1. Setting the research agenda

It is well known that the exchange of heat and moisture between the surface and atmosphere plays a key role in the earth’s climate system (e.g., Randall et al. 2007). Science questions related to land–atmosphere interactions have remained an active topic of research, both inside and outside of the ARM Program, for a considerable period of time (e.g., Betts et al. 1996; Betts 2003, 2004; Dirmeyer et al. 2006; Betts 2009; Santanello et al. 2009; Betts and Silva Dias 2010). Given the sustained interest by the scientific community in regards to the impacts of land–atmosphere interactions on both the climate and the hydrologic cycle, this focus is likely to remain for the foreseeable future.

The ARM Program has played an important role in the research community by collecting data relevant for understanding land–atmosphere interactions and by supporting research efforts designed to address questions related to the coupling of land and atmosphere. At the start of the ARM Program, Stokes and Schwartz (1994) listed three different projects that were related to land surface processes: point–area relationships for global climate modeling led by Chris Doran; area-representative estimates of surface heat flux led by Richard Coulter; and remote sensing of surface fluxes important for cloud development led by Fairley Barnes. Two additional projects related to boundary layer clouds were led by Steve Ghan and the team of Ronald Stull (of which the lead author of this chapter was a member). The ARM Program’s research efforts have since grown from these original projects to include diverse teams of scientists working at National Laboratories, academia, and private industry. Most of this chapter will focus on two research areas in which the ARM Program has made significant progress:

- Understanding the impact of small-scale variations in the surface fluxes, how these variations should be represented in large-scale atmospheric models, and land-use-induced circulation patterns driven by differential land use.
- Determining how to properly represent subgrid variability in the planetary boundary layer and how that variability is related to the onset and maintenance of boundary layer clouds.

While the central focus of this chapter is on these two areas, significant progress has been made in understanding several other important atmospheric processes including understanding the amount of downwelling radiation at the surface and the surface albedo, understanding the carbon cycle, and evaluating a wide range of atmospheric and coupled land–atmosphere models. These latter topics will be covered in a more abbreviated fashion.

2. Relevant ARM instrument systems

The ARM Program deployed several critical instrument systems to enable studies related to land–atmosphere
interactions. Often, these instrument systems are not as high profile as other systems, but they form the basis of many of the results presented in the rest of this chapter. Measurements of the most relevant properties (e.g., surface sensible and latent heat fluxes, soil surface heat flux, soil moisture, near-surface air temperature, and humidity) are made using a suite of instrument systems deployed at extended facilities around the primary central facility of each site [e.g., the Southern Great Plains (SGP); Sisterson et al. (2016, chapter 6)]. The Surface Meteorological Observations Systems (SMOS), later called Surface Meteorological and Temperature Systems (SWATS). While networks of surface measurements are relatively common, measurements of soil moisture profiles through the root zone are not common. The SWATS are collocated with the other ARM surface observations to enable measurement of the impact of soil moisture on the surface energy budget (e.g., Schneider et al. 2003). These measurements are used in a number of the studies identified in the next section and can be used to evaluate land surface and fully coupled models. Soil moisture measurements can be used to nudge model simulations, enabling researchers to more easily evaluate the representation of other processes in models. One example is the work of Berg and Zhong (2005), who used ARM-observed soil moisture measurements to adjust modeled soil moisture, so that the parameterization of the surface fluxes used in the model could be evaluated.

In addition to the routine measurements at the ARM sites, intensive field studies have been a hallmark of the program from its initiation. During the summer of 2007, the ARM community performed a major field study with the goal of better understanding land surface interactions and boundary layer clouds. This study was called the Cloud and Land Surface Interaction Campaign (CLASIC; Miller et al. 2007). The study used a suite of seven research aircraft as well as enhanced surface measurements to investigate the links between surface properties, the thermodynamic state of the atmosphere, and summertime, fair-weather clouds. Additional measurements made during CLASIC included passive and active remote sensing retrievals of soil moisture that were made from one of the research aircraft (Bindlish et al. 2009). Additional measurements were made during the DOE Atmospheric Science Program (ASP) Cumulus Humilis Aerosol Processing Study (CHAPS; Berg et al. 2009).

