Chapter 20

ARM’s Progress on Improving Atmospheric Broadband Radiative Fluxes and Heating Rates

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1. Introduction and motivation

The geographical and vertical distribution of absorption of solar radiation and emission of longwave (LW) radiation in the atmosphere and at the surface are major drivers of the large-scale circulation and the hydrological cycle. Understanding and modeling the processes by which atmospheric gases, clouds, and aerosol particles affect the distribution of radiant energy in the atmosphere are essential to accurate simulations of Earth’s climate. Figure 20-1 shows the key elements of Earth’s energy budget (Trenberth et al. 2009). While satellites provide measurements of the global distribution of reflected and emitted broadband fluxes at the top of the atmosphere (TOA), less information is available on the radiative budget at the surface and the vertical distribution of absorption and emission in the atmosphere. Key goals of the Atmospheric Radiation Measurement (ARM) Program are to quantify the radiative energy balance profile in Earth’s atmosphere, to understand the physical processes controlling this balance, and to improve the representation of these processes in global climate models (GCMs; DOE 1990).

To address these questions, the ARM site measurements were planned to provide a full characterization of the radiatively important properties of the atmospheric column, as well as measurements of the radiative fluxes themselves. The simultaneous measurement of surface broadband radiative fluxes (Michalsky and Long 2016, chapter 16) and cloud/aerosol properties (Shupe et al. 2016, chapter 19; McComisky and Ferrare 2016, chapter 21) enables both assessment of the overall impact of clouds and aerosol on the surface radiation budget as well as analysis of how those impacts vary with changes in cloud and aerosol properties. Additionally, comparison of measured broadband surface fluxes to those calculated using atmospheric properties measured or retrieved from other ARM instruments provides a test of how well the ARM measurements are able to characterize the full set of cloud, aerosol, atmospheric state, and surface properties in the vertical column. Such “radiative flux closure” exercises can identify weaknesses in measurements, retrievals, or radiative transfer models and indicate under what conditions ARM measurements are representative of the large-scale atmospheric conditions.

While spectral radiance and fluxes are important for understanding details of specific atmospheric processes that affect the radiative balance (Mlawer and Turner 2016, chapter 14), accurately measuring and modeling broadband radiative fluxes is critical since they represent the integrated impact of atmospheric processes on Earth’s energy budget. In this chapter, we describe the contributions that the ARM Program has made toward understanding and characterizing the processes that control broadband radiative fluxes and radiative heating.
in the atmosphere. In particular, we focus on the impact of clouds on broadband surface fluxes and atmospheric heating rate profiles.

2. Early efforts to close the radiation budget

Around the time that the ARM Program was being established, several studies (Cess et al. 1995; Pilewskie and Valero 1995; Ramanathan et al. 1995; Zhang et al. 1997) reported large differences between estimates of broadband shortwave (SW) absorption in the column derived from radiative transfer calculations and those derived from combining satellite and ground-based observations of broadband radiative fluxes. In these studies, radiative transfer models typically underestimated the amount of absorption in the atmosphere relative to the observationally derived estimates, by up to 40% (Cess et al. 1995). These results led to the theory that there was an unknown source (or sources) of atmospheric absorption being neglected in radiative transfer models. The detailed observations of clouds and radiative fluxes at the ARM site, as well as several dedicated field experiments, were instrumental in helping resolve the “anomalous absorption” issue.

a. Clear sky

Using ARM data, several detailed clear-sky broadband flux closure studies were performed to explore whether clear-sky conditions were contributing to the uncertainty in modeled cloudy-sky absorption. Several studies (e.g., Kato et al. 1997; Halthore et al. 1997; Halthore and Schwartz 2000) used collocated measurements of atmospheric state, aerosol optical depth (AOD), and downwelling direct and diffuse SW irradiances from the ARM Southern Great Plains (SGP) site to compare modeled and observed fluxes under non-cloudy conditions. These papers found that radiative transfer models overestimated total downward SW irradiance by up to 5% and that the overestimate was almost entirely in the diffuse flux. Discrepancies in clear-sky radiative transfer contributed to the cloudy-sky flux anomaly but were not the major factor. However, detailed investigations of potential uncertainties in the model calculations did not identify a clear cause for the clear-sky diffuse discrepancy. The results of these studies prompted further examination of pyranometer measurements and measurements of input parameters to the radiative transfer models (particularly aerosol and surface albedo properties).

Several ARM studies (e.g., Haeffelin et al. 2001; Dutton et al. 2001) identified and developed correction procedures for large offsets in pyranometer measurements due to thermal loss in the instruments. These instrument offsets could produce underestimates in measured diffuse SW of up to 10 W m\(^{-2}\), which may have accounted for some of the model/measurement discrepancies in the earlier studies. While Halthore and Schwartz (2000) did account for this thermal offset, they noted that their conclusions showed some dependence on the method used to estimate the offset. Detailed
studies of the offset issue by ARM scientists (see Michalsky and Long 2016, chapter 16) led to correction procedures for the pyranometer measurements (Younkin and Long 2003) as well identification of a new standard for diffuse measurements.

Later clear-sky radiative closure studies at the SGP site performed as part of ARM’s Broadband Heating Rate Profile (BBHRP) project (Mlawer et al. 2002, 2003), discussed in depth below, and by Michalsky et al. (2006) were able to achieve agreement with measured diffuse fluxes (after corrections for nighttime offsets). The latter study examined several different radiative transfer models and found significant effects on the calculated diffuse flux from the assumptions used to treat the spectral dependence of AOD and surface albedo in the radiative transfer models. Using new observations of wavelength-dependent AOD and surface albedo, they were able to achieve agreement to within 1.9% of measured diffuse fluxes and concluded that overestimates of diffuse fluxes in previous studies were due primarily to details of the specification of the spectral dependence of aerosol and surface properties.

b. Cloudy sky

To improve understanding of SW absorption in cloudy skies, ARM sponsored many theoretical studies, as well as two observationally focused experiments. Marshak et al. (1997, 1999b) performed a series of theoretical radiative transfer studies to examine various issues (e.g., horizontal and vertical offsets between aircraft measurements, cloud inhomogeneity, and method of estimating absorption) associated with estimating cloud absorption from measurements above and below clouds and identified methods to minimize these biases in analyzing observational results. Li and Trishchenko (2001) found that surface estimates of cloud radiative effects (CREs) were much more sensitive to clear-sky scene identification than satellite estimates, potentially leading to overestimates in atmospheric absorption derived from combined satellite/surface measurements. Several other studies (e.g., O’Hirok and Gautier 1998; Marshall et al. 1998; Titov 1998; Fu et al. 2000b) examined the potential impact of neglecting three-dimensional (3D) effects in the radiative transfer calculations of cloud absorption and found that including 3D radiative transfer effects in the calculations resulted in small increases in calculated column absorption, but not enough to account for the reported discrepancies.

