Large-Scale Forcing Impact on the Development of Shallow Convective Clouds Revealed From LASSO Large-Eddy Simulations

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Abstract Real-world large-eddy simulations (LES) are driven by time-varying large-scale forcings (LSF)—e.g., temperature advection, moisture advection, and subsidence—derived from large-scale weather models. This study investigates the impact of the uncertainty in LSF on real-world LES in terms of the development of shallow convection at the Atmospheric Radiation Measurement (ARM) Southern Great Plains (SGP) atmospheric observatory for the June 11, 2016 case using LES provided by the U.S. Department of Energy’s LES ARM Symbiotic Simulation and Observation (LASSO) activity. The LASSO data set provides an ensemble of LES for the selected case, which consists of LES runs that were driven by different LSF. The two contrasting LES runs investigated here generate different types of convective clouds, i.e., nonprecipitating shallow clouds and precipitating cumulus congestus, mainly due to the difference of LSF in temperature advection in the free troposphere. The temperature advection modulates the strength of the capping inversion and therefore the buoyancy of the air parcels rising from the atmospheric boundary layer (ABL). The inversion, together with large-scale updrafts, controls the penetration of the ABL thermals into the free troposphere, leading to cumulus congestus in the case of a weaker inversion. In contrast, clouds remain shallow in the case of a strong inversion. Differences between the two simulations are amplified over time, as mixed-phase clouds are formed near the top of the congestus in the weaker inversion case. This high dependency of LES results to LSF stresses the importance of accurate LSF by large-scale models to real-world LES simulations.

Plain Language Summary Shallow convective clouds play an important role in weather and climate systems by changing the global energy budget and water cycle of the atmosphere. These shallow convective clouds have horizontal spatial scales of 1 km or smaller, while the initiation, development, and decay of these clouds are affected by weather systems at much larger scales. Therefore, to accurately simulate the shallow convective clouds using computer models, detailed simulations are needed that use very fine model grid spacings and are driven by accurate large-scale weather forcings. However, the forcings are usually derived from numerical weather prediction outputs at much coarser model resolutions, which are unavoidably uncertain. Here, we investigate how the uncertainty in large-scale forcings impact the fine-scale detailed simulations of shallow convective clouds. Our case study shows that the uncertainty in large-scale forcings has big impacts on the detailed cloud simulations by changing the depth, water/ice contents, and surface precipitation of the simulated convective clouds.

1. Introduction

Shallow convection plays a crucial role in weather and climate systems by modulating Earth’s radiation balance and vertically transporting heat, moisture, and momentum in the atmosphere. The involvement of shallow convection in energy budget and water cycle occurs over a wide range of temporal and spatial scales by, for example, transitioning to precipitating convective clouds such as cumulus congestus and deep convection, and clustering into organized mesoscale convective systems (e.g., Kurowski et al., 2018; Zhang & Klein, 2010; Zhuang et al., 2017). This transitional and multiscale nature of shallow convection by
complex interactions with the surface and large-scale environment poses challenges to observing and understanding the life cycle of shallow convection (Fast et al., 2019). As a result, the parameterization of shallow convection is a major source of uncertainty in weather and climate models (e.g., Bechtold et al., 2014; Bony et al., 2015; Zhang et al., 2013). Large-eddy simulations (LES), however, resolve three-dimensional small-scale details of atmospheric processes over large domains that cannot be obtained from observations. LES have advanced our understanding of the development of shallow convection (e.g., Brown et al., 2002; Hinkelmann et al., 2005; Lee et al., 2019; Xiao et al., 2018; Zhang et al., 2017) and provided benchmarks for development of parameterizations for mesoscale models. These fine-scale simulations, in principle, largely reduce simulation errors by explicitly resolving energy-containing large eddies and minimizing the usage of physical parameterizations. However, the cloud and turbulence structures in these fine-scale simulations for real-world cases inevitably depend on the accuracy of large-scale forcings (LSF)—e.g., suites of temperature advection, moisture advection, and subsidence—derived from large-scale and mesoscale weather models (e.g., Gustafson et al., 2020; Heinze et al., 2017; Schemann et al., 2020; Vogelmann et al., 2015), as the development of continental cumulus convection can be sensitive to small changes in large-scale environmental conditions (e.g., Kurowski et al., 2020; van Laar et al., 2019).

