1. Introduction

The European Centre for Medium-Range Weather Forecasts (ECMWF) is one of the leading centers in operational global numerical weather prediction (NWP) and provides forecasts for days to monthly and seasonal time scales across a range of resolutions. Parameterization of subgrid physical processes are a key part of the model [the Integrated Forecast System (IFS)] and, for global application, must be appropriate for all meteorological regimes and regions across a wide range of spatial and temporal scales. The parameterizations of cloud, precipitation, and radiation and their interactions are of particular importance for the effects on atmospheric heating and cooling, the hydrological cycle, and the dynamics of the atmosphere. To make progress and continue to increase the accuracy of model forecasts for NWP and longer time scales (model climate), a wide range of observations is required for evaluation of model systematic errors and for inspiring innovative developments to model parameterizations.

The ARM Program historically has played a key role in all of these areas. There are many examples where the ECMWF model has benefitted from comparison with ARM observations from the Arctic, midlatitudes, and tropics over the past two decades (e.g., Mace et al. 1998; Morcrette 2002b; Comstock and Jakob 2004; Tselioudis and Kollias 2007; Klein et al. 2009; Agustí-Panareda et al. 2010), as well as for exploration of new data assimilation techniques (Lopez et al. 2006). Cheinet et al. (2005) performed an evaluation of the ECMWF model at the ARM Southern Great Plains (SGP) site, which provides an example of how the comprehensive instrumentation, high-quality data, and extensive temporal coverage of ARM site data can characterize deficiencies in the model and give insight into potential model parameterization improvement. Not every aspect of ARM’s impact on NWP at ECMWF can be covered in detail here. The focus of this chapter is therefore to relate three primary examples of model innovation, parameterization development, and evaluation at ECMWF that were directly motivated and facilitated by the ARM Program:

1) the development of an innovative boundary layer parameterization,
2) the operational implementation of new accurate and efficient radiation parameterizations, and
3) a process-oriented model evaluation with ARM observations to guide development of cloud and radiation parameterizations.

All three areas have contributed to the ongoing drive for improvement of the ECMWF model in medium-range weather forecasting. Readers interested in ECMWF operational model changes beyond the scope of this paper are referred to the ECMWF web page (http://www.ecmwf.int/en/forecasts/documentation-and-support/changes-ecmwf-model) for a brief summary of model cycles and links to further information.

2. Boundary layer parameterization innovation inspired by ARM observations

a. Background

The first generation of boundary layer schemes in global climate models (GCMs) were designed to
reproduce the first-order impact of unresolved turbulence and convection on the vertical transport of heat, moisture, and momentum and their contribution to fractional cloudiness and condensate. This approach has led to demonstrable improvement in weather and climate predictions (e.g., Tiedtke 1989). The initial success inspired the further sophistication and development of these boundary layer schemes. Typically, schemes were developed and tested for certain cases based on relevant observational data obtained during meteorological field campaigns (e.g., Holland and Rasmusson 1973; Yanai et al. 1973). An often-applied technique in model development has been the time integration of the suite of subgrid parameterizations in a single-column model (SCM) in an offline, “isolated” mode, using prescribed large-scale forcings and boundary conditions (Randall et al. 1996). The absence of interaction with the larger scale simplifies the model analysis, giving insight into the behavior of parameterizations at process level.

The advent of large-eddy simulation (LES; e.g., Sommeria 1976) has enhanced the opportunities for the evaluation and development of boundary layer parameterizations significantly. In pre-LES days, progress in model development was often hampered by lack of key observations of small-scale variability related to turbulence and clouds. The capability of LES to provide four-dimensional fields (in space and time) at high turbulence- and cloud-resolving resolutions has now been demonstrated and implies that it can act as a virtual laboratory, giving access to relevant data for parameterization development at a level that is still unprecedented and unmatched by present-day instrumentation. LES simulations can thus “fill the gap” in the instrument coverage of key parameters.