3. Improving our understanding of the land surface and its impact on weather and climate

a. Local- and regional-scale fluxes

Scaling point measurements of the surface sensible and latent heat fluxes up to larger spatial/temporal
scales has remained an important challenge in climate science (e.g., Sellers et al. 1995). The issue can be divided into two aspects: estimating the grid-scale flux, and the relative importance of subgrid variability of the flux and small-scale circulations that could be introduced by surface heterogeneity.

In practice, two different methods can be used to determine average regional-scale fluxes, either by scaling up based on the application of boundary layer scales (e.g., Brutsaert and Kustas 1987; Sugita and Brutsaert 1990) or based on the conservation of scalars within the boundary layer (e.g., McNaughton and Spriggs 1986). ARM SGP measurements have been used for a large number of studies, because of the extensive distribution of surface stations and surface flux measurements. Stull (1994) proposed a new method to represent the surface fluxes by using a “buoyancy velocity scale” that could be applied in cases with very small mean wind speeds, a case when traditional bulk parameterizations fail. This method improved the simulation of the surface fluxes relative to the measurements. This work was extended by Xu et al. (1999) with the addition of two new constraints: the inclusion of 1) standard deviation of the wind and temperature and 2) soil moisture and a simple soil–vegetation model. The model was further refined by Zhou and Xu (1999) to retrieve soil moisture and surface skin temperature. The SGP 1997 Hydrology Experiment was an ARM-supported field study that included a component related to the computation of regional-scale fluxes. In their work, Peters-Lidard and Davis (2000) used the conservation approach and compared their results to surface flux measurements made across the SGP site. They found good agreement between the estimated and measured sensible heat flux (Fig. 23-1) for periods in which mixed-layer depth was sufficiently shallow that it could be sampled with a tethersonde system.

Simplified models can also be used to gain insight into the effect of soil moisture on regional-scale fluxes. Santanello et al. (2007) used ARM radiosonde and surface flux measurements in conjunction with a one-dimensional atmospheric model to investigate the effect of soil moisture on a number of different boundary layer variables. This led to a methodology for describing the regional-scale fluxes. Based on their analysis they described two limiting cases: instances where conditions...
are limited by the thermodynamic properties of the atmosphere and instances where conditions are limited by soil properties. In the case defined as atmosphere limited, they found a strong relationship between soil water content and sensible and latent heat fluxes only when the soil water content was less than 10%. For greater soil water content they found that the correlation was much weaker. They postulated that this weaker correlation was the result of an essentially unlimited supply of water at the surface, plus the balance of moistening of the boundary layer by surface evaporation and drying by entrainment of dry air from aloft.

b. Land-use-induced circulation patterns

Prior to 1995, it was speculated that a heterogeneous landscape with a pattern of alternating land use and soil moisture, such as broad bands of alternating crops, could give rise to organized mesoscale circulations. It was thought that accurately accounting for the subgrid spatial variability of surface fluxes could be important for climate simulations (e.g., Anthes 1984; Ookouchi et al. 1984; Yan and Anthes 1988; Pinty et al. 1989; Pielke et al. 1991; Avissar and Chen 1993). In this conceptual model, alternating bands of convection are expected to form over relatively moist areas (Fig. 23-2), similar to the circulation patterns associated with sea-breeze circulations common around oceans or large lakes. In their work, Avissar and Chen (1993) pointed out that atmospheric models in use at that time did not account for subgrid mesoscale circulations that could develop as a result of differences in land use within the model grid box. However, the majority of these studies were based on model simulations of an idealized atmosphere.