The ARM Enhanced Shortwave Experiment (ARESE) consisted of collocated measurements of upwelling and downwelling broadband fluxes on two aircraft flying above and below the cloud (Valero et al. 1997a). Initial results (Valero et al. 1997b; Zender et al. 1997; O’Hirok et al. 2000) appeared to confirm that clouds absorbed significantly more SW radiation than theoretical estimates. However, further analysis of the ARESE results indicated potential calibration problems with the aircraft and satellite measurements that may have affected the estimates of column absorption from the observations (Li et al. 1999; Minnis et al. 2002). To address these issues, a second campaign (ARESE II) was sponsored by the ARM Program. Three sets of broadband solar radiometers were mounted on the Twin Otter aircraft and used in combination with the ground-based instruments at the SGP site to examine atmospheric absorption. Instrument redundancy and cross-calibration of measurements were key components of this campaign (Michalsky et al. 2002). Ackerman et al. (2003), O’Hirok and Gautier (2003), and Asano et al. (2004) analyzed measurements and radiative transfer calculations for several case studies observed during ARESE II (Fig. 20-2). Calculated and observed fluxes agreed within 10% for the clear-sky days and two of the three cloudy-sky days and within 14% for the third cloudy day. Including AOD in the cloudy-sky calculations reduced differences to approximately 5%. Around the same time, Li et al. (2002) was able to match observed surface and TOA fluxes for other cases at the SGP by including realistic representations of surface albedo, particularly in the near infrared, in the radiative transfer calculations. These studies indicated that although there were still some disagreements between the modeled and estimated absorption, they were much less than those identified in the early studies, and could generally be attributed to sampling issues, inhomogeneity of the cloud field, or were within the known uncertainties of the observations and model inputs.

3. Broadband Heating Rate Profile

Motivated by both the value and limitations of previous ARM radiative closure studies, ARM investigators initiated the BBHRP project in the early 2000s (Mlawer et al. 2002). In the decade before BBHRP began, several important achievements resulted from an ARM Quality Measurement Experiment (QME; Turner et al. 2004; Mlawer and Turner 2016, chapter 14) in which many years of radiation measurements from the Atmospheric Emitted Radiance Interferometer (AERI) at SGP were compared to corresponding calculations by a line-by-line radiation code. This AERI QME led to improvements to the instrument, radiation code, and the specification of the atmospheric profile above the site. Despite these successes, the focus on radiation rather than flux limited this effort’s significance to the climate modeling community. BBHRP was designed to be a comprehensive flux-based expansion of ARM’s
successful radiative closure initiatives, taking advantage of the long time series of ARM observations to run extended measurement–calculation comparisons for a range of atmospheric, aerosol, and cloud conditions. By running a long-term closure experiment instead of focusing on case studies, more statistical evaluation of closure results could be performed, leading to identification of issues in input data streams and/or radiative transfer models, as well as providing better understanding of atmospheric conditions for which closure worked well and the ARM observations could be considered representative of the large-scale atmospheric state.

The goals of the BBHRP project were to

- extend long-term flux closure studies, which had been limited to clear-sky surface longwave flux at SGP, to cloudy conditions, TOA flux, the shortwave spectral region, and sites other than SGP;
- generate radiative heating rates directly from measurement-based specifications of the atmospheric state using a validated radiation code;
- generate a long-term dataset of calculated radiative fluxes and heating rates along with the corresponding atmospheric state; and
- establish a “test suite” that would allow researchers to use radiative closure to evaluate new approaches with respect to any of the components of the closure study.

This last goal was especially targeted at the evaluation of cloud retrieval algorithms.

The breadth of the BBHRP project led to the involvement of multiple ARM working groups, resulting in the development of several “best estimate” products to specify the needed input for the radiative transfer calculations. The Instantaneous Radiative Flux Working Group provided the overall leadership as well as the radiation code [the rapid radiative transfer model (RRTM); Mlawer et al. 1997], flux measurements at the surface and TOA, microwave retrievals of precipitable water vapor and liquid water path, spectral surface albedo, and trace gas profiles. The Aerosol Working Group provided a best estimate vertical profile of aerosol optical properties (Flynn et al. 2012). The Cloud Properties Working Group (CPWG) developed a baseline best estimate cloud retrieval product, called Microbase (Dunn et al. 2011; also see Shupe et al. 2016, chapter 19), and a product that provided a continuous specification of the temperature and water vapor profiles above the site (Mergeson; Troyan 2010). The radiative closure studies performed within the BBHRP project were then used to further develop and refine all of these best estimate products, particularly Microbase.

Although different methodologies were explored for the closure studies, the final methodology chosen was to use each individual cloud retrieval at 60-s resolution as input to a separate radiation calculation, average the calculated flux values over a 30-min period, and compare to the instantaneous flux measurement at the middle of that time period. The 30-min averaging was determined to give optimal results for this type of measurement–calculation comparison for the different cloud types at SGP (Mlawer et al. 2007).

In a series of conference presentations and papers, the results from the radiative closure studies were presented. Even though the first dataset analyzed included cases from only a single month, March 2000, notable conclusions were attained. The average measurement–calculation...
differences for clear-sky cases were 4.2 W m\(^{-2}\) [standard deviation (std dev) 5.9 W m\(^{-2}\)] for SW diffuse and 5.1 W m\(^{-2}\) (std dev 8.1) for direct normal, demonstrating agreement within the overall uncertainty and providing persuasive evidence against clear-sky anomalous absorption (Mlawer et al. 2003). Analysis of this same dataset showed that the radiative closure results for ice clouds were much improved if the effects of aerosols also were included in the calculation. The expansion of this dataset to a full year (March 2000 to February 2001) established that vertical profiles of clear-sky total radiative heating rates, especially in the lower troposphere, had relatively little seasonal dependence despite the extensive seasonal variability of the LW and SW heating rates (Fig. 20-3; Mlawer et al. 2006). In subsequent years the SGP dataset was extended to 5 years and ARM’s North Slope of Alaska (NSA) site dataset was developed for 2 years. These longer datasets firmly established that radiative transfer model calculations using the ARM best estimate products as inputs were well able to reproduce clear-sky surface LW and SW diffuse fluxes, two fields that were key motivators for the genesis of the BBHRP project. For these fields, the measurement–model difference over the multiple years of data averaged to just 2.4 W m\(^{-2}\) (>22,600 cases, std dev 4.1 W m\(^{-2}\)) for clear-sky surface LW fluxes and ~2.4 W m\(^{-2}\) (>7700 cases, std dev 4.0 W m\(^{-2}\)) for clear-sky surface SW diffuse fluxes.

The detailed and systematic analysis performed as part of the BBHRP project detected several problems with various ARM data streams that were not obvious from other analyses. Examples of these issues (which were all corrected) include calibration issues impacting measurements by the Normal Incidence Pyrhieliometer and LW pyrgeometers, systematic errors in the AOD obtained from the multifilter rotating shadowband radiometer (MFRSR), issues with microwave retrievals of liquid water path, and systematic time-dependent inaccuracies in the TOA fluxes obtained from the Geostationary Operational Environmental Satellite (GOES). Although detection of these issues proved very helpful to the ARM Program and led to improvements in the best estimate products, their resolution led to significant delays in the BBHRP project.