The U.S. Department of Energy’s LES Atmospheric Radiation Measurement (ARM) Symbiotic Simulation and Observation (LASSO) activity (Gustafson et al., 2020) provides a unique observation and LES data set for 95 continental shallow convection cases at the ARM Southern Great Plains (SGP) atmospheric observatory. This rich data set has contributed to gaining new insights into convective clouds over land, such as the structure of the cloud population (Neggers et al., 2019), cloud overlap (Sulak et al., 2020), cloud radiative effect (Gristey et al., 2020) and has provided comprehensive benchmarks for mesoscale model simulations in which atmospheric boundary layer (ABL) and/or shallow convection parameterizations are used (Angevine et al., 2018). Another unique aspect of LASSO is that it provides an ensemble of LES for each case, which consists of multiple simulations driven by different LSF from various analysis sources (i.e., weather forecast models, observations, and data assimilation systems) at different scales which is an aspect that has not been heavily investigated.

In this study, we demonstrate how the uncertainty in LSF influences the real-world case simulations of the development of continental shallow convective clouds by analyzing two contrasting LES runs selected from the LASSO ensemble from June 11, 2016. The objectives of this study are to understand physical mechanisms at different spatial scales linking LSF and cloud simulations for the June 11, 2016 case and to emphasize the importance of accurate LSF by large-scale models to real-world weather simulations at LES resolutions, by presenting a case of striking LSF impacts. Section 2 describes the LASSO simulations being analyzed in this study. Section 3 presents analysis results which identify links among LSF, mean meteorological profiles, turbulence statistics, and cloud properties. Summary and concluding remarks follow in the final section.

2. LASSO Simulations

The LASSO activity (https://www.arm.gov/capabilities/modeling/lasso; Gustafson et al., 2020) provides a unique research database combining observations, LES inputs and outputs, diagnostics, and skill scores for clouds (liquid water path [LWP], cloud fraction, lifting condensation level [LCL], and cloud base height) and near-surface parameters (surface and boundary-layer temperature, relative humidity, and vapor mixing ratio) for well-identified continental shallow convection events that occurred at the ARM SGP atmospheric observatory in north-central Oklahoma, US. For each case, LASSO provides an ensemble of LES runs, which consists of using different LSF—i.e., suites of temperature advection, moisture advection, and subsidence—from various analysis sources (weather forecast models, observations, and data assimilation systems). For the years 2015–2016, additional members for different LES models and microphysics schemes are also available.

Among the 95 cases from 2015 to 2019, the June 11, 2016 case is selected for an in-depth analysis in this study. A wide spread of cloud skill scores among the LES runs for a given LASSO case is an indicator of diverse cloud-simulation results, and, in this context, implies a significant impact of LSF on the simulation behavior. The June 11, 2016 case includes simulations with relatively high and low cloud-simulation skill.
score values compared to other LASSO cases, so this case demonstrates the strong impact of the LSF. We use the total cloud skill scores provided by LASSO, which combine time series skill scores of one-dimensional (1-D) cloud fraction and 1-D LWP, and the two-dimensional (2-D) cloud mask skill score (see Gustafson et al., 2019, Section 4.2 for specifics regarding the skill scores). The time series skill scores quantify the agreement in terms of phase, correlation, and relative mean, and the 2-D skill score quantifies the agreement of cloud occurrence using equitable threat score (ETS). For this shallow convection case, two LASSO LES simulations are selected that show contrasting cloud skill scores and that solely differ in LSF: a high cloud skill score simulation (hereafter, high skill simulation) driven by the multiscale data assimilation (MSDA) forcing at a 150-km scale (Li et al., 2016; Li, Feng, et al., 2015; Li, McWilliams, et al., 2015), and a low cloud skill score simulation (hereafter, low skill simulation) driven by the ARM Variational Analysis (VARANAL) forcing at a 300-km scale (Xie et al., 2004; Zhang & Lin, 1997; Zhang et al., 2001). The high skill and low skill simulations are initialized by identical initial conditions from the radiosonde sounding at 12:00 UTC and both use the surface fluxes from VARANAL for the lower boundary condition. The details of the LSF profiles and cloud properties of these two simulations are presented in the next section.