With early support from the ARM Program, Doran et al. (1995) conducted a field study over eastern Oregon, in an area with an alternating patchwork of native semiarid steppe and irrigated farmland, to investigate the nature of induced circulations in the real atmosphere. While not one of the official ARM sites, this area appeared ideal for investigating mesoscale flows because of the small amount of annual rainfall in the Columbia basin and the large extent of irrigation. During the course of the study, they measured sensible heat flux over nonirrigated steppe that was a factor of 4 greater than was measured over irrigated fields. Their work focused on two case studies with different ambient wind speeds. For the case with relatively weak ambient wind speeds (4–7 m s\(^{-1}\)) evidence of a local circulation was observed, while for the case of moderate wind speed (7–10 m s\(^{-1}\)) no local circulations were observed. These results led them to conclude that advection and large-scale forcing play a key role in the formation of local circulations. To investigate further, Zhong and Doran (1995) conducted additional analyses, including running a suite of simulations using the Regional Atmospheric Modeling System (RAMS) model. The simulations included several different cases: simulations with real topography and land use, simulations with real topography and uniform land use, uniform topography and real land use, and uniform topography and land use. An example simulation is shown in Fig. 23-3, which highlights regions of confluence and diffluence within the model domain. Based on the observations and simulations, they concluded that while local circulation

![Fig. 23-2. Anticipated effect of bands of vegetation and dry soil in a semiarid region. Changes in the effect, either positive or negative, are indicated by the pluses or minuses. [Courtesy of Anthes (1984).]](unauthenticated|downloaded 06/28/24 08:24 PM UTC)
patterns are possible, they can be masked by the complex interplay of advection, large-scale subsidence, and shear-generated turbulence.

The deployment of ARM instruments at the SGP site, as well as advances in regional-scale land surface models, provided the opportunity to investigate the role of land-use differences in the development of local-scale circulations over the SGP. During the summer of 1996, a field study was conducted (Hubbe et al. 1997) to investigate local-scale circulations over the SGP region. This study included additional radiosonde launches at three additional sites, each approximately 150 km from the central facility: Elk Falls, Kansas; Meeker, Oklahoma; and Plenva, Kansas (Fig. 23-4). These locations were selected because of the differences in land use between them. In addition to the surface flux measurements and the calculation of the fluxes from changes in the thermodynamics profile, the Simple Biosphere Model (SiB2; Sellers et al. 1996) was used to estimate surface fluxes over the entire SGP site. Two days (7 and 12 July 1995) were selected because of large contrasts in the surface flux measurements between locations (Fig. 23-5), which ranged from approximately 600 W m$^{-2}$ near the central facility, to near 0 W m$^{-2}$ in the northeast corner of the domain. Based on their findings, Hubbe et al. (1997) concluded that local-scale circulations were nonexistent during their study period. In additional simulations of the same field study using RAMS driven with surface fluxes generated by SiB2, Zhong and Doran (1998) showed that the perturbations to the velocity field associated with land-use-induced circulations were quite small, on the order of 1 m s$^{-1}$ in the northeast corner of the domain (cf. an ambient flow of approximately 4 m s$^{-1}$; Fig. 23-6). They also found that the spatial variability of surface fluxes did not have an impact on the average temperature and humidity profiles calculated over spatial scales representative of a global climate model (GCM) grid box. As part of their study, they repeated the analysis using an idealized checkerboard pattern for representing the surface fluxes and different ambient wind speeds. They obtained similar results; the subgrid land-use pattern did not have a significant impact on the average fluxes.

c. Variability in the planetary boundary layer and boundary layer clouds

By their nature, atmospheric models predict the gridbox mean values of temperature and moisture. Within the convective planetary boundary layer (PBL), however, there can be significant horizontal variability, even at small spatial scales. The subgrid variability is thought to be very important for determining the onset of boundary layer clouds (e.g., Wilde et al. 1985). Using data from the Hydrologic Atmospheric Pilot Experiment (HAPEX), Schrieber et al. (1996) presented joint frequency distributions (JFDs) of temperature and humidity and found that their size and shape could be related to the underlying surface properties. For long flight
legs, the JFDs were quite complicated, but when the flight pattern was broken up by land-use type, the observed JFDs were monomodal and better behaved (Fig. 23-7). Their worked stopped short of developing a parameterization for the size and shape of the JFDs that could be derived from atmospheric models. Stull’s research team addressed this issue by relating the size and shape of the distributions to the jump in temperature.

Fig. 23-4. Map of the SGP ACRF as it was configured during the study of Hubbe et al. (1997), showing the location of ACRF extended facilities, Oklahoma and Kansas State Mesonets, and NWS sites. Winds were only measured at the indicated sites and extra radiosondes were launched from Plevna and Elk Falls, KS; and Meeker, OK. [Courtesy of Hubbe et al. (1997).]