Extensive analysis was performed of the closure results to assess different cloud retrieval methods. Analysis of the Microbase cloud retrieval method determined that the ice cloud optical depths provided by this retrieval approach were too large (Fig. 20-4). Here, the power of using the long-term statistics to evaluate cloud retrievals is evident as the large scatter indicates that a few case studies probably would not have been able to show the systematic error in the calculated fluxes as a function of ice water path. The BBHRP test bed was also used to examine the performance of five other cloud retrieval algorithms at SGP (provided by the CPWG) and one mixed-phase cloud property retrieval at NSA compared to Microbase (Shupe et al. 2015). Radiative closure results from these studies established that the Microbase liquid cloud retrieval was superior to the radar-based liquid cloud retrieval of Frisch et al. (1995), but other methods with simple, but different, assumptions than Microbase about the cloud’s microphysical properties provided more or less the same level of agreement as Microbase (Mlawer et al. 2008). This result may reflect a limit in retrieval quality for approaches involving simple microphysical assumptions, or the inherent cloud inhomogeneity might impose a limit on the ability of a flux-based analysis like BBHRP to distinguish between more and less accurate retrieval approaches.

At the NSA, the comparison for mixed-phase clouds between the Microbase retrieval provided more definitive results, with the multisensor Shupe–Turner retrieval (Shupe et al. 2015) showing superior closure results, particularly in the downwelling LW (Fig. 20-5).
Two primary reasons for the superior results of the Shupe–Turner algorithm were that it used a multisensor methodology, rather than a simple temperature threshold, to determine cloud phase and the location of liquid water and it used improved liquid water path retrievals (Shupe et al. 2015). Additional studies inspired by BBHRP, and using similar methodology, have examined ice cloud retrievals at the Darwin site (Comstock et al. 2013).

The BBHRP dataset was also used to evaluate advances in radiation parameterizations used in GCMs. Closure results (Mlawer et al. 2007) demonstrated that the GCM version of RRTM (RRTMG) using the Monte Carlo Independent Column Approximation (McICA; Pincus et al. 2003; Barker et al. 2008) stochastic approach to cloud overlap had similar residuals as the reference approach used with RRTM in BBHRP, but performed significantly better than the existing European Centre for Medium-Range Weather Forecasts (ECMWF) operational shortwave code. ECMWF subsequently adopted RRTMG/McICA as its new shortwave code (Ahlgrimm et al. 2016, chapter 28). In addition, the BBHRP dataset also provided most of the cases used in the Continuous Intercomparison of Radiation Codes (CIRC; Oreopoulos and Mlawer 2010), an initiative sponsored by the Global Energy and Water Exchanges (GEWEX) Radiation Panel and the International Radiation Commission to evaluate the quality of radiation codes used in global models. The measurement–calculation radiative closure for LW and SW flux at both the surface and TOA for the BBHRP cases used in CIRC was critical to providing confidence in the validity of the input profiles and reference line-by-line calculations used in the study.

BBHRP uses ARM observations both to derive the atmospheric state inputs to the radiative transfer calculation and to provide radiative fluxes for evaluating those radiative transfer calculations. The Clouds and the Earth’s Radiant Energy System (CERES)/ARM/GEWEX Experiment (CAGEX; Charlock and Alberta 1996; Rutan et al. 2006) used a combination of ARM measurements and satellite data for the purpose of evaluating satellite-based retrievals of the surface and atmospheric radiative fluxes. The CAGEX investigators considered the model inputs, the evaluation datasets, and the model itself as an integrated framework—any component of which needed to be evaluated as a possible source of error. Issues investigated included 3D CREs; challenges with satellite measurements, including calibration and narrow band to broadband conversions; the representativeness of the surface validation measurements; and potential issues with the radiative transfer code, including the water vapor continuum. The CAGEX studies and evaluation methodology were important in developing improved algorithms and quantifying uncertainties in the CERES Surface and Atmospheric Radiation Budget (SARB) product.

4. Impact of clouds on broadband surface fluxes and radiative heating profiles

Clouds impact the climate system directly through their reflection of SW radiation and absorption and emission of LW radiation, but also indirectly through feedbacks associated with their effects on surface and atmospheric heating that in turn affect the large-scale circulation (Stephens 2005; Mace et al. 2006b). To accurately simulate cloud feedbacks, models must
accurately partition the cloud radiative impact between the surface and the atmosphere and how that partitioning might change as temperature and humidity profiles change in a warmer climate. A given cloud has different effects on the TOA, surface, and atmospheric radiation budgets, and the sign and magnitude of these radiative effects are complex functions of cloud temperature, phase, and optical properties and also depend on the geographic location, atmospheric profile, and surface properties. The effect of clouds on the TOA radiation budget has been documented both globally and regionally by satellite instruments such as the Earth Radiation Budget Experiment (ERBE) and CERES. However, the effect of clouds on the radiation budget at the surface and within the atmosphere is less well known because of the relative lack of surface observations and detailed observations of cloud vertical structure. Studies indicate that accurate simulation of the TOA radiation budget is not adequate to constrain cloud feedbacks because multiple vertical structures with different distributions of atmospheric and surface heating can produce the same TOA budget (Webb et al. 2001). Stephens (2005) presents a review of cloud–climate feedbacks and emphasizes that studies of cloud feedbacks must move beyond examination of surface and TOA budgets to consider perturbations to the atmospheric radiative heating, which “dictate the eventual response of the global-mean hydrological cycle of the climate model to climate forcing.”

The long-term observations at the ARM sites have been used to make significant advances in quantifying our understanding of the impact of clouds on broadband surface fluxes and atmospheric heating rate profiles and have provided important datasets for evaluating model simulations. As discussed in Stokes (2016, chapter 2), each of the ARM fixed sites was located in a climatically important geographic location where CREs need to be better understood. The simultaneous observations of the vertical distribution of clouds and the broadband surface fluxes across the diurnal cycle at various geographic locations provide a unique dataset for studying how the macrophysical (cloud base and top height, cloud vertical structure) and microphysical (water content, phase, particle size) properties of clouds alter the clear-sky radiative fluxes. In the remainder of this section, we discuss results from studies using ARM data to quantify the impact of clouds on surface fluxes and heating rate profiles, which we refer to as the CRE. Throughout this field, investigators have used different terminology and methods to quantify the impacts of clouds on the energy budget, which in some cases makes it difficult to directly compare studies at different sites. In describing the results of each study, we try to clarify the methods and terminology used, although in some cases readers may need to refer to the original paper to obtain all of the details of the methodology.