Together, the SCM and LES can form a powerful set of tools in parameterization development. A continuing effort to combine both techniques has been applied by the Boundary Layer Working Group (BLWG) of the GEWEX Cloud System Studies (GCSS). Their strategy has been to bring together the international boundary layer modeling community by organizing model intercomparison studies for SCM and LES. Observational datasets have played a key role in this process 1) for building “prototype” cases for boundary layer regimes that still provide challenges for boundary layer schemes in GCMs and 2) for confronting SCM and LES results on turbulent transport and clouds. To this purpose, “golden days” were identified at some locations of interest where relevant measurements were available.

Many of the first prototype intercomparison cases focused on marine quasi-steady-state boundary layers. The assumption of a balanced prognostic budget allows application of equilibrium assumptions, which could be powerful tools for the modeler as they might enhance numerical model stability. Also, because the boundary layer does not change fundamentally in time, the tendency has been to design schemes in such a way that different modes or regimes are represented by unique combinations of hard-coded settings. In practice, this has led to the representation of separate convective boundary layer regimes by means of separate schemes; examples are the dry convective boundary layer, the stratocumulus-capped boundary layer, and shallow-cumulus-capped boundary layer. Examples of past GCSS intercomparison studies on steady-state cases are those based on the Barbados Oceanographic and Meteorological Experiment (BOMEX) (Siebesma et al. 2003) and the Atlantic Tradewind Experiment (ATEX; Stevens et al. 2001) field campaigns.

b. The ARM case

Compared to steady-state situations, the case of a boundary layer over land represents a much more difficult situation for parameterization schemes. The reason is that the convective boundary layer is highly transient, experiencing a diurnal cycle of initiation at sunrise, growth or deepening during the day, and decay at sunset when the surface-driven turbulence dies out. In this daily life cycle, the boundary layer can experience a series of transitions between separately defined regimes as mentioned above. The GCSS BLWG case based on ARM observational data for 21 June 1997 at the SGP site was developed to address the question of how both LES and SCM perform for this situation (Brown et al. 2002; Lenderink et al. 2004). Figure 28-1 presents some measurements and LES data to highlight the key aspects of the boundary layer on this day. Since its formulation, this case has become used so frequently as a testing ground for model development that within the community it is often simply referred to as “the ARM case.”

One of the main results of the GCSS intercomparison study on the ARM case showed that while LES codes agree reasonably well on the vertical structure and time development of the thermodynamic and cloudy state of the cumulus-capped boundary layer (Brown et al. 2002), the participating SCMs have problems reproducing these LES results (Lenderink et al. 2004). For example, Fig. 28-2 illustrates the significant scatter that exists among SCM codes for the total cloud cover. For some SCM realizations, the oscillations were linked to the occurrence of discrete transitions between regimes, as a result of the use of separate schemes for different boundary layer regimes in the GCM. These artificial transitions can then lead to unrealistic, often numerical, instability.
The poor SCM performance for the transient ARM case has motivated a structural rethink of the design of boundary layer schemes in the last decade. In particular, it has driven a move toward model unification; this is the idea that all regimes are represented by a single, internally consistent conceptual model, which is theoretically and practically capable of representing smooth transitions in response to smooth variations in the applied forcing. Operational forecast centers such as the ECMWF can provide a rigorous testing ground for new parameterizations as the model is confronted continuously with observations during data analysis, thus maintaining a model state close to reality. This allows a direct, day-to-day comparison between modeled clouds and observations such as those from the ARM sites. Forecast scores also routinely provide an objective measure of overall model performance to complement more process-oriented model evaluation.