Fig. 23-5. Spatial distribution of sensible heat fluxes over the SGP ACRF, calculated using the SiB2 model at 1300 LST 7 and 12 Jul 1995. [Courtesy of Hubbe et al. (1997).]
and moisture at the surface and at the top of the PBL (Berg and Stull 2004). Their conceptual model is shown in Fig. 23-8 for a JFD of potential temperature $\theta$ and water vapor mixing ratio $r$. A number of different processes act to change the mixed-layer mean values of $\theta$ and $r$, including the surface fluxes, entrainment flux at the boundary layer top, and advection. Equipped with data collected during Boundary Layer Experiment 1996 (BLX96) using a research aircraft over the SGP site (Stull et al. 1997), they used their new method to represent the size and shape of the JFDs as a function of height within the PBL (Fig. 23-9).

Distributions such as these were related ultimately to the formation of boundary layer clouds by Berg and Stull (2005) with their development of the Cumulus Potential (CuP) scheme for shallow clouds. They used the JFDs of $\theta$ and $r$ to define the distribution of thermodynamic properties in the mixed layer. In their scheme, the virtual potential temperature $\theta_v$ is compared to the mixed-layer mean value of $\theta_v$ to determine which parcels rise. Of the parcels that rise, those that reach their lifting condensation level ($z_{LCL}$) will form clouds. The cloud fraction is computed as a function of the fraction of parcels represented by the JFD that form clouds, the cloud-base height is the height of the $z_{LCL}$, and the cloud-top height is determined by the altitude at which the clouds reach their level of neutral buoyancy. Their parameterization was consistent with the results of Zhu and Albrecht (2002), who reported that the formation of the shallow clouds was a complicated function of processes within the boundary layer, including the fluxes at the top of the convective boundary layer.

Other ARM-supported studies included efforts to evaluate the performance of large-eddy simulation (LES) models and their simulation of boundary layer clouds. In intermodel comparisons of an idealized case of shallow boundary layer clouds over the SGP, Brown et al. (2002) found that subcloud conditions simulated by various LES models agreed well with standard boundary layer scales. They also pointed out the important impact of cloud-layer stability in the formation and maintenance of cloud fields. Using data from the same case study, Neggers et al. (2004) evaluated the mass flux closure scheme using both an LES and a single-column model to help understand the inner workings of the respective models.

Other researchers have focused on the formation of nocturnal stratus clouds over the SGP site. Zhu et al. (2001) used LES to investigate the role of turbulence in the formation of nocturnal clouds. They found that the height of the lifting condensation level and the critical level, which they defined to be a function of the Monin–Obukhov length, could be used to help define the onset of clouds.

d. Carbon cycle

Given its location in the central United States, and long-term record of a wide range of meteorological parameters, the SGP site has attracted the attention of scientists interested in the carbon cycle, including the exchange of carbon at the surface and at the top of the planetary boundary layer. Since 2001, the ARM Carbon Project has been conducted by scientists from Lawrence Berkeley National Laboratory (LBNL). This effort has included both surface measurements (Billesbach et al. 2004) and a unique long-term airborne component operated in collaboration with aerosol measurements made by scientists from the National Oceanic and Atmospheric Administration (NOAA) Earth System Laboratory (Andrews et al. 2004; Biraud et al. 2013). Rather than the short-duration aircraft studies commonly used in atmospheric research, the LBNL and NOAA groups utilized a small single-engine aircraft that could be operated on a regular schedule (biweekly weather conditions allowing) from the Ponca City, Oklahoma, airport. This type of deployment is unique, and at the time the program started, it was the only such effort over the central United States. Two different measurement systems have been deployed during the course of the study: a flask-based system to measure bulk CO$_2$ properties along horizontal flight legs; and starting in June 2007, a continuous CO$_2$ analyzer (Biraud
et al. 2013). The long-term measurements show a systematic increase in CO$_2$ concentration over the SGP ACRF, as well as a strong seasonal cycle (Fig. 23-10). Figure 23-10 indicates more variability in CO$_2$ concentration within the PBL than above it, which is consistent with the turbulent nature of transport within the PBL. Fischer et al. (2007) used surface measurements from near the SGP Central Facility to document the effects of crop type, land use, and soil moisture on the carbon exchange for the land types that were included in their study.