a. Surface cloud radiative effects

Long and Ackerman (2000) pioneered a method of deriving SW surface clear-sky radiation from broadband radiometer measurements, enabling estimation of SW CREs at the surface from observations alone. Further work by Long et al. (2006) developed a method for retrieving cloud fraction from the SW radiometer measurements, and Long and Turner (2008) extended the methodology to broadband LW measurements, providing estimates of LW CREs. These radiative flux analysis methods have been applied to all ARM sites for multiple years, resulting in a comprehensive dataset of the magnitude and variability of cloud SW and LW CREs at the surface in a variety of different geographic regions.
Figure 20-6 shows the monthly averages of LW and SW CREs at the surface from each of the ARM fixed sites. Here we define CRE as the difference between the measured all-sky and the estimated clear-sky fluxes at each time. The LW CRE is relatively small and fairly constant at the three tropical sites, because of the large amounts of water vapor in the tropical atmosphere. However, LW CRE is larger for SGP, with some seasonal and interannual variability. The LW CRE dominates the energy budget at Barrow, especially during the winter months when there is little solar radiation. The SW CRE also varies substantially across the sites. Manus has the largest-magnitude SW CRE, and the values are fairly steady across all the years of data. Nauru shows significant interannual variability in CREs—some years are similar in magnitude to Manus while other periods have much smaller magnitude of the SW CREs. Darwin shows strong interseasonal variability associated with the Australian monsoon—values of SW CREs are as large as those at Manus during the wet season but significantly smaller during the dry season. SGP and Barrow also show significant seasonal cycles, with the SW CREs going to zero during the winter at Barrow.

To further understand how cloud properties impact the magnitude and variability of surface fluxes, ARM scientists have combined the CRE estimates from the broadband radiometer measurements with measurements from other instruments (e.g., radars, lidars, microwave radiometers, and ceilometers) that provide information on cloud macrophysical and microphysical properties. Studies have been conducted at all of the ARM fixed sites to relate the observed broadband CREs...
to specific cloud characteristics, such as cloud fraction, type, altitude, phase, and optical depth (e.g., Dong and Mace 2003; Dong et al. 2006; McFarlane and Evans 2004; McFarlane et al. 2013).

1) Southern Great Plains

Dong et al. (2006) performed a comprehensive study that examined the surface radiative impact of single-layer clouds at the SGP and found large seasonal and diurnal variability in cloud amount and radiative impact as a function of cloud type (Fig. 20-7). Here, they include upwelling surface fluxes when defining the CRE. Overall, they find that the net CRE at the surface was $\sim 20 \text{ W m}^{-2}$, and the magnitude of SW cooling at the surface was approximately twice as large as the LW heating. Low clouds dominated the total surface CRE.

**Fig. 20-7.** Observed monthly mean (a) LW, (b) SW, and (c) net cloud radiative forcing (CRF) for overcast clouds as a function of cloud type at the ARM SGP site from 1997 to 2002. Monthly average cloudy- and clear-sky surface fluxes were calculated by the following procedure: 1) bin observed fluxes by sky conditions (clear or cloudy), 2) average binned fluxes over 1-h intervals, 3) calculate the monthly mean diurnal cycle by averaging all of the means corresponding to the same hour of the day within the month, and 4) average over the mean diurnal cycle to produce a monthly mean flux. CRF was then calculated as the difference between the monthly averaged net surface fluxes (downwelling minus upwelling) for observed cloudy and clear conditions (figure from Dong et al. 2006).
and corresponding to seasonal changes in cloud frequency, their impact was greatest during the spring and fall and least during summer. Dong et al. (2006) also quantified the impact of changes in the environment associated with clear and cloudy conditions on the CRE. Typical estimates of CREs from observations alone simply subtract average observed clear-sky fluxes from average observed cloudy-sky fluxes, neglecting the fact that atmospheric profiles are often different in cloudy and clear skies. Over the ARM SGP site, for the single-layer cloud cases examined in Dong et al. (2006), changes in humidity and surface albedo between clear and cloudy conditions offset 20% of the net radiative impact of the clouds alone. Their analysis indicated that for monthly averaged CREs, changes in cloud properties dominate the SW CREs, while the increase in water vapor between clear and cloudy conditions was a significant contributor to the LW flux changes.

Berg et al. (2011) focused specifically on the radiative impact of midlatitude shallow cumuli, a cloud type that is often not captured well in large-scale models or satellite measurements because of its small-scale variability. Although the net effect of the shallow cumuli was to decrease the SW flux at the surface, the spatial and temporal inhomogeneity of cumuli also resulted in periodic episodes of cloud-induced enhancement of the surface SW flux. These events occurred approximately 20% of the time that cumuli existed and produced occurrences of positive SW CREs with instantaneous values as large as $+75 \text{ W m}^{-2}$.

2) NORTH SLOPE OF ALASKA

The Arctic is one of the most rapidly changing regions on the planet, and clouds play an important role in climate feedbacks in this region (Curry et al. 1996; Stamnes et al. 1999). The melting of snow and sea ice in the Arctic is influenced strongly by the amount of downwelling LW radiation at the surface, which depends primarily on cloud amount and microphysical properties. Determining the characteristics of Arctic clouds from satellite observations is difficult because the highly reflective surface makes it difficult to distinguish clouds from the surface with visible wavelengths, and the nearly constant presence of a surface-based inversion makes thermal techniques challenging, as the cloud and the surface can be nearly the same temperature. Therefore, ground-based instruments provide a critical set of observations for determining properties of Arctic clouds and their concurrent impacts on the surface radiative budget. The Surface Heat Budget of the Arctic (SHEBA) campaign (in which ARM participated) provided an unprecedented dataset on cloud and radiative properties over the Arctic sea ice for a year (e.g., Shupe and Intrieri 2004) while the ARM NSA site near Barrow, Alaska, which has been operating since 1997, provides a unique source of long-term data for studying the seasonal and interannual variation of Arctic cloud properties and their impact on the surface radiative budget (Verlinde et al. 2016, chapter 8).

At NSA, single-layer overcast low-level stratus clouds show a significant annual cycle, with cloud fraction increasing significantly in the spring, staying high and relatively constant in the summer, and then decreasing from November to the following March (Dong and Mace 2003; Dong et al. 2010). The surface LW CRE, which is also influenced by changes in cloud liquid water path and temperature, shows a corresponding strong seasonal variation with a maximum in August and minimum in March. The SW CRE has maximum values during July and August. Although the annual average net surface CRE is only $3.5 \text{ W m}^{-2}$, there is a seasonal dependence with low-level stratus clouds cooling the surface during the summer and warming the surface during spring and fall (Dong and Mace 2003; Dong et al. 2010). The Arctic stratus clouds appear to produce a positive feedback on Arctic change; relative to cloud-free skies, the presence of clouds increases the downwelling LW at the surface, which acts to enhance the melting of snow and ice in the spring and slows the freezing of the ice in the fall.

