Arctic clouds and radiative fluxes in large-scale atmospheric reanalyses

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INTRODUCTION

Despite their potentially broad impact on the global climate, the evolution and formation of Arctic clouds and their associated radiative interactions are complex and poorly understood. This is due to several factors, e.g. 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 often a multi-layered cloud regime in the lowest kilometer of the atmosphere, with an apparent decoupling of the upper and lower layers (Stamnes et al. 1999). The physical processes involved in forming these ubiquitous and persistent multi-layered clouds are not clear.

Recently a major research activity, the Atmospheric Radiation Measurement (ARM) program, was undertaken to provide comprehensive observational datasets to document the physical processes in the Arctic involving clouds, radiation, and the surface energy budget. ARM is an ongoing multi-year atmospheric measurement and modeling project directed toward improved understanding of the processes that affect atmospheric radiation with a particular focus on cloud radiative feedback. The North Slope of Alaska (NSA) Cloud and Radiation Testbed site at Barrow, Alaska is one of several intensive sites for the ARM project. A primary objective of the NSA site is to provide high spatial- and temporal-density measurements of Arctic clouds and radiation designed to elucidate high-latitude processes and effectively incorporate these processes into Global Climate Models (GCMs).

While GCMs are the primary tool for projecting global climate change, validations with observed data, such as those produced by the ARM program, are only possible in a climatological sense. That is, direct day-by-day and hour-by-hour comparisions between GCM output and direct observations are meaningless. Atmospheric reanalyses, however, use many of the same cloud and radiative formulations as GCMs in their cloud and radiation representations, and they provide time-specific output. In the following analysis, we use the ARM/NSA data from Barrow as guidance in evaluating the arctic cloud-radiative interactions for four currently available reanalyses: National Centers for Environmental Prediction (NCEP), European Center for Medium Range Forecasting (ERA40), North American Regional Reanalysis (NARR) and the Japanese 25-year Reanalysis Project (JRA25). The archived reanalysis variables we are comparing to ARM/NSA archived variables 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. 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. Our assessment seeks to identify systematic biases in cloud-radiative fields of the reanalyses across seasonal to diurnal timescales, capitalizing upon the time-specific reference frame common to the reanalyses and the ARM measurements.

RESULTS

In order to illustrate the biases of the reanalysis-derived cloud coverage, Figure 1 shows the observed monthly mean cloud fraction (left-panel) 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). ERA40 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. 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. The biases in these reanalyses throughout the year, however, are very large, ranging from -10% (winter) to -19% (summer) for the JRA25 and -24% (winter) to -29% (summer) for the NCEP reanalysis. ERA40 summer cloud fractions are very well simulated but the smallest cloud fractions observed in winter are not simulated by the ERA40, as illustrated by a bias of +11% in winter. Winter cloud fraction biases for the NARR are similar to ERA40 (+11%) and the NARR is too clear in summer with a bias of -16% relative to the ARM/NSA measurements.