e. Model evaluation

Long-term, high-quality measurements of surface sensible and latent heat fluxes over a wide geographic area are relatively rare. The data collected by the ARM Program helps to fill this void and has been used by several researchers to evaluate the performance of mesoscale atmospheric models. Some of these (e.g., Oncley and Dudhia 1995; Berg and Zhong 2005) focused directly on the ability of regional-scale models to predict the surface fluxes. Oncley and Dudhia (1995) showed that the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5), when using the Blackadar boundary layer scheme, could successfully predict the surface fluxes if the correct values of surface roughness and soil moisture were used. Berg and Zhong (2005) also used MM5 and evaluated the surface fluxes predicted by...
three different turbulence parameterizations, including both local turbulence kinetic energy (TKE)-based schemes and nonlocal parameterizations designed for convective conditions. In addition to the ARM surface flux measurements, they also used airborne observations to evaluate the fluxes aloft and the PBL depth. They found that while the modeled latent heat fluxes agreed reasonably well with measurements, sensible heat flux was overestimated because of an overestimate of net radiation (Fig. 23-11). Cooley et al. (2005) used MM5 coupled with the Land Surface Model 1 to investigate the impact of the winter wheat harvest in the region around the SGP site. They found that an early wheat harvest, indicative of warmer and dryer conditions, produced a positive feedback on the climate system and even more drying.

Other studies have focused on the representation of the linkages between the land or ocean and the atmosphere in GCMs. Sud et al. (2001) used measurements from the SGP site to evaluate the Goddard Earth Observing System (GEOS-2) GCM single-column model. They investigated linkages between surface properties and rainfall, and precipitation recycling. Dirmeyer et al. (2006) evaluated the performance of 12 different climate models in regards to the simulation of the surface fluxes using measurements from the SGP, a flux site at Bondville, Illinois, and a number of surface stations located in Europe. They found that the individual models often did a poor job of simulating the surface fluxes and soil moisture.

More recently, SGP measurements have been used to evaluate land–atmosphere interactions in cloud-resolving models (CRMs). Zeng et al. (2007) compared results from two-dimensional and three-dimensional CRMs. Their study was unique because of the relatively long 20-day simulation periods and the detailed attention that was paid to the land surface model. They found that the treatment of the damping of the vertical velocity in the two-dimensional models was suspect, leading to rapid changes in the surface precipitation and unrealistic drying aloft compared to the three-dimensional simulations.

f. Surface radiation

The ARM Program has made important contributions to the understanding of radiative transfer within the atmospheric column, as described in detail in McFarlane et al. (2016, chapter 20). For land–atmosphere interactions,
the focus is primarily on issues related to the surface energy budget and the surface albedo. In most cases, the majority of solar radiation is absorbed at the surface, making our understanding of the amount of downwelling radiation and the surface albedo critical to our interpretation of the surface energy budget and the partitioning of sensible, latent, and soil surface heat flux. The normalized difference vegetation index (NDVI), which is computed using radiances measured in the near-IR and visible parts of the spectrum, is a commonly used metric that provides information about the leaf-area index, biomass, and other land-use parameters. Gao et al. (1998) used NDVI to estimate the surface roughness in their model Parameterization of Subgrid-Scale Processes (PASS). Regional-scale sensible and latent heat fluxes were derived and were compared to the SGP EBBR surface flux measurements.