Mixed-phase clouds and aerosol indirect effects also play an important role in the Arctic surface radiation budget. Mixed-phase stratiform clouds are a prevalent cloud type in the Arctic and one of the most difficult for models to capture correctly. Lubin and Vogelmann (2011) used unique spectral SW irradiance measurements made during the ARM Indirect and Semi-Direct Aerosol Campaign (ISDAC) to examine the influence of mixed-phase stratiform clouds on the surface SW irradiance. Compared with liquid-water clouds, mixed-phase clouds during the Arctic spring cause a greater reduction of SW irradiance at the surface. Two studies in Nature (Garrett and Zhao 2006; Lubin and Vogelmann 2006) used aerosol and radiation measurements from the ARM NSA site to show that elevated aerosol concentrations in the Arctic affect the properties of Arctic clouds and hence increase the downwelling LW surface fluxes under cloudy skies by $3.3–5.2 \text{ W m}^{-2}$. Given the small average net surface CRE, these studies indicate that small changes in cloud or aerosol properties may have a large impact on the surface radiative budget in the Arctic.

3) TROPICAL WESTERN PACIFIC

Understanding cloud radiative impacts in the Tropical Western Pacific (TWP) is extremely important as the
absorption of solar energy in the tropics and transport of the excess energy to the poles is a primary driver of the meridional general circulation. However, because of the remote location and difficulty of finding observational sites in the tropics with suitable infrastructure, most understanding of tropical cloud radiative impacts was derived from short-term field experiments or satellite measurements. The establishment of the ARM tropical sites on Manus (1996) and Nauru (1998) provided the first long-term, detailed measurements of collocated cloud and radiative properties in the oceanic tropical western Pacific (Long et al. 2016, chapter 7). The extension of the ARM measurements to the Darwin site (2002) provided contrasting data from a tropical land site that exhibits strong seasonal variability associated with the Australian summer monsoon.

Because of their locations, the three ARM TWP sites exhibit very different time series of cloud properties and surface radiative fluxes. McFarlane et al. (2013) characterize the climatological mean and variability of the surface CRE at the three ARM tropical locations and examine differences in the CREs as a function of simple cloud type definitions that could be applied easily to climate models. The Nauru and Darwin sites show significant variability in sky cover, downwelling radiative fluxes, and surface CREs due to El Niño–Southern Oscillation (ENSO) and the Australian monsoon, respectively, while the Manus site (which is located in the tropical warm pool) shows little intraseasonal or interannual variability (Fig. 20-6). As at the other sites, clouds with low bases are the primary contributors (approximately 70%) to the surface SW and LW CREs, although clouds with midlevel and high bases also have important impacts on the surface radiative budget.

b. Impacts on atmospheric heating profiles

Clouds impact not only surface and TOA fluxes, but also redistribute energy within the atmosphere, which is important for climate feedbacks on the large-scale circulation and hydrological cycle. Before the ARM Program was established, understanding of the details of this redistribution of energy was limited by the lack of information on cloud vertical structure. Estimates of radiative heating profiles were limited to theoretical examination of idealized cases, a few case studies from field campaigns, and estimates from satellite measurements, which required large assumptions about cloud vertical structure. ARM investigators pioneered the use of combining retrievals of cloud microphysical properties from remote sensing instruments (Shupe et al. 2016, chapter 19) with detailed radiative transfer calculations to study the impacts of cloud microphysical properties and cloud vertical structure on atmospheric heating rate profiles. Figure 20-8 illustrates an example of the detailed structure of the atmospheric heating rate profile that could be calculated from the high-resolution ARM measurements.

Since there are very few observational constraints on radiative heating profiles, the flux closure concept described above is generally used to validate the calculated broadband surface and/or TOA fluxes in these studies, providing confidence in the derived cloud properties and the radiative transfer models used to calculate the heating profiles. However, the flux closure method

![Figure 20-8](image-url)
cannot definitively evaluate the shape of the derived heating rate profiles, as there might be multiple profiles that produce the same fluxes. Early ARM studies examined the vertical structure of radiative heating profiles for case studies of common cloud types, including tropical cirrus (Comstock et al. 2002) and tropical precipitating convection (Jensen and Del Genio 2003). As the ARM sites gathered multiple years of data, later studies moved beyond the case study approach and used the multiple years of ARM measurements to characterize the vertical structure of SW and LW radiative heating profiles at the SGP (Fig. 20-9; Mace et al. 2006a,b; Mace and Benson 2008), the tropical sites (Fig. 20-10; Fueglistaler and Fu 2006; Mather et al. 2007; McFarlane et al. 2008), NSA site (Zwink 2013), and during ARM Mobile Facility deployments (Powell et al. 2012).

These ARM studies were the first to use observations to examine the detailed redistribution of energy between the surface and atmosphere and within the atmosphere by clouds on diurnal, monthly, and seasonal time scales. Applying similar methodologies to the datasets measured at the different ARM sites provides important information on similarities and differences in the impacts of clouds on atmospheric heating profiles at different geographic locations. Many of these radiative heating datasets have been released to the community as ARM Principal Investigator (PI) data products (http://www.arm.gov/data/pi).

Figure 20-9 shows the average CRE on the atmospheric heating profiles from 12 years of data at the ARM SGP site, while Fig. 20-10 illustrates the average CRE profiles at the TWP sites (Manus, Nauru, and Darwin). For both of these figures, CRE is defined as the heating profile calculated using a radiative transfer model with thermodynamic and cloud profiles derived from ARM observations minus the heating profile calculated using the same atmospheric thermodynamic profile, but with no clouds included in the calculations. At all of these ARM sites, clouds have a small net influence on the column atmospheric heating, but produce a significant vertical redistribution of radiant energy within the atmosphere. Different cloud types have quite different effects on the magnitude and location of heating and cooling within the atmosphere, with upper tropospheric clouds producing a net heating of the upper troposphere and boundary layer clouds producing a net cooling of the lower troposphere (Mace and Benson 2008; Mather et al. 2007). At the tropical sites, midlevel clouds associated with detrainment near the freezing level also have a large impact on the radiative heating profiles. Detailed studies of the heating

Fig. 20-9. Average CRE (black line) on atmospheric (left) SW, (center) LW, and (right) net heating profile calculated from over 20 years of data at SGP. Zero CRE is indicated in each panel by the red line. See text for more details. Figure courtesy of Jay Mace and Sally Benson, University of Utah.
rate profiles associated with different cloud types (Mather and McFarlane 2009) also illustrate that the existence of multiple cloud layers can have complex impacts on the resulting radiative heating profiles; reflection of SW by overlying cirrus can reduce the expected SW heating by water vapor at lower levels, and reduced upwelling LW emission from the surface due to low clouds can reduce the expected LW heating at the base of a cirrus layer. Several studies (Fueglistaler and Fu 2006; Mather et al. 2007) examined the potential impact of tropical cloud radiative heating on atmospheric dynamics. Fueglistaler and Fu (2006) found that the impact of clouds relative to clear-sky conditions was particularly large around 60 hPa, which is the base of the “tropical pipe.” Their results suggested that gradients in upper tropospheric radiative heating rates may be partially responsible for stratospheric mixing. More recent studies (Thorsen et al. 2013; Protat et al. 2014) have combined the ARM ground-based data with satellite data to more fully characterize upper tropospheric tropical clouds and heating profiles.