Some important LASSO LES setup details are as follows. The LES model used is the nonhydrostatic Weather Research and Forecasting (WRF) model version 3.8.1 (Skamarock et al., 2008). The horizontal domain size is 14 × 14 km² and the model top is at 14.7 km above ground level. The horizontal grid spacing is 100 m, and the vertical grid spacing is 30 m from the surface to 5 km and then stretches up to 300 m to the model top. The 1.5-order Smagorinsky-Lilly subgrid-scale (SGS) model based on a prognostic SGS turbulence kinetic energy is used (Deardorff, 1980; Lilly, 1966) to parameterize SGS turbulent fluxes. The Morrison two-moment scheme (Morrison et al., 2009) is used for cloud microphysics. Simulations are driven by horizontally homogeneous and time-varying LSF profiles and surface fluxes, and doubly periodic lateral boundary conditions are applied in the horizontal directions. Simulations are initialized at 12 UTC on June 11, 2016 and integrated for 15 h. The specific simulation identification numbers within the LASSO library for these MSDA and VARANAL-based simulations are 4 and 7, respectively. For more information on the LASSO data bundle product, refer to Gustafson et al. (2019, 2020).

3. Results

Cloud properties of shallow cumulus observed at the ARM SGP site on June 11, 2016 are presented in Figure 1 alongside the two LASSO simulations. One variable shown is the time series of (horizontal) cloud fraction observed by the total sky imager (TSI). The other variable shown is the time series of observed in-cloud column integrated liquid water amount, also called liquid water path (LWP). The retrieved LWP we use comes from the LASSO data set and is derived from spectral downwelling radiation emitted at microwave and infrared wavelengths measured by, respectively, a two-channel microwave radiometer and an infrared spectrometer. The optimal estimation framework used to perform the retrievals (Turner & Löhnrert, 2014) produces LWP at a frequency of about 20–30 s with an uncertainty of 10–20% for LWP below 50 g m⁻² (Vogelmann et al., 2015; Appendix B) and 20–30 g m⁻² for LWP above 50 g m⁻² (Turner et al., 2007).

In Figure 1, the time series of observed LWP and the cloud fraction show the primary peak around 11 local standard time (LST; LST = UTC − 6) and the secondary peak around 14–15 LST (Figures 1a and 1b). Note that the peak timings of LWP and cloud fraction do not necessarily coincide, since the former is a vertically integrated quantity while the latter is a horizontal coverage value. The rapid development of clouds in the early morning is distinct from the afternoon peak (~13:30 LST) of typical shallow convection cases at the ARM SGP site, in which shallow cumulus clouds are locally generated by surface forcing (Zhang et al., 2017). The timing of the secondary peak of the observed clouds in this case is delayed by 0.5–1.5 h, compared to the typical afternoon peak that develops under no significant LSF. These differences from the typical cases indicate impacts of LSF in this June 11, 2016 case. The two LASSO simulations capture both morning and afternoon peaks, but the low skill simulation consistently overestimates LWP. We note that the estimated LWP retrieval error is much smaller than the difference between the two LASSO simulations. Figures 1c and 1d show that the clouds that develop in the high skill simulation remain shallow until they dissipate, whereas the low skill simulation generates cumulus congestus, reaching up to ~6 km with light surface precipitation (not shown) during the secondary peak. The clouds extend above the freezing level forming cloud ice near the cloud top in the late afternoon in the low skill simulation (not shown). This June
In the 11, 2016 case, in which the two simulations produce different types of convective clouds solely due to LSF (i.e., nonprecipitating shallow convective clouds and precipitating cumulus congestus) stresses a critical role played by LSF in the simulations of the development of convective clouds.