c. An innovation for boundary layer parameterization

The boundary layer schemes in most operational GCMs are at the core formulated in terms of only two basic models for vertical transport. These are the eddy diffusivity (ED) model and the mass flux (MF) model. While the ED model represents small-scale motions that transport properties exclusively in the downgradient direction, the MF model has an advective nature and can transport properties against gradients. In the IFS these two models are combined into a single framework, named EDMF (Siebesma and Teixeira 2000), in which
the volumetric turbulent flux of a property $\phi$ that is conserved for moist adiabatic ascent is formulated as

$$\overline{w'\phi'} = -K \frac{\partial \phi}{\partial z} + \sum_{i=1}^{I} M_i (\phi_i - \overline{\phi}),$$

(28-1)

where $K$ is the eddy diffusivity coefficient, $M_i$ is the volumetric mass flux of an updraft $i$, the overbar indicates the gridbox mean, and $I$ is the number of updrafts that are explicitly modeled by the mass flux approach (Neggers et al. 2009).

In most mass flux schemes to date, only one advective updraft is modeled ($I = 1$), argued to represent the total transport done by all unresolved updrafts within the gridbox. This effective updraft is commonly referred to as the “bulk” updraft. For (quasi) steady-state situations, in which the ensemble of (cloudy) updrafts does not change that much in time, this choice could be defended; the constants of proportionality applied in the parameterization of the amplitude and vertical structure of the updraft-related terms in Eq. (28-1) might be representative within a single regime. However, the GCSS intercomparison study on the ARM case emphasized that in a transient situation, like the diurnal cycle over land, the ensemble of updrafts can change significantly in time. Starting out as a completely dry collection of thermals the ensemble experiences partial condensation later in the day, the degree of which in itself is highly time dependent (Neggers et al. 2009). One wonders if the number of degrees of freedom provided by the single bulk updraft limit of Eq. (28-1) is actually too small to allow a parameterization to capture this gradual variation.

The goal of this ARM-funded project was to address this problem by revisiting the basic design of the EDMF boundary layer scheme, in particular the number of degrees of freedom included. The approach was guided by the following basic question: What is the minimum level of complexity required in a mass flux scheme to enable the representation of the major convective boundary layer regimes, including potentially smooth transitions between them?

When external forcings vary smoothly in time, any transitions between regimes also should evolve smoothly, and ideally a scheme should be able to reproduce this for the right reasons. As argued by Neggers et al. (2009), a unified representation of all boundary layer regimes by a mass flux scheme can be achieved by expanding the number of updrafts in Eq. (28-1). On the other hand, the limited computational efficiency of supercomputers still constrains this number. For these reasons, a dual mass flux (DualM) configuration is proposed, as schematically illustrated in Fig. 28-3a. This configuration contains two transporting bulk updrafts: one representing all dry thermals and the other all moist (i.e., cloudy) thermals. Flexibility is introduced by assigning flexible weights to each updraft category (see Fig. 28-3b). This in principle enables a gradual onset and decay of the two main updraft modes, as well as their simultaneous coexistence. It can be argued that this configuration allows the representation of transport in

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**Fig. 28-2.** The cloud cover as produced by various SCM simulations for 21 June 1997 at the ARM SGP site. The LES results are included for reference (solid black line). Note that local time at the SGP site lags UTC time by 6h. Figure reproduced from Lenderink et al. (2004), copyright Royal Meteorological Society (RMETS). Reproduced with permission of John Wiley and Sons Ltd. on behalf of the RMETS.
well-mixed boundary layers as well as internally decoupled boundary layers and transitions between the two.

Figure 28-4 shows SCM results with the DualM setup of the EDMF for the ARM case. The figure illustrates that key aspects in the time development of the transient cumulus-capped boundary layer are reproduced, such as 1) the development of the moist updraft lifting condensation level and termination height, as well as 2) the total cloud cover. Comparison against the LES shows that the deepening of the cloud layer is well captured by the DualM scheme. Comparison against various available measurements of the cloud cover shows that both the LES and the DualM scheme in the SCM reproduce the gradual decay of cloud cover in the second part of the day; note that the observations of cloud presence between 1400 and 1600 UTC also include some clouds situated at much higher altitudes that were not part of the convective boundary layer.