All of the ARM sites exhibit substantial variability in radiative heating profiles at various time scales. At the SGP, although the TOA LW CRE is relatively constant over the annual cycle, the details of the radiative heating profile within the atmosphere change substantially over the year as the relative frequency of low and high clouds changes (Mace and Benson 2008). At the tropical sites, the radiative heating and atmospheric absorption profiles vary considerably depending on the amount of convection, associated with ENSO at Nauru and the Australian monsoon at Darwin (Mather et al. 2007; McFarlane et al. 2008). The sites also show distinct diurnal cycles in clouds and associated heating rates that vary with the large-scale dynamics and resulting cloud properties. At the NSA site, understanding the relative impact of liquid and mixed-phase clouds on radiative heating profiles (Fig. 20-11) is complicated by the concurrent changes in cloud properties (phase, depth, and liquid water content) and solar zenith angle with season. These results indicate that changes in the vertical distribution of clouds on seasonal and interannual time scales have important impacts on the redistribution of heating within the troposphere, and simply reproducing the average net surface and TOA effects of clouds in models will not capture essential cloud feedbacks on the general circulation.

Since the ARM sites have limited spatial sampling, an important question is how representative conclusions drawn at the sites are for the larger area. Jakob et al. (2005) used tropics-wide satellite data to define four tropical cloud regimes (two convective and two more suppressed regimes) and found that all four regimes exist at the Manus site and showed distinct differences in
cloud and radiative properties measured at the site. Mather and McFarlane (2009) examined differences in the structure of the radiative heating profiles at Manus and Nauru and found that the frequency of specific cloud types, and therefore the mean radiative heating profile, differed between the two sites. However, the characteristic heating profiles of individual cloud types at the two sites were remarkably similar. These studies indicated that if the frequency of different cloud types across a region were known from another source, such as satellite measurements, the cloud and heating rate profiles derived from the ARM data for each cloud type could be applied to estimate the vertical structure of cloud and heating rates over a larger area.

Another important question is the relative contribution of radiative heating to the total diabatic heating profile. Jensen and Del Genio (2003) estimated that the maximum radiative heating was 10%–30% of the maximum latent heating profiles for cases of mature deep convection near local solar noon. Li et al. (2013) combined the ARM-derived tropical radiative heating profiles with latent heating profiles derived from the Tropical Rainfall Measuring Mission (TRMM) satellite to examine the relative contributions of radiative and latent heating to the total diabatic heating profile of tropical clouds. They found that radiative heating of tropical upper-level clouds contributed 20% of the total column-integrated diabatic heating. A model simulation forced with the derived radiative and latent heating profiles suggested that the impact of radiative heating on large-scale tropical circulation was primarily from indirect impacts on convective feedbacks.

c. ARM Mobile Facility

The advent of the ARM Mobile Facility (AMF) in 2005 allowed ARM investigators to explore the impact of clouds on broadband fluxes and heating rates in additional geographical locations, including Pt. Reyes,
California; Niamey, Niger (Slingo et al. 2009); the Black Forest in Germany (Ebell et al. 2011); and the Maldives (Feng et al. 2014).

In particular, the AMF deployment to Niamey, Niger, was designed specifically to study the radiative flux divergence in the atmosphere in a region (the Sahel) with large variability in water vapor column amounts, aerosol loading, and cloud cover (Miller and Slingo 2007). An advantage of the Niamey deployment for examining atmospheric radiative heating was the location of the Niamey site under the Geostationary Earth Radiation Budget (GERB) instrument on the Meteosat-8 European weather satellite. GERB provides broadband SW and LW fluxes every 15 min at about 50-km resolution. The combination of the TOA flux measurements from GERB and the surface flux measurements from ARM allowed the first direct estimation of broadband radiative flux divergence through the atmosphere at high temporal resolution for such an extended period of time. Slingo et al. (2009) examine the factors that control the surface and TOA fluxes, as well as the atmospheric radiative flux divergence at Niamey (Fig. 20-12). The high aerosol loadings throughout the year affect both the SW and LW fluxes while the LW fluxes also are impacted significantly by the large seasonal changes in column water vapor (CWV) and temperature between the wet and dry seasons. These effects on the LW fluxes somewhat counteract each other, as the highest temperatures occur at the end of the dry season when the CWV is lowest while the lowest temperatures in the wet season

Fig. 20-12. Scatterplots of the atmospheric shortwave divergence at Niamey vs (a) column water vapor and (b) aerosol extinction at 870 nm for data measured during the wet season (blue) and dry season (red). In (a), cloudy points are indicated by open squares (figure from Slingo et al. 2009).
occur at the same time as the highest CWV values. The SW fluxes are affected strongly by clouds and by the seasonal changes in CWV. The LW total atmospheric divergence shows relatively small variations through the year, because of compensation between the seasonal variations in the outgoing longwave radiation (OLR) and surface net LW radiation due to the changes in temperature and CWV. The SW atmospheric divergence is mainly determined by the CWV and aerosol loadings (Fig. 20-12), while the effect of clouds is much smaller than on the surface and TOA fluxes.

Additional studies based on the AMF deployment examined other aspects of the radiative budget at Niamey, including comparisons of observed and modeled LW fluxes (Bharmal et al. 2009), the effect of heterogeneities on radiative divergence (Settle et al. 2008), detailed studies of aerosol impacts on SW and LW surface fluxes (Slingo et al. 2006; McFarlane et al. 2009; Turner 2008), diurnal and seasonal cloud radiative impacts (Bouniol et al. 2012), radiative heating of convective anvils (Powell et al. 2012), seasonal contrasts in the components of the surface energy balance (Miller et al. 2009), and the ability of GCMs to reproduce the observed cloud radiative effects and atmospheric divergence (Miller et al. 2012).

d. Evaluating model representations of surface and atmospheric radiative fluxes

The climatologies of surface radiation and cloud properties from the ARM sites, such as those described above, have been used for evaluating simulations of the surface radiation budget in a wide variety of models, including operational forecast models (e.g., Hinkelman et al. 1999; Morcrette 2002; Yang et al. 2006; Ahlgrimm and Forbes 2014), reanalysis models (Allan 2000; Kennedy et al. 2011), single-column models (Somerville and Iacobellis 1999; Lane et al. 2000; Iacobellis et al. 2003), regional models (Pinto et al. 1999), and GCMs (Xie et al. 2003; Qian et al. 2012; Miller et al. 2012). While multiple sites around the world have surface radiative flux measurements that can be used to evaluate model radiative fluxes (e.g., the Baseline Surface Radiation Network), the simultaneous measurements of cloud, aerosol, and atmospheric properties within the column along with the surface radiative fluxes at the ARM sites allow scientists to not only identify errors in the models’ surface radiative budgets, but to diagnose which aspects of the model contribute to those errors.