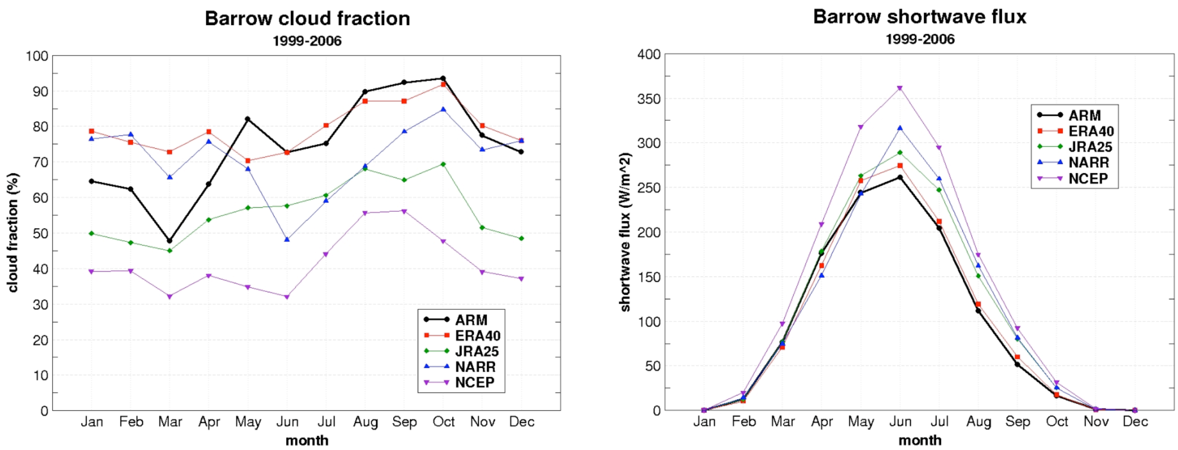

Figure 1 **Monthly mean cloud fraction (left-panel) at the Barrow-NSA site from ARM-observations (black), the ERA40 reanalysis (red), the JRA25 reanalysis (green), the NARR (blue), and the NCEP/NCAR reanalysis (violet); Monthly mean surface downwelling shortwave flux (right-panel) at the Barrow-NSA site from ARM-observations (black), the ERA40 reanalysis (red), the JRA25 reanalysis (green), the NARR (blue), and the NCEP/NCAR reanalysis (violet).**

The relatively large seasonal cloud 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 (Figure 1, right-panel). Shortwave flux biases averaged over June-August for the ERA40 are +6 Wm^{-2} but are much more significant for the JRA25 (+16 Wm^{-2}), NARR (+25 Wm^{-2}), and NCEP (+43 W/m^{-2}) reanalyses corresponding directly to the under-simulated summertime cloud fraction biases.

Comparisons of cloud fraction and longwave flux biases are presented in detail in the 6-hour averages of the downwelling longwave flux during June of 1999-2006 from the Barrow ARM site measurements and from the NCEP reanalysis (Figure 2). Also shown are corresponding 6-hour cloud fractions from the same two sources. The characteristics of summertime observed Barrow cloudiness (black) are clearly missed in the NCEP reanalysis (blue). The observed six-hour average cloud fraction distribution appears bimodal with a majority of the six-hour periods characterized as 100% cloud covered. Less frequently, clear or nearly clear skies are recorded and, only rarely are partly cloudy conditions are observed. In contrast, the 6-hour average cloud fractions simulated by the NCEP reanalysis are very rarely 100% and are most often in the partly cloudy range. The impacts of simulated cloud biases on the surface downwelling longwave flux are substantial. Periods when the NCEP reanalysis cloud fractions closely match the observed cloud fractions (e.g., first half of June, 2006) show NCEP-simulated downwelling longwave flux values that 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). The impacts on downwelling solar radiation (not shown) are even greater when the sun is well above the horizon, i.e., during mid-day in the summer.

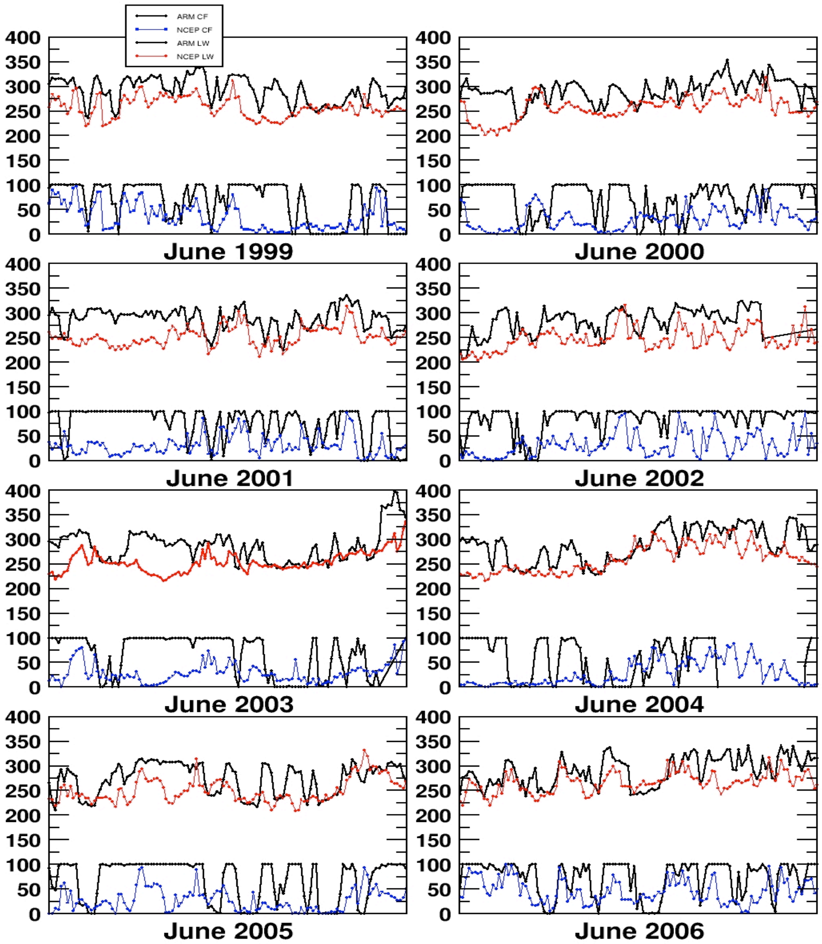

Figure 2 **Six-hour mean June 1999-2006 surface downwelling longwave flux at the Barrow-NSA location from ARM observations (black, thin) and the NCEP reanalysis (red) plotted with corresponding six-hour mean cloud fractions for ARM observations (black, thick) and the NCEP reanalysis (blue). Cloud fractions in lower portion of each panel range from 0 to 1.**

The impact of clouds on the Arctic surface energy budget can be summarized by the total surface cloud forcing, defined as the net radiation at the surface (shortwave + longwave) for all cloud conditions relative to the net surface radiation under clear sky conditions for corresponding dates and times. We define clear sky conditions as less than 10% cloud fraction to ensure enough clear sky reference values throughout the annual cycle. Figure 3 shows the total surface cloud radiative forcing at Barrow, AK derived from ARM observations and the four reanalyses. The observed cloud forcing (black) illustrates that clouds at Barrow cool the surface for 3.5 months of the year (May through mid August). The ERA40 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 clouds in summer but the period of cooling is only two months (June – July). The impact of clouds 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 clouds on the surface energy budget throughout the year. During non-summer months, the ERA40 and NARR are also notably good performers. The exception would be a positive net radiation bias of +10 to +15 Wm^{-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 temperatures are still relatively warm. Again, the ERA40 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.

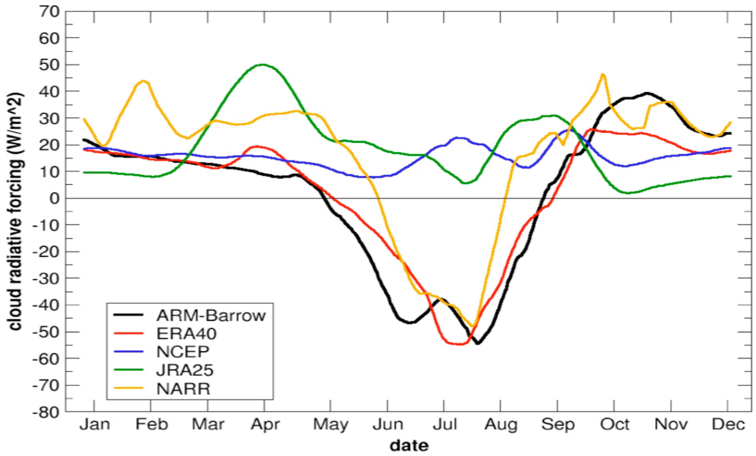

Figure 3 **Total surface cloud radiative forcing derived from ARM observations (black), ERA40 (red), NCEP (blue), JRA25 (green), and NARR (orange) reanalyses at the Barrow-ARM grid cell.**

In an attempt to isolate the cloud 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 minus the corresponding clear sky net radiative flux as a function of cloud fraction and calendar month (Figure 4).

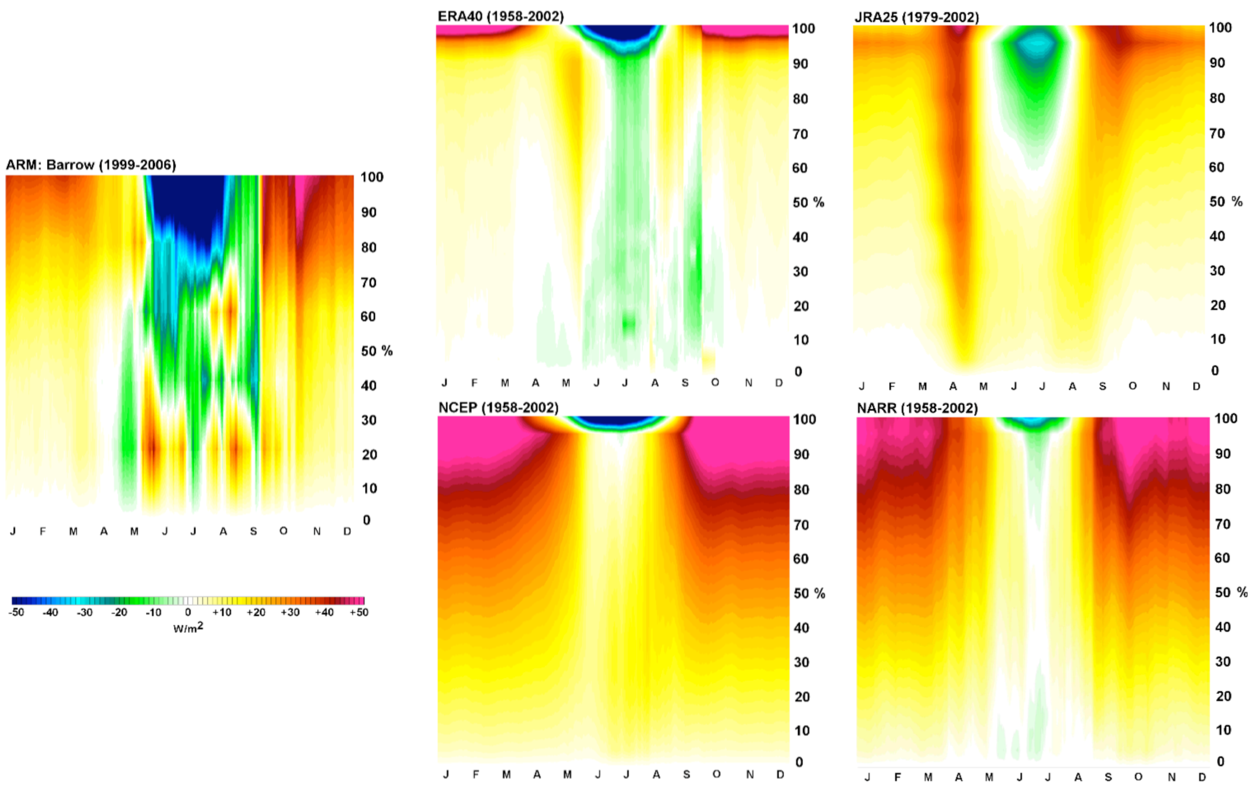

Figure 4 **Variable cloud radiative forcing derived from ARM observations (left) and four atmospheric reanalyses at the Barrow-ARM grid cell plotted as a function of cloud fraction (ordinate) and month (abscissa).**