It is instructive to interpret these results from a broader perspective. The SCM simulations for the ARM case show that a dual bulk-updraft setup of EDMF, including flexible weights, already contains enough degrees of freedom to conceptually enable the simulation of a gradual onset, amplification, and decay of the cloudy (cumulus) part of the updraft ensemble during highly transient situations. This capability is arguably the key element of progress.
introduced by the DualM scheme. There are other situations in which the boundary layer undergoes similar internal transitions between updraft regimes. A good example highly relevant for climate science is the transition within the marine subtropical boundary layer, changing from well mixed and stratocumulus capped to internally decoupled and shallow-cumulus capped (e.g., Albrecht et al. 1995; Bretherton and Wyant 1997). Accordingly, the DualM limit significantly enhances the general applicability of the EDMF approach.

d. Outlook

The ARM Program has played a key role in model development by providing observational datasets that can be used to build prototype cases as well as long time series to test and evaluate new parameterizations for a wide range of situations. Its observational database has been used by international projects such as GCSS to 1) build cases that can act as a testing ground during parameterization development and 2) evaluate schemes and constrain parametric functions. What this ARM-funded project at ECMWF has illustrated is that this strategy can be effective in driving the modeling effort forward, both in a theoretical and applied engineering sense.

The focus on continental transient cumulus cases has forced the modeling community to study more complex situations than considered previously. Transient cases, including the ARM case, have by now become key testing grounds for existing and new parameterization schemes (e.g., Bretherton et al. 1999). The realization that nature seldom behaves like an idealized "golden day" but exhibits great day-to-day variability has motivated the modeling community to move from single case studies to continuous, long-term SCM and LES evaluation (e.g., Jakob 2010; Neggers et al. 2012; Neggers and Siebesma 2013). The benefit of this strategy is that the modeling result maintains its statistical significance, allowing the SCM result to be representative of the full model climate. On the other hand, the strategy still preserves the high model transparency typical of single-case model studies at process level. The continuous and long-term measurements required for this approach are typically provided by the various ARM permanent and Mobile Facility sites established at locations from the Arctic to the tropics considered to represent key regimes in the earth’s climate and make ARM data invaluable for such long-term evaluation studies.

3. Advances in the parameterization of radiation transfer

Radiative transfer calculations are an expensive part of the forecast model in terms of computational cost. Cost-saving compromises such as longer time steps, coarser grid resolution, or limited spectral resolution are often made to cope with the expense of radiative transfer calculations. Thus, the development of faster, yet more accurate methods, to calculate radiative transfer has been and remains an ongoing development effort in GCMs and for the ECMWF IFS global model.

In the late 1990s, an evaluation of the IFS downward longwave radiation with observations from ARM, the Baseline Surface Radiation Network (BSRN), and the National Oceanic and Atmospheric Administration (NOAA) Surface Radiation Network (SURFRAD) sites highlighted systematic model errors present under cloudy as well as clear conditions (Chevallier and Morcrette 2000). Surface shortwave irradiance was overestimated, usually with the error linked primarily to cloudy conditions, while the surface downward longwave radiation was underestimated in clear as well as cloudy conditions. In addition, an increase in vertical resolution from 37 to 60 levels was planned for the IFS. The cost to run the model's emissivity scheme operational at the time (Morcrette 1991) scaled quadratically with the number of model levels; thus leading to an unacceptable increase in computational cost for the envisaged increase in vertical resolution.