Figure 2 compares time-height structures of LSF of temperature, moisture, and vertical velocity for the high skill and low skill simulations. The two LSF share some common features, such as advection of cold and moist air below the LCL during the afternoon and evening hours, and large-scale updrafts across the LCL in the early morning and midafternoon. Noticeable differences between the two LSF are the strength and the vertical extent of large-scale updrafts around the time of cloud initiation and the advection of warm and dry air above cloud top in the high skill simulation. In the following sections, we investigate physical mechanisms linking LSF and cloud properties by separating the life cycle of the selected shallow convection event into three stages: the first stage ranging from initiation to the primary peak of convective clouds (08–11 LST), the second stage from the primary peak to the secondary peak (11–14 LST), and the last stage from the secondary peak to dissipation (14–18 LST).

3.1. Cloud Initiation and the Primary Peak (08–11 LST)

This shallow convection case exhibits the primary peak of clouds around 10 LST (cloud fraction) and 11 LST (LWP) in both simulations, with a rapid growth of the cloud top between 09 and 10 LST (Figure 1). A moderate and gradual increase of surface heat fluxes alone does not explain these features (Figure 2g). The
A diurnal increase in surface heat fluxes is important for the shallow cloud formation, as demonstrated by the large vertical velocity variance below the LCL that develops throughout the day (Figures 5a and 5c). The large-scale updrafts across the LCL around 09 LST provide an additional boost to the lifting of the air parcels from the ABL allowing them to rise above the LCL (Figures 2c and 2f), initiating clouds and facilitating the sudden increase in cloud depth in both simulations. The large-scale advection in the ABL is warmer and moister during the early hours for the high skill simulation (Figure 2), but it does not significantly change the buoyancy of air parcels in the ABL as seen from the sounding plots (compare Figures 3a and 3c). In the high skill simulation, the warm and dry advection in the free troposphere strengthens the capping inversion (Figures 4a and 4b) suppressing the penetration of surface-driven thermals and hindering the cloud top growth, as indicated by the vertical velocity variance and the vertical moisture flux below the cloud top.

Figure 2. Time-height structures of large-scale (a, d) potential temperature (θ) forcing (10^{-4} K s^{-1}), (b and e) water vapor mixing ratio (q_v) forcing (10^{-4} g kg^{-1} s^{-1}), and (c and f) vertical velocity (w) (10^{-2} m s^{-1}) for the simulations with of high skill (top) and low skill (bottom). The time series of lifting condensation level (LCL) and cloud top height are shown with white dots and white triangles, respectively, as in Figure 1. The time series of surface forcings are presented in (g): sensible heat flux (W m^{-2}; solid black) and latent heat flux (W m^{-2}; dotted black).
The inversion strength (\(\partial<\theta>/\partial z\)) in the high skill simulation is intensified by up to \(\sim 10\) K km\(^{-1}\) at 11 LST, which is three times stronger than the capping inversion in the low skill simulation. In the low skill simulation, the cold advection in the free troposphere weakens the capping inversion permitting the ABL parcels to rise farther by increasing the buoyancy of the air parcels (Figures 3c, 4c, and 4d). Therefore, the cloud top reaches higher beyond the weak capping inversion, growing up to \(\sim 4\) km in 2 h after the initiation of cloud. To summarize the early stage of cloud development for this case, the differences in LSF impact cloud simulations mainly by modulating surface-driven thermals.

