the International Satellite Cloud Climatology Project (ISCCP). Intrieri et al.’s (2002) analysis of Arctic surface cloud forcing used SHEBA data. They found the length of the summertime negative cloud forcing (2 days versus a few weeks) was dependent on the measured input albedo. The albedo with the shortest negative cloud forcing was a single site measurement over multiyear ice, while the other one was measured over a line with varying ice conditions. The shared seasonality of these results indicates that the ARM data at Barrow capture at least the first-order characteristics of the cloud–radiation feedback in the Arctic region.

Cloud radiative forcing displayed as a function of cloud fraction and season illustrates the major differences between the ARM- and reanalyses-derived radiation fields were for partly cloudy conditions. In summer all of the reanalyses, to varying degrees, underestimate the net cooling effect of clouds under partly cloudy conditions. In winter, the NCEP and NARR reanalyses overestimate the net warming effect of clouds, while ERA-40 and JRA25 underestimate it under partly cloudy conditions.

![Fig. 16](image)

**Fig. 16.** (top) Variable cloud radiative forcing derived from ARM observations and (bottom) four atmospheric reanalyses at Barrow, AK.
conditions. Biases in radiative forcing under partly cloudy conditions could occur because of oversimplified model parameterizations or physics formulated for the tropics and/or midlatitudes. For example, cloud overlap assumptions and 3D cloud radiative effects at high latitudes (high solar zenith angles) are potential candidates. Accordingly, partly cloudy conditions are at the core of two priorities identified by this study: 1) the need to reduce the bias toward too-frequent occurrences of partly cloudy conditions in the reanalyses and 2) the need to simulate more realistically the radiative impacts of a partial cloud cover.

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