a. The Rapid Radiative Transfer Model

The Rapid Radiative Transfer Model (RRTM) developed by Atmospheric and Environmental Research (AER), Inc. (Mlawer et al. 1997, 2016, chapter 15) promised better performance at lower cost. This model is conceptually much more closely related to a line-by-line radiation scheme, has 16 spectral bands (versus 6 in the previous scheme), and the two-stream calculation of the RRTM scales linearly with the number of model levels—an attractive property with the prospect of an increase in vertical resolution. The RRTM’s performance compared favorably with line-by-line radiation models and ARM spectral surface observations (Mlawer et al. 1996). It was tested successfully as a replacement for the longwave radiation scheme in the IFS (Morcrette et al. 1998) and other models (Iacono et al. 2000) and eventually implemented operationally on 27 June 2000. The comparative performance of the old and the new longwave radiation scheme in the IFS was documented in Morcrette (2002a) and showed that the RRTM longwave scheme greatly reduced the surface downward longwave radiation bias under clear-sky conditions.

Further evaluation of the model’s surface radiation was performed at the ARM SGP site (Morcrette 2002b). This study confirmed the good performance of the RRTM longwave scheme for clear-sky and overcast conditions (when cloud base height is predicted correctly), but
highlighted problems in surface shortwave irradiance, which was overestimated under all conditions. The clear-sky bias in surface shortwave irradiance was attributed primarily to a somewhat outdated shortwave parameterization, which slightly underestimated water vapor absorption and did not adequately separate between the UV and visible spectral bands. Inadequate representation of aerosol also was implicated as a secondary factor. Under cloudy conditions, the model's assumed cloud properties, such as a fixed effective radius of 10 m, likely contributed to the model error. To address these issues, the spectral intervals in the shortwave scheme were increased (from 4 to 6), and a slightly more sophisticated diagnostic scheme for liquid effective radius was introduced (Martin et al. 1994).

b. Representing subgrid inhomogeneity: The Monte Carlo independent column approximation

Another challenge in radiative transfer is the representation of cloud inhomogeneity within a model grid box. Initially, radiative transfer was calculated on plane-parallel clouds, ignoring inhomogeneity within a model grid box and layer. Tiedtke's cloud scheme (Tiedtke 1993) used in the IFS accounts for one aspect of cloud inhomogeneity—namely, the partitioning of the model grid box into a cloudy and a clear fraction—with a prognostic cloud fraction variable. However, cloud liquid was assumed initially to be horizontally and vertically uniform within the cloudy part of the grid box, ignoring the natural variability of liquid water content observed in clouds. This plane-parallel homogenous assumption leads to an albedo bias in the radiative transfer calculations (Cahalan et al. 1994, 1995). To account for the albedo bias, a correction factor was introduced in the longwave and shortwave radiative transfer calculations in the operational IFS on 16 December 1997 (Tiedtke 1996) based on Cahalan et al.'s (1994) study of cloud inhomogeneity in stratocumulus clouds. While improving results, this fixed parameter was merely a stop-gap measure, failing to relate to the actually modeled cloudy conditions.

If the variability of the cloud liquid water is known, the albedo bias can be avoided largely by dividing the model grid box into subcolumns, with each subcolumn representing part of the liquid water distribution, and performing radiative transfer calculations for each of the subcolumns [independent column approximation (ICA); Cahalan et al. 1994; Barker et al. 1999], then averaging the result. While accurate, this approach is expensive, increasing the number of radiative transfer calculations by a factor equal to the number of subcolumns chosen.

The Monte Carlo Independent Column Approximation (McICA; Barker et al. 2003; Pincus et al. 2003; Barker et al. 2008), developed as part of ARM-funded projects, offers a less expensive yet elegant solution to this problem (Mlawer et al. 2007, chapter 15). As for the ICA, the grid box is subdivided into independent columns. For each model level, some columns are cloudy and some clear, reflecting the predicted cloud fraction at this level and allowing further sampling of the cloud's water distribution. However, in the McICA approach, spectral intervals also are assigned randomly one per column, and radiative transfer is calculated in a plane-parallel fashion for each column. Thus, the sub-columns collectively sample both the radiation spectrum and the cloud's water distribution at the same time. This elegant approach allows a more physical, situation-dependent representation of cloud inhomogeneity at limited additional expense. The McICA scheme was implemented in the IFS on 5 June 2007 together with the shortwave version of the RRTM (Iacono et al. 2004). This combined radiation upgrade (McRad; Morcrette et al. 2008) improved model performance on shorter and longer time scales (for seasonal/climate applications). The new scheme modified the relative vertical distribution of the shortwave and longwave heating as well as the amount of surface shortwave irradiance, with consequences for the boundary layer structure and the strength of convection in the tropics. The altered tropical convection had an impact on the global circulation and resulted in improved low-level winds in the tropics and overall better model performance (Morcrette et al. 2008).