3.2. Development of Cumulus Convection in the Early Afternoon (11–14 LST)

Large-scale warm and dry advection in the free troposphere continues during the early afternoon in the high skill simulation, together with the horizontal cold advection within the capping inversion and large-scale subsidence across the inversion (Figures 2a–2c). Therefore, the high skill simulation maintains a strong inversion layer below the free troposphere (Figures 3b, 4a, and 4b), limiting the height of cloud top to approximately 3 km despite a gradual increase of turbulence intensity in the ABL (Figures 5a and 5b). Figure 6 presents histograms of cloud top height and cloud-core top height, where “cloudy” is defined as the

(Figures 5a and 5b). The inversion strength (\(\partial<\theta>/\partial z\)) in the high skill simulation is intensified by up to \(\sim 10\) K km\(^{-1}\) at 11 LST, which is three times stronger than the capping inversion in the low skill simulation. In the low skill simulation, the cold advection in the free troposphere weakens the capping inversion permitting the ABL parcels to rise farther by increasing the buoyancy of the air parcels (Figures 3c, 4c, and 4d). Therefore, the cloud top reaches higher beyond the weak capping inversion, growing up to \(\sim 4\) km in 2 h after the initiation of cloud. To summarize the early stage of cloud development for this case, the differences in LSF impact cloud simulations mainly by modulating surface-driven thermals.

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sum of cloud water and ice mixing ratios larger than 0.001 g kg\(^{-1}\) and “cloud cores” are cloudy regions with positive buoyancy. These histograms show flat-top distributions at 12 LST for both cloudy and cloud-core tops in the high skill simulation, indicating the presence of a strong inversion, in contrast to bottom-heavy distributions at 09 LST (compare Figures \(6a\) and \(6b\)). In the low skill simulation, the weak cold advection in the free troposphere continuously allows rapid growth of clouds generating a deeper cloud layer with cloud top over 5 km and light surface precipitation, i.e., cumulus congestus. The sounding plot shows the narrow area of convective available potential energy (CAPE) related to the cold environment (Figure \(3d\)). The positive buoyancy area extends to ~200 hPa beyond the cloud top at ~550 hPa (marked with a blue

![Figure 4. Vertical profiles of domain-averaged (a, c) potential temperature (K) and (b and d) water vapor mixing ratio (g kg\(^{-1}\)) for simulations with high skill (top) and low skill (bottom) at local standard times of 7, 9, 11, 13, 15, and 17.](image)
cross), indicating the role of large-scale downdraft and entrainment of environmental air in limiting the development of clouds. Temperature and moisture profiles at 13 LST and 15 LST indicate that the capping inversion continuously merges into the free troposphere (Figures 4c and 4d), and the middle troposphere is colder and moister than in the high skill simulation. Histograms of cloud top height at 12 LST show a secondary peak at around 3.5 km, while the cloud-core top shows a bottom-heavy distribution (Figure 6f). This suggests that the secondary peak of cloud top distributions is associated with atmospheric processes that are not necessarily positively buoyant, e.g., the detrainment of moisture from the rising thermals near the cloud top where they lose buoyancy.