SGP measurements have been used to evaluate the impact of solar zenith angle on the surface albedo and to examine the assumption that the albedo is only a function of the solar zenith angle, and not other surface properties. Using surface, as well as satellite measurements, Minnis et al. (1997) found that surface albedo was consistently greater in the morning than was observed during periods in the afternoon with the same solar zenith angle. This result was attributed to dew on the surface in the morning (Fig. 23-12). In subsequent work, Yang et al. (2008) used measurements collected at the SGP and Tropical Western Pacific (TWP) sites, in addition to NOAA SURFRAD sites, to derive the surface albedo from the Moderate Resolution Imaging Spectroradiometer (MODIS) using parameters commonly applied in models, including those from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS). In contrast to the results presented by Minnis et al. (1997), they found that the albedo was not always higher in the morning (Fig. 23-13). They offered several possible explanations for the difference in results, in particular that the data record they used was significantly longer (ranging from 2 to 8 years depending on the location) than was available to Minnis et al. (1997), Gao et al. (1998) identified biases in the MODIS data products and suggested that it is possible to parameterize the albedo only as a function of the solar zenith angle, while ignoring the land cover (assuming that the surface is snow free). The contrasting results found when using short-duration versus long-duration data records prove the value of long-term deployments like those associated with the ARM Program.

g. Results from beyond the SGP

While the majority of the results presented in this chapter are focused on the SGP site, other ARM-supported research efforts related to land–atmosphere interactions have been conducted at the TWP and North Slope of Alaska (NSA) sites as well as at deployments of the ARM Mobile Facility (AMF), which was first deployed at Pt. Reyes, California, during 2005.

The TWP sites included the deployment of measurement systems at a number of remote island locations. When using data collected at these sites, it is important to understand the impact of the island on both the in situ and remote sensing measurements as well as on the populations of clouds themselves (e.g., McFarlane et al. 2005). These efforts are described in detail in Long et al. (2016, chapter 7), and the interested reader should review that chapter to understand the important progress that has been made for these sites.

The development of the AMF marked an opportunity to examine the coupling of land and atmosphere at sites well removed from the fixed ARM sites. The Convective and Orographically Induced Precipitation Study (COPS; Wulfmeyer et al. 2011) focused on improving our understanding of precipitation in regions of complex terrain and included the deployment of the AMF to the village of Heselback in the Murg Valley of Germany. Using soil moisture data collected at 47 stations within the COPS domain, Hauck et al. (2011) showed that the model they applied generally had a dry bias. They documented that the bias has a large impact on the simulated precipitation, although no systematic relationships were found. Similar results were reported by Barthlott and Kalthoff (2011), who found consistent changes in the near-surface moisture and latent heat fluxes, but only saw a systematic increase in precipitation for simulations that were relatively dry.

ARM-supported research has demonstrated that land–atmosphere coupling is important in the Arctic, and it can have a measurable impact on boundary layer clouds. Using data from the microwave radiometers (MWRs) deployed at Barrow and Atqasuk, Alaska, Doran et al. (2002) showed that the cloud liquid water path (LWP) associated with low clouds was generally
larger near the ocean at Barrow than 100 km inland at the Atqasuk site, but this relation was a function of the month. They also compared the ARM observations to simulations using the European Centre for Medium-Range Weather Forecasts (ECMWF) model and found that the model had a dry bias in regards to relative humidity and tended to underpredict the cloud LWP (Doran et al. 2002). This work was extended to include a multiyear study period, and an analysis of the cloud optical depth by Doran et al. (2006). In contrast to their earlier study, they found that the clouds at Atqasuk had a larger optical depth and cloud LWP for cases with onshore flow. They attributed this behavior to an increase in the sensible and latent heat fluxes associated with air parcels moving inland over the relatively warm tundra.

4. Looking to the future

The focus of this chapter has been an overview of research conducted prior to the merger of the ASP and ARM Science Programs into the Atmospheric System Research (ASR) Program (Mather et al. 2016, chapter 4). While the ASP and ARM Science Programs led to significant advances and increases in our scientific understanding, they do not mark the end of studies of land–atmosphere interactions supported by the ARM Program. Research related to land–atmosphere interactions
has continued and more recent research has made use of a range of old and new ARM data streams to address relevant science questions.