Figure 28.5 illustrates one aspect of the improvements: a better agreement with the National Aeronautics and Space Administration (NASA) Clouds and the Earth’s Radiant Energy System (CERES) observations for top-of-atmosphere longwave cloud forcing. The model results in this figure are from a small three-member ensemble of year-long forecasts, showing that the improvements to the model's energy budget extend into the long range and are not confined to the short-term forecast range alone.

While the McICA scheme provides a framework that allows a better representation of cloud inhomogeneity in the IFS, the current model does not yet take full advantage of this capability. A single inhomogeneity function is applied currently to the cloud water content within each grid box, irrespective of the cloud type or regime, and while this function is used in the radiative transfer calculations, the cloud water content is still assumed to be uniform for microphysical processes. Further improvements to the treatment of cloud inhomogeneity are part of the IFS development plans, and the ARM Program provides a rich set of observations to guide future changes.
4. Process-oriented model evaluation with ARM observations in the IFS: Reducing systematic errors

A key area for parameterization improvement is to reduce the systematic errors associated with the representation of cloud and interactions with radiation. Since 1995, the cloud and precipitation parameterization scheme in the IFS was based on Tiedtke (1993), parameterizing the sources and sinks of cloud and precipitation due to the main generation and destruction processes from convection and microphysics. Although modified in several ways over the years, the basic structure remained with three prognostic variables: water vapor, a combined liquid–ice cloud condensate, and a cloud fraction. Although performing well in the context of an NWP model, further improvements could be made to address some of the shortcomings of the cloud scheme. Two examples are highlighted here for mixed-phase and warm-phase cloud processes.

a. An ARM case study for improving the representation of supercooled liquid water

A model intercomparison study (Klein et al. 2009) based on the Mixed-Phase Arctic Cloud Experiment (MPACE) at the ARM North Slope of Alaska site highlighted an issue with the representation of mixed-phase cloud in many GCMs, including the IFS. The single prognostic cloud condensate variable required a diagnostic partitioning into cloud liquid and ice, and a temperature-dependent function was used to determine the liquid fraction for temperatures between 0°C and −23°C, assuming all condensate to be frozen below −23°C. Considering that temperature generally decreases with height, this type of function will diagnose a larger liquid fraction at cloud base than at cloud top. Despite the ability of the IFS to predict the large-scale state of the atmosphere well during MPACE (Xie et al. 2006), the diagnostic phase partitioning left the model unable to represent the observed mixed-phase structure of the Arctic clouds with liquid layers near the top of the cloud and led to an underestimation of the liquid fraction. The limitations of the representation of the mixed-phase cloud in the original Tiedtke scheme, together with several other issues (precipitation advection on an increasingly finer horizontal grid, numerical issues, physical realism) prompted an extension of the cloud scheme to include separate prognostic variables for cloud liquid and ice and additional prognostic variables for snow and rain (Forbes...
and Tompkins 2011; Forbes et al. 2011). Separate variables for liquid and ice provide additional degrees of freedom to represent the variability of supercooled liquid water observed at a given temperature and also provide new opportunities to revisit processes such as ice deposition, sedimentation, etc., that act as sources and sinks for the prognostic cloud variables.

