



Drizzle drives model differences in the Southeastern Atlantic Stratocumulus Transitions with Aerosol-Rain-Radiation interactions (SEA STARR) large eddy simulation intercomparison project

Michael S. Diamond¹, Andrew S. Ackerman², Alejandro Baró Pérez^{3,4}, Ann M. Fridlind², Ehsan

5 Erfani⁵, Caspar Jungbacker⁶, Hyunho Lee⁷, David Painemal⁸, Frida A.-M. Bender^{3,4}, Annica M. L. Ekman^{3,4}, Franziska Glassmeier⁹, Graham Feingold¹⁰, Fredrik Jansson⁶, David A. Johnson¹, Matthias Schwarz¹¹, Robert Wood¹³, Takanobu Yamaguchi^{10,12}, Jianhao Zhang^{10,12}, Xiaoli Zhou¹⁴, and Paquita Zuidema¹⁵

¹Department of Earth, Ocean and Atmospheric Science, Florida State University, Tallahassee, FL, USA

10 ²NASA Goddard Institute for Space Studies, New York, NY, USA

³Department of Meteorology, Stockholm University, Stockholm, Sweden

⁴Bolin Centre for Climate Research, Stockholm, Sweden

⁵Division of Atmospheric Sciences, Desert Research Institute, Reno, NV, USA

⁶Department of Geoscience & Remote Sensing, Delft University of Technology, Delft, the Netherlands

15 ⁷Department of Atmospheric Science, Kongju National University, South Korea

⁸NASA Langley Research Center, Hampton, VA, USA

⁹Max Planck Institute for Meteorology, Hamburg, Germany

¹⁰NOAA Chemical Sciences Laboratory, Boulder, CO, USA

¹¹Geosphere Austria, Vienna, Austria

20 ¹²Cooperative Institute for Research in Environmental Sciences, University of Colorado, Boulder, CO, USA

¹³Department of Atmospheric and Climate Science, University of Washington, Seattle, WA, USA

¹⁴Department of Physics and Atmospheric Science, Dalhousie University, Halifax, Nova Scotia, Canada

25 ¹⁵Department of Atmospheric Sciences, Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, FL, USA

Correspondence to: Michael S. Diamond (msdiamond@fsu.edu)

Abstract. The transition from overcast stratocumulus clouds to broken cumulus cloud fields as air is advected over warmer waters is important for controlling cloud cover and thus the radiative budget in the subtropics. Stratocumulus clouds can transition into scattered cumulus via an entrainment-driven “deepening-warming” process or into an open mesoscale cellular convective organization via a precipitation-driven “drizzle-depletion” process. The Southeastern Atlantic Stratocumulus Transitions with Aerosol-Rain-Radiation interactions (SEA STARR) large eddy simulation (LES) intercomparison project described herein uses a composite trajectory of cloud transitions in the southeastern Atlantic to assess the extent to which different LES model setups simulate similar deepening-warming or drizzle-depletion transitions under identical meteorological and aerosol forcings. Results are evaluated in light of observations from the ORACLES, CLARIFY, and LASIC field campaigns.

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The default setup includes abundant smoke ($\sim 1,000 \text{ mg}^{-1}$) from southern African biomass burning and is compared with simulations using the same large-scale meteorology but cleaner (100 or 30 mg^{-1}) free tropospheric aerosol concentrations. In the control, all five LES models simulate deepening-warming transitions that track satellite observations in terms of cloud fraction; exhibit boundary layer deepening somewhat greater than is consistent with observations; and maintain higher cloud droplet number concentrations than observed during nearby aircraft campaigns despite similar below-cloud aerosol number concentrations. In the cleaner cases, however, some models produce drizzle-depletion transitions while others maintain deepening-warming transitions. LES model differences are tied to large discrepancies in simulated rain formation for a given cloud state in terms of total condensate and droplet concentration.

1 Introduction

How low altitude clouds have changed due to historic pollution and how they will change due to ongoing greenhouse-gas-driven warming are two of the largest uncertainties in climate science (Forster et al., 2021). The subtropical stratocumulus-to-cumulus transition (SCT) — the transition between overcast stratocumulus cloud fields near the western coasts of continents to more broken trade cumulus cloud scenes as air is advected over warmer waters offshore — has long been an interest of the cloud physics community because of its implications for overall cloud cover and therefore Earth’s radiation budget (Albrecht et al., 1995). The classical explanation for the transition is via a “deepening-warming” mechanism in which the marine boundary layer (MBL) starts in a well-mixed state under relatively cold sea surface temperatures (SST) and deepens and decouples (stratifies between a well-mixed surface layer and a more quiescent subcloud layer) to form a cumulus-coupled state as the underlying sea surface becomes warmer. Eventually, strong cumulus updrafts drive increased turbulent cloud-top entrainment of warm and dry air from the free troposphere (FT) into the subcloud layer and the remaining stratocumulus clouds evaporate, leaving a scattered trade cumulus field (Bretherton and Wyant, 1997; Wyant et al., 1997). Precipitation plays only a minor role in this conception of the SCT, with the strength of the MBL-capping inversion dominating the speed of the transition (Sandu and Stevens, 2011).

With the more recent development of interactive aerosol schemes for large eddy simulations (LES), however, debate on the role of precipitation in driving stratocumulus transitions has been reopened (Yamaguchi et al., 2017). This is because of a potentially powerful positive feedback mechanism that can develop between aerosol number concentration (N_a) and drizzle production. When drizzle is initiated, it depletes the cloud drop number concentration (N_c) and therefore N_a via the collision-coalescence process that can collect hundreds or thousands of cloud droplets and aerosol particles into a single rain droplet. As MBL N_a concentrations decline, fewer cloud condensation nuclei are available to be activated at cloud base, further decreasing N_c and therefore enhancing drizzle (Albrecht, 1989), which leads to further aerosol depletion, and so on. Strong precipitation-driven transitions have been simulated under low aerosol conditions in subtropical SCTs in the northeast Pacific between California and Hawaii (Erfani et al., 2022; Yamaguchi et al., 2017) and in the southeast Atlantic off the coast of Namibia toward Ascension Island (Diamond et al., 2022b; Yamaguchi et al.