One major focus of recent ASR research has been to improve our understanding of the life cycle and impact of boundary layer clouds. Using radiometric measurements from the SGP site, Berg et al. (2011) documented the impact of shallow clouds on the surface energy budget and found that the radiative forcing at the surface associated with shallow cumuli was $-45.5 \text{ W m}^{-2}$ (out of $612 \text{ W m}^{-2}$ estimated for clear-sky conditions). Measurements from the ARM cloud radar and micro-pulse lidar has been combined into the active remotely sensed clouds locations (ARSCL) data product developed by Clothiaux et al. (2000). This product has been used to investigate the diurnal macrophysical properties (cloud cover, cloud-base, and cloud-top heights) of fair-weather cumuli (Berg and Kassianov 2008). Using measurements from ARM instrument systems, Zhang and Klein (2010) documented systematic differences in the thermodynamic structure of the atmosphere associated with the transition from shallow to deep convection. Measurements from the SGP have been used to document improvements in the prediction of shallow cumuli. Berg et al. (2013) showed significant improvement in the forecast of downwelling shortwave.
Fig. 23-13. Surface shortwave albedo as a function of solar zenith angle measured at ARM and SURFRAD stations. [Courtesy of Yang et al. (2008).]
irradiance in the regional-scale Weather Research and 
Forecasting (WRF) Model using an improved parameteri-
zerization for shallow clouds.

Other efforts have focused on improving our un-
derstanding of the hydrologic cycle and the balance
between evapotranspiration and precipitation, com-
monly called precipitation recycling. Precipitation
recycling is defined as precipitation within a domain
of interest that originates from evapotranspiration rather
than through transport through the sides of the control
volume (e.g., Trenberth and Guillemot 1998). Lamb
et al. (2012) used measurements and reanalysis products
to document the relative importance of precipitation
recycling for years that were both very wet (as was ob-
served during the CLASIC field campaign in 2007) and
very dry. They found that, with the exception of the very
wet conditions during the CLASIC period, precipitation
is smaller than evapotranspiration and that the differ-
ence in them was balanced by horizontal moisture flux
divergence within the control volume over the SGP. In
contrast, during the CLASIC year, precipitation was
greater than evapotranspiration. One important change
in land use in the central United States has been an in-
crease in the use of irrigation on agricultural land. Irri-
gation adds moisture to the surface, and leads to a
decrease in the Bowen ratio, but many modeling studies
currently ignore this potentially important moisture
source. To address this shortcoming, Qian et al. (2013)
implemented a simple representation of irrigation in
WRF and simulated the water budget and water re-
cycling for the same periods analyzed by Lamb et al.
(2012). They documented changes in the simulated
surface sensible and latent heat fluxes, PBL height, and
$z_{LCL}$, but found no systematic change in the simulated
precipitation.

5. Conclusions and summary

Throughout its history, the ARM Program has sup-
ported, via the collection of detailed datasets and the
direct support of research scientists, a wide range of
projects aimed at improving our understanding of land–
atmosphere interactions. In this chapter, we have fo-
cused on two specific scientific areas for which signifi-
cant progress has been made: understanding the
importance of small-scale variations of surface fluxes
and how best to scale those variations up from point
measurements to the model grid scale, and un-
derstanding the role of subgrid variability on the initia-
tion and maintenance of shallow clouds. Results showed
that much of the details of the small-scale variability of
the surface fluxes, such as spatial variability in the grid
box, can be ignored within the context of large-scale
models. The subgrid variability plays a role in the for-
mation of clouds, but the research supported by the
ARM Program indicates that it is sufficiently repre-
sented by using probability density functions (PDFs).
The PDFs have been related to the grid-resolved vari-
ables through the development of new parameteriza-
tions. Other important areas of study, such as
understanding the CO$_2$ cycle, the detailed evaluation of
models (including land surface models), and the best
methods for representing the surface albedo also were
discussed briefly.

After the merger of the ASP and ARM Science Pro-
grams into ASR, research related to land–atmosphere
interactions has continued, but with a renewed focus on
the various aspects of boundary layer clouds, including
their radiative impact, their macrophysical properties
derived from a suite of remote sensing instruments, their
formation, and the transition from shallow to deep
convection. Long-term studies also have focused on
precipitation recycling using measurements and re-
analysis products, and have documented the effect of
irrigation on surface sensible and latent heat fluxes, PBL
height, and $z_{LCL}$. While important progress has been
made in these areas of study, significant hurdles remain,
and research related to land–atmosphere interactions
will likely continue well into the future.

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