Shortly after the operational implementation of the new cloud scheme in November 2010, a cold bias in 2-m temperature was identified in wintertime northern Europe, and an investigation found a link with a lack of supercooled liquid in clouds over wintertime Europe. A revisit of the MPACE case study illustrates the problem (Fig. 28-6). For these cold clouds between 0°C and −23°C, the diagnostic scheme with a temperature-dependent mixed phase by definition has small amounts of supercooled liquid water present, although much too little and with the wrong vertical structure. The new cloud scheme with separate prognostic liquid and ice variables, however, produces a qualitatively better cloud structure with supercooled liquid in the upper half but is unable to sustain the liquid layer throughout the test case period.

FIG. 28-6. (left) Cloud fraction, (center) cloud liquid water content, and (right) cloud ice water content for a single-layer mixed-phase cloud observed during 8 and 9 Oct 2004 at the NSA site during MPACE. (a) Observations, (b) IFS with previous cloud scheme with diagnostic mixed phase, (c) IFS with new cloud scheme with separate prognostic liquid and ice variables, and (d) the new cloud scheme with revised ice deposition rate. From Forbes and Ahlgrimm (2014).
time series are explored in the following section. A simple parameterization to encapsulate the effect of these processes in reducing the ice deposition rate near cloud top was added to the new cloud scheme in November 2010, enabling the model to better sustain supercooled liquid layers (Fig. 28-6d). The model’s improved ability to represent mixed-phase clouds was reflected in more accurate 2-m temperature forecasts over Northern Hemisphere continents, but also improved the radiation over the Southern Ocean where supercooled topped boundary layer clouds is abundant (Forbes and Ahlgrimm 2014).

Case studies such as MPACE, using remote sensing and in situ data from the ARM Program, proved invaluable to evaluate the model and inform the improved representation of specific processes in the model cloud parameterization in the IFS. However, the ARM Data Archive also contains long time series of continuous radiation and cloud observations. Conditional sampling of these time series and subsequent compositing can help to establish a link between model errors and particular aspects of the model formulation. These long time series are explored in the following section.

b. Long time series of ARM observations to improve warm-phase cloud and precipitation

It is common for model errors to compensate to a degree, and while this may be immediately beneficial for a better performance, it poses a problem for future development. An improvement of one model aspect can easily result in a deterioration of the forecast when another existing error is no longer compensated. The following example illustrates how the long-term observations from the ARM SGP site, after thoughtful compositing, helped to identify specific aspects of the boundary layer and shallow convection parameterizations in need of improvement.

The observational record at the ARM SGP site shows that the ECMWF model has a long-standing bias in surface shortwave irradiance, allowing too much shortwave radiation to reach the surface. Previous work comparing the model to observations from SGP for a month-long period (Cheinet et al. 2005) suggested that a lack of shallow convective clouds in the model, such as those commonly observed in the summertime fair-weather cumulus regime at SGP, might be contributing to the bias. To test this hypothesis, a large number of days (146) with fair-weather cumulus clouds were chosen from the long-term record and composited, and cloud occurrence, properties, and surface radiation were examined. Compensating errors between cloud occurrence and cloud properties were identified in the model. On some days, the model did not produce any cloud at all, but on days with predicted clouds, their liquid water path and effective radius would be overestimated. This suggested several areas for revision (e.g., convection triggering, moisture transport, assumed CCN concentration), but since the errors in surface shortwave irradiance from clear and cloudy days largely compensated for the fair-weather cumulus regime, this could not fully explain the long-term bias in surface shortwave irradiance at the SGP site.