These studies have generally indicated that model errors in simulating surface radiation arise from a combination of sources. For example, Hinkelman et al. (1999) found biases of 50 W m$^{-2}$, on average, in the downwelling SW radiation at the surface in the Eta model and attributed half of the excess to errors in the treatment of water vapor and aerosol in the model and the other half to errors in the treatment of clouds. Similarly, Kennedy et al. (2011) showed that the North American Regional Reanalysis has significant positive biases in downwelling SW and negative biases in downwelling LW under both clear-sky and all-sky conditions. The biases were found to result from a combination of errors in aerosol, water vapor, and clouds in the model. Qian et al. (2012) used ARM observations at multiple sites to examine the relationships between cloud fraction and surface radiative flux in the GCMs used in the Intergovernmental Panel on Climate Change assessment reports. They find that errors in modeled total cloud fraction and normalized cloud radiative effect are similar in magnitude, but both are larger than model errors in downwelling SW radiation, indicating that the reasonable agreement in surface radiation is due to compensating errors in cloud vertical structure, overlap assumption, optical depth, and/or cloud fraction. These studies indicate the utility of the ARM observations in diagnosing reasons for errors in model-simulated fluxes.

ARM observations also have been used to evaluate how well models are able to represent broadband atmospheric radiative heating profiles. McFarlane et al. (2007) compared the ARM-derived vertical profiles of tropical cloud properties and associated BBHRP to results from two global atmospheric models and found large differences in the vertical profiles and diurnal cycle of cloud amount, water content, and radiative heating profiles. The differences in the heating rates between the models and the ARM-derived values were due to a combination of differences in the cloud properties (cloud frequency, vertical location of clouds, and cloud optical thickness) and the radiative transfer calculations (parameterization of LW absorption coefficient as a function of particle size). Powell et al. (2012) examined the ability of several microphysical schemes to reproduce the vertical structure of cloud properties and radiative heating observed in anvil clouds at Niamey. They found that all of the schemes underestimate the optical thickness of thin anvils and cirrus, resulting in a bias of excessive net anvil heating in all of the simulations.

An advantage of ARM datasets compared to shorter-term field experiments is that the multiple years of measurements provide enough samples to classify the data into different meteorological regimes. Regime analysis allows investigation of the effects of particular dynamical or meteorological conditions on cloud properties and radiative impacts, but it also provides a dataset for model evaluation that can be used to
separate dynamical errors and parameterization errors (e.g., Marchand et al. 2009). Marchand et al. (2006), Evans et al. (2012), and Mülmenstädt et al. (2012) use objective methodologies to classify the multiple years of observations at the SGP, Darwin, and NSA sites, respectively, into distinct meteorological regimes. At each site, significant differences in cloud properties and the associated surface radiation fields are found between the different categories, indicating the potential utility of the classification for examining how dynamics influence cloud and radiative properties in observations and models.

5. Three-dimensional radiative transfer

The 3D radiative transfer effects cannot be included in climate models because of computational limitations that require radiative transfer calculations to be treated efficiently, and because GCMs do not contain information on the full 3D cloud scene within a grid box. Therefore, climate models have to make simplifying assumptions about cloud horizontal structure within a model grid box and how clouds in different vertical layers overlap, and they must use 1D radiative transfer models to calculate gridbox-average fluxes and heating rates. ARM has made significant advances in using sophisticated 3D radiative transfer models to understand the impacts of these assumptions on calculated broadband fluxes and heating rates and developing methodologies to reduce these biases in GCMs. More detail about development of new methods for radiative transfer in GCMs is given in Mlawer et al. (2016, chapter 15); here we focus primarily on ARM studies that used state-of-the-art radiative transfer models to quantify the impact of neglecting 3D effects on calculated fluxes and heating rates as well as the use of ARM data to understand inhomogeneity in real clouds.

a. Biases due to neglect of 3D effects

As discussed previously, ARM scientists conducted several important theoretical radiative transfer modeling studies that illustrated that errors due to neglecting 3D effects when deriving estimates of atmospheric absorption derived from surface and satellite (or aircraft) observations would contribute to the discrepancy between observations and 1D models, but could not explain all of it (e.g., O’Hirok and Gautier 1998; Marshak et al. 1998; Titov 1998; Fu et al. 2000b). ARM scientists also performed key studies characterizing the accuracy of the independent column approximation (ICA), a method to move beyond plane-parallel radiative transfer. In the ICA, a domain is divided into individual columns (or pixels), 1D radiative transfer is calculated on the cloud properties within each column, and then the contributions of each column are summed to obtain the domain-averaged fluxes of heating rates. ARM studies showed that GCM-scale domain-averaged errors in surface and TOA fluxes calculated using the ICA were generally less than 20 W m$^{-2}$, and those in atmospheric heating rates were typically less than 3% (Marshak et al. 1995, 1999a; Barker et al. 1999; Cole et al. 2005a).

The detailed radar and lidar observations from the ARM sites provided key information for studies on the impact of horizontal and vertical inhomogeneity of real clouds, rather than idealized or modeled clouds, on radiative fluxes (Fu et al. 2000a; Carlin et al. 2002). Várnai (2010) used multiple years of ARM radar data at the SGP, NSA, and TWP sites to perform a comprehensive study on the impact of horizontal photon transport effects on solar radiative heating calculations. The results show that average 2D effects are fairly small, but individual cases can have much larger impacts, especially for cases of high sun or convective clouds. Additionally, 2D effects at oblique sun angles often enhance surface heating. Assumptions about vertical inhomogeneity are also important for radiative transfer calculations, and cloud overlap statistics from the ARM radar data (e.g., Mace and Benson-Troth 2002) have been used to examine formulations of vertical overlap assumptions used in climate models (Stephens et al. 2004).

To examine multidimensional radiative transfer effects using the ARM vertically pointing radar and lidar data, researchers typically used the “frozen turbulence” assumption, in which a horizontal advection velocity is used to convert the temporal dimension of the data into a spatial dimension in order to create 2D cloud fields. Using model-simulated cloud fields, Pincus et al. (2005) show that because there are fewer cloud edges in 2D than 3D scenes, such studies systematically underestimate the magnitude of the 3D effect. Additionally, the limited sampling observed by the vertically pointing radar produces noise of up to 20% in estimates of the 3D effect. To move beyond these limitations of sampling from vertically pointing data, ARM scientists developed methods for stochastically generating multidimensional cloud fields that match observed statistics of optical depth and cloud structure (Evans and Wiscombe 2004; Prigarin and Marshak 2009).