Figure 7 displays the time-height structures of energy-containing horizontal length scales ($L$), which correspond to power spectral peaks for vertical velocity ($w$) and water vapor mixing ratio (moisture) ($q_v$). For more mathematical details of this methodology of calculating $L$, refer to Section 2.b.1 of de Roode et al. (2004). These length scales can be interpreted as spatial scales of physics processes that dominate horizontal variability of each variable at each corresponding time and height. For example, the length scale of the vertical velocity ($L_w$) (Figures 7a and 7c) shows that it ranges between 2–3 km for heights above the middle of the
ABL, proportional to the ABL depth, since the turbulence eddies that dominate the horizontal variability of meteorological fields in the ABL have scales on the order of the ABL depth (de Roode et al., 2004). \( L_w \) increases from the surface to the middle of the ABL as the scale of ABL turbulence increases with height above the surface. \( L_w \) does not vary that much from the middle of the ABL to cloud top, as ABL thermals control convective updrafts in shallow cumulus (Lareau et al., 2018). Overall, \( L_w \) is larger in the low skill simulation than in the high skill simulation, as the ABL grows deeper and thermals reach higher due to the weak inversion. Time-height structures of \( L_\theta \) exhibit similar features (not shown). Moisture fields show distinct characteristics. First, \( q_v \) in the ABL is larger than \( L_w \) and \( L_\theta \) in the afternoon, indicating the influence of large-scale moisture advection (Figures 2b and 2e). Second, the low skill simulation shows the increase of \( L_{q_v} \) near the cloud top, \( L_{q_v} \sim 6 \) km, at heights consistent with the locations of the secondary peaks of cloud top distributions: \( \sim 3.5 \) km at 12 LST, \( \sim 4 \) km at 15 LST, and \( \sim 5.5 \) km at 18 LST (gray histograms in Figures 6f–6h). This ABL-decoupled feature of \( L_{q_v} \) near the cloud top supports our previous argument that the secondary peaks of cloud top distributions are associated with the detrainment near the cloud top, which has larger spatial scales than surface-driven convection. During this intermediate stage, the differences in LSF impact cloud simulations mainly by the changes in the timing of the decay of the capping inversion and the associated changes in cloud depth.

### 3.3. The Secondary Peak and Cloud Dissipation (14–18 LST)

This selected case shows the secondary cloud peak in the midafternoon, at 14–15 LST in observations and 14–16 LST in simulations (Figures 1a and 1b). The profiles of LSF in Figure 2 show that moisture advection in the ABL and updrafts across the LCL together contribute to this afternoon cloud peak. Water vapor mixing ratio profiles in Figures 4b and 4d show increasing moisture above the ABL by turbulent transport from
the ABL (Figures 5b and 5d) but no noticeable reduction of moisture in the ABL. In the high skill simulation in particular, the moisture advection extends to the cloud top, and moisture increases in the entire layer below the cloud top from 13 LST to 17 LST. Note that the moisture supply by the surface latent heat flux peaks at 13 LST (Figure 2g). This confirms the contribution of additional moisture supply by the moisture advection to the secondary peak.

In the late afternoon and the early evening, cloud top in the low skill simulation extends above the freezing level, generating ice clouds near the cloud top. Therefore, in this stage, the cloud microphysical processes in the two simulations are related to different water phases: liquid-phase processes in the case of high skill simulation and mixed-phase processes in the case of low skill simulation. Note that cloud microphysical processes remain SGS at LES resolutions, requiring parameterizations. Uncertainties in cloud microphysics parameterization schemes are larger for mixed-phase processes than liquid-phase processes (Morrison et al., 2020). Therefore, we expect the role of microphysical processes and the sensitivity to microphysics schemes to be different between the two simulations. Figure 8 displays two additional LASSO simulations, which have exactly the same model configurations as the high skill and low skill simulations, except that the Thompson microphysics scheme (Thompson et al., 2008) now replaces the Morrison microphysics scheme.

Figure 7. Time-height structures of dominant length scales calculated from the horizontal power spectra of (a and c) vertical velocity (L_w; km) and (b and d) water vapor mixing ratio (L_qv; km) for simulations with high skill (top) and low skill (bottom).
These two simulations with the Thompson microphysics scheme are referred to as high skill_MPS and low skill_MPS, respectively. The specific simulation identification numbers within the LASSO library for these MSDA and VARANAL-based simulations are 11 and 14, respectively. As expected, the high skill simulation, which produces shallow convection, does not show large sensitivities to the representation of microphysics processes (cf., Figures 1c and 8a; Figures 6d and 8b). In contrast, the low skill simulation shows large sensitivities to the representation of microphysics processes when mixed-phase clouds exist, i.e., after 16 LST and above 5 km (cf., Figures 1d and 8c; Figures 6h and 8d). During this final stage, the differences in LSF impact cloud simulations by also changing cloud microphysics processes. This case shows that when the uncertainty of LSF is combined with the uncertainty of microphysics, the sensitivity of real-world LES results to LSF could become even larger.

Figure 8. Sensitivity of simulations with high skill (top) and low skill (bottom) to microphysics schemes (MPS): (a and c) cloud mixing ratio ($q_c$; g kg$^{-1}$), and (b and d) histograms of cloudy top and cloud-core top heights at 18 LST. In (a and c), the time series of lifting condensation level (LCL) and cloud top height are shown with white dots and white triangles, respectively, as in Figure 1.
4. Summary and Concluding Remarks

In this study, we investigated the impact of LSF on the real-world simulations of the development of continental shallow convection (timings of the initiation and decay of convection, and the amount and vertical extent of clouds) at the ARM SGP atmospheric observatory by using LES provided by the DOE’s LASSO activity. The objectives of this study were to understand the physical mechanisms linking LSF and cloud simulations for the June 11, 2016 case and to emphasize the importance of accurate LSF by large-scale models to real-world weather simulations at LES resolutions by presenting a case of striking impacts of LSF. For this purpose, we selected the June 11, 2016 shallow convection case, which showed a wide range of LES cloud skill scores depending on LSF. The two contrasting simulations generated different types of convective clouds, i.e., nonprecipitating shallow cumulus and precipitating cumulus congestus, solely due to the differing LSF. Multiscale analysis linking LSF, mean profiles, turbulence statistics, and cloud properties revealed that the crucial difference in LSF between the two simulations was the horizontal temperature advection in the free troposphere, which modulated the strength of the capping inversion and therefore the buoyancy of the air parcels rising from the ABL. The inversion strength, together with the large-scale updraft forcing in the early morning, modulated the penetration of the ABL thermals into the free troposphere, leading to cumulus congestus in the case of a weaker inversion. As the congestus grew to ~6 km, a secondary cloud peak was generated near the cloud top that was decoupled from the positively buoyant convective core. The analysis of dominant length scale of the moisture field indicated that the secondary peak was associated with the detrainment near cloud top, which had larger horizontal scales than the surface-driven convective core. In contrast, clouds remained shallow in the case of a strong inversion. Differences between the two real-world simulations, which resulted from the uncertainty in LSF, were amplified over time, as mixed-phase clouds were formed near the top of the congestus in the weaker inversion case. This high dependency of real-world LES results to LSF stresses the importance of accurate LSF by large-scale and mesoscale models to real-world weather simulations at LES resolutions. This case, in particular, shows that when the uncertainty of LSF is combined with the uncertainty of microphysics, the sensitivity of LES results to LSF can become even larger.

One of the major differences between the two large-scale forcings used in this study (MSDA and VARANAL) is the ARM observations ingested into these forcings. MSDA assimilates atmospheric soundings and radar-derived wind profiles at the ARM SGP atmospheric observatory, while VARANAL is constrained by in situ surface fluxes (Gustafson et al., 2020). These two forcing types also use different frameworks to incorporate the observations, which can lead to different forcing values. MSDA uses the Gridpoint Statistical Interpolation (GSI) three-dimensional (3-D) Variational Analysis algorithm (Li et al., 2016; Li, Feng, et al., 2015; Li, McWilliams, et al., 2015), while VARANAL uses a variational technique that relies more on the surface fluxes and precipitation (the latter of which does not happen on the chosen case) to constrain the profiles of horizontal moisture and temperature fluxes (Xie et al., 2004; Zhang & Lin, 1997; Zhang et al., 2001). In the July 11, 2016 case, the inversion layer plays an important role in determining the fate of clouds. The incorporation of observed meteorological profiles in MSDA may have resulted in better cloud simulations in this particular case. A more systematic analysis of the impact of different large-scale forcings on the real-world LASSO LES runs will be performed in the future study.

Data Availability Statement

LASSO LES and observations data presented in this paper are available via the LASSO Bundle Browser at https://adc.arm.gov/lassobrowser and more information at www.arm.gov/capabilities/modeling/lasso.

References