To identify the cause of the bias without an a priori guess, the observed and modeled clouds were then classified by type and ranked by their contribution to the overall surface shortwave irradiance bias. This approach highlighted cloud regimes that are particularly relevant to the surface shortwave irradiance bias and revealed that low-cloud conditions do contribute significantly, though it is during overcast conditions that the model overestimates the surface shortwave irradiance. Cloud cover is often underpredicted when overcast low clouds are observed, and liquid water path is too low (Ahlgrimm and Forbes 2012). For broken low-cloud conditions, on the other hand, liquid water path tends to be overestimated, as was evident during the fair-weather cumulus days. The assumption of a fixed cloud water inhomogeneity distribution for all conditions proved to be ill suited to represent both broken and overcast low-cloud regimes. Thus, surface shortwave irradiance errors from broken and overcast low-cloud regimes partially compensate, with the bias from the overcast regime dominating. These contrasting model errors for broken and overcast low-cloud conditions may explain why the surface shortwave irradiance bias has persisted in the model for many years and through many model changes. A simple increase or decrease of cloud cover or liquid water path for low clouds would not address the underlying problem fully. Instead, broken low clouds, generally produced by the shallow convection parameterization in the IFS, and overcast low clouds, produced by the stratocumulus parameterization embedded in the boundary layer scheme, or the cloud scheme, need to be addressed individually.

The IFS, in common with other global models, also overestimates the occurrence of light precipitation and can underestimate the occurrence of heavier precipitation. The 19-month-long observational dataset
obtained from the ARM Mobile Facility located on Graciosa Island in the Azores (Rémillard et al. 2012) provided an opportunity to evaluate the representation of precipitating marine boundary layer clouds in the IFS. In contrast to satellite-based observations, a comparison with the detailed profiles of precipitation retrieved from ground-based radar allows an attribution of the model’s overestimate in surface precipitation occurrence to in-cloud generation and subcloud evaporation. As anticipated, the model overestimated monthly mean precipitation occurrence both at cloud base and at the surface compared to the observations (Fig. 28-7). The overestimate was similar in both the full IFS and a single-column version of the model (SCM). Thus, the SCM could be used to test parameterization changes for the entire 19-month period, an undertaking that would be too expensive to perform with the full model. Several parameterization changes were tested to improve the precipitation distribution with an initial focus on warm-phase rain formation from boundary layer clouds. An alternative parameterization of the autoconversion and accretion processes (Khairoutdinov and Kogan 2000) led to reduced generation of light precipitation. A parameterization of rain evaporation that represents more realistically the higher evaporation rates of small droplets (Abel and Boutle 2012) also reduced the occurrence of light rain at the surface.

The impact of combined parameterization changes to the parcel entrainment in the boundary layer (based on the insights gained from the ARM SGP low cloud investigation), as well as to the warm rain autoconversion–accretion and evaporation parameterizations significantly improved the precipitation occurrence (Fig. 28-7), low-cloud cover, and agreement with observed surface radiation in the SCM and in the full model (Ahlgrimm and Forbes 2014).

Only two examples are discussed here in detail, but observational data from other sites, such as the Tropical Western Pacific (Lin et al. 2012) and the ARM Mobile Facility in Niamey (Agustí-Panareda et al. 2010), have also contributed to our understanding of model biases in the IFS.

5. Conclusions

The long-standing interaction between the ARM Program and ECMWF has shaped the development of the IFS global model over many years and contributed directly to the improvement of NWP at ECMWF and indirectly to developments in the wider weather and...
climate modeling community. This is arguably most evident in the RRTM and McICA schemes for radiative transfer, but ARM observations have continued to provide inspiration and valuable insights into parameterization formulations, from novel boundary layer parameterization developments such as the DualM scheme to warm-phase and mixed-phase cloud improvements in the IFS. By providing the necessary observational datasets to develop and test new model parameterizations, whether at ECMWF or in the wider research community, ARM has enabled process-oriented evaluation efforts to identify and target systematic model errors. In turn, the NWP environment at ECMWF, with stringent requirements for forecast performance and synoptic weather systems always close to reality in the short-term forecasts, allows model evaluation in a deterministic way to make the most of observations from the ARM Program.

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