For the four reanalyses, the VCRF is determined as an area-weighted mean over the 70-90°N domain, while the observed VCRF (left panel in Figure 4) is valid for the ARM-Barrow location only. In both the VCRF derived from ARM-observations and those from the reanalyses (right-most four panels in Figure 4), VCRF is positive throughout most of the year indicating that clouds have a net warming influence on the Arctic surface during the cold months. For two-three months during the summer, the sign of the VCRF changes to negative, (i.e., clouds have 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 the ERA40 and NCEP reanalyses 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, at least for an Arctic domain. 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 JRA-25 and ERA40 simulate too little net surface radiative flux for partly cloudy conditions.

CONCLUSION

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 ERA40, 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 clouds at Barrow, the radiative fluxes are generally well-simulated. When clouds are undersimulated, positive biases in monthly surface downwelling shortwave flux range from +4 Wm^{-2} to +43 Wm^{-2} and the negative downwelling longwave flux biases range from -15 Wm^{-2} to -21 Wm^{-2}. Our intercomparison of 6-hourly time series of cloud fractions and radiative fluxes during June at Barrow for NCEP/ARM and ERA40/ARM confirms that radiative flux biases in the reanalyses can be traced to the inability of the underlying cloud models to accurately simulate the summertime cloudiness. Although not shown here, the impacts of these 6-hourly cloud fraction biases can range from +200 to +400 Wm^{-2} in the surface downwelling shortwave flux at mid-day when insolation is greatest, and more than -50 Wm^{-2} in the surface downwelling longwave flux. Intercomparison of the 6-hourly data also indicates that the ERA40, relative to the NCEP and other reanalyses, simulates more accurately the frequency distribution of summertime cloud fractions and downwelling radiative fluxes.

For the winter months, cloud fraction climatologies show that the NARR and the ERA40 oversimulate cloud fractions at Barrow, while the JRA25 and NCEP reanalyses undersimulate cloud fractions. This is reflected in positive longwave biases of +22 Wm^{-2} for the NARR and negative longwave biases of -9 Wm^{-2} to -18 Wm^{-2} for the JRA25 and NCEP, respectively. Cloud fraction biases in the ERA40 are not apparent in the longwave or the shortwave fluxes in either winter or summer.

While the results presented here are limited to the ARM-NSA site at Barrow, Arctic-wide (70-90°N) cloud fraction climatologies were found to be similar to those at the Barrow location, indicating that the ARM observations at Barrow are representative of the broader Arctic domain. For this broader domain, the results show that

- when the cloud fraction is well simulated 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 Wm^{-2};
- when cloud fractions are undersimulated (oversimulated), the monthly mean net surface *longwave* flux are negatively (positively) biased by 50 to 80 Wm^{-2} .

Cloud radiative forcing calculations made for the ARM data at Barrow show that clouds have a net warming effect throughout the year except for 2-3 months in the summer. This is consistent with the findings of Walsh and Chapman (1998) based on measurements from Russian drifting stations during 1950-1990. Curry et al.'s (1993) computational approach produced a slightly shorter (~weeks) period of positive cloud radiative forcing, although their seasonality is consistent with that obtained here. This commonality is another indication that the ARM data at Barrow captures at least the first order characteristics of the cloud-radiation feedback in the Arctic region. The ERA40 and NARR reanalyses correctly represent this seasonal cloud forcing, while the NCEP and JRA25 reanalysis models misrepresent the cloud's impacts as a net warming influence on the Arctic surface for the entire year.

Cloud radiative forcing displayed as a function of cloud fraction and season illustrate that 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 the ERA40 and JRA25 underestimate it under partly cloudy conditions. 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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