While the studies of 3D radiative transfer described above focused primarily on the effects on SW fluxes and heating rates, a comprehensive set of studies by Ellingson and colleagues examined the impacts of 3D cloud structure on LW radiative transfer and found that they could be important for cloud fractions between 0.2 and 0.8. These studies included theoretical calculations...
to quantify the impact on LW fluxes and heating rates using idealized (Killen and Ellingson 1994) and observed (Han and Ellingson 1999) cloud geometries, identifying conditions under which LW scattering needs to be included in calculations (Takara and Ellingson 1996, 2000), and testing parameterizations for LW radiative effects against ARM observations (Han and Ellingson 2000; Taylor and Ellingson 2008).

b. Impact of 3D effects on cloud evolution

While models need to produce accurate domain-averaged fluxes and heating rates in order to correctly simulate interactions with the large-scale circulation, subgrid-scale interactions between clouds and radiation also can have important influences on cloud evolution. Several ARM studies using high-resolution cloud models have examined the impact of neglecting interactions between radiation and clouds on the evolution of different types of cloud fields. These studies indicate that the impact of neglecting 3D radiative transfer effects in models depends in part on the resolution of the model simulations.

Simulations of tropical cumulus convection indicated that direct radiative-convective interactions through LW cloud-top cooling and SW radiative heating are more important in determining the diurnal cycle of tropical precipitation than indirect radiative–dynamical–convective interactions through differential heating of clear and cloudy regions (Xu and Randall 1995). Vogelmann et al. (2001) found that cloud-top height variability and the structure of cloud edges in deep convective clouds could produce regions of intense local SW heating that occupied only a small area of the climate model grid cell but dominated the grid-mean value. Explicitly resolving these hot spots requires model grid sizes of approximately 20–30 km². Models that cannot resolve these hot spots and use typical cloud overlap assumptions to represent subgrid variability overestimate the solar heating above the cloud and underestimate it below the cloud, impacting the turbulence and vertical velocity within the cloud layers and having potential consequences for simulation of cloud evolution and feedback in weak dynamical regimes in GCMs. In high-resolution (horizontal resolutions of 50–100 m) model simulations, Mechem et al. (2008) found that neglecting multidimensional LW radiative effects had only small impacts on the cloud dynamics of boundary layer cloud systems. Although the spatial structure of the radiative forcing was changed significantly in model simulations using full 3D radiative transfer calculations, there were few systematic differences in the overall cloud fields, indicating the ICA approach was sufficiently accurate for these simulations.

Two studies examined the neglect of subgrid-scale cloud–radiation interactions on GCM scales. Gu and Liou (2006) implemented a cirrus inhomogeneity factor in a GCM simulation and found that it increased the global mean net solar flux at TOA by 5 W m⁻². Inclusion of inhomogeneity also produced geographic differences in cloudiness, radiation, and precipitation in the model, indicating the indirect effects of cloud–radiation interactions in cirrus clouds on the climate simulation. Cole et al. (2005b) found unresolved cloud–radiation interactions on the scale of a GCM grid box significantly affected the statistics of cloud fraction and cloud radiative effects. When local cloud–radiation interactions were neglected, high cloud amount at most latitudes tended to be larger while marine stratocumulus cloud fractions were smaller. For high clouds, the small-scale structure in cloud-top radiative cooling entrains dry air into the cloud layer, reducing the cloud amount, while for marine stratocumulus the cloud-top radiative cooling tends to maintain the layer.

c. New radiative transfer methods

Along with applying state-of-the-art radiative transfer methods to understand cloud impacts on the radiative budget (as discussed above) and improving the representation of radiative transfer in GCMs (as discussed in Mlawer et al. 2016, chapter 15), ARM investigators have played a significant role in developing new state-of-the-art radiative transfer methods that calculate fluxes and heating rates more efficiently or more accurately. Improvements to 1D radiative transfer models supported by ARM include computationally efficient methods for solving the two-stream equation (Gabriel et al. 1993), improved correlated-k distribution methods (Mlawer et al. 1997; Kato et al. 1999), and new methods for treating horizontal variability (Wood et al. 2005). Improvements to 3D radiative transfer modeling techniques include the development of the spherical harmonic spatial grid method (Evans 1993), a new spectral radiative transfer method (Gabriel et al. 1993), and applications of photon diffusion theory and Green’s function to remote sensing problems (e.g., Davis and Marshak 2002). ARM scientists have played key roles in developing stochastic radiative transfer methods for atmospheric applications (Lane et al. 2002; Kassianov 2003; Lane-Veron and Somerville 2004; Kassianov and Veron 2011) and have used ARM data both to develop statistics of cloud properties for stochastic models (Lane-Veron and Somerville 2004) and to evaluate their performance (Foster and Veron 2008; Kassianov et al. 2003). ARM also contributed to the development of easy-to-use, community radiative transfer codes, including the Santa Barbara Discrete
Ordinate Radiative Transfer (DISORT) Atmospheric Radiative Transfer (SBDART) 1D model (Ricchiazzi et al. 1998) and the community Monte Carlo 3D model (Pincus and Evans 2009).

d. Other 3D radiative transfer activities

ARM and NASA jointly support the Intercomparison of 3D Radiation Codes (I3RC) project (Cahalan et al. 2005), which aims to improve the treatment of 3D radiative transfer (RT) through “documentation of errors and limitations of 3D methods, sharing and development of 3D tools, and atmospheric science education in 3D RT.” Many ARM scientists have participated in the I3RC intercomparison studies, and one of the intercomparison cases is based on ARM radar data. ARM also provided support for a monograph on 3D radiative transfer techniques in cloudy atmospheres (Marshak and Davis 2005), and over half of the contributing authors were members of the ARM Science Team.

6. Conclusions

As described in this chapter, ARM has made important advances in quantifying the role of clouds on broadband surface fluxes and atmospheric heating rate profiles and providing important information for model evaluation and improvement. We see two primary areas where ARM will continue to move forward in this area: the BBHRP test bed and use of 3D cloud fields from scanning radar data.

The recent automation of the BBHRP procedure (e.g., McFarlane et al. 2011) allows scientists to quickly and systematically evaluate the accuracy of cloud retrievals with respect to surface broadband flux and test the impact of changing the assumptions made in the retrievals on both the surface fluxes and broadband heating rates. Initial studies have started to use the BBHRP methodology to study an ensemble of cloud retrievals to provide information on retrieval uncertainty to cloud modelers (S. Xie 2013, personal communication), and we anticipate this type of activity will continue.

ARM scientists have already made important contributions to understanding the 3D radiative effects of clouds through the use of model-simulated 3D cloud fields and 2D cloud fields derived from vertically pointing radar instruments. However, the new ARM scanning cloud radars (Ackerman et al. 2016, chapter 3; Mather et al. 2016, chapter 4) will provide unprecedented information on the 3D structure of real cloud fields. An early study has already been conducted to quantify errors in calculated surface fluxes from radar-produced 3D cloud scenes associated with radar sensitivity, scan strategy, and method of scene reconstruction (Fielding et al. 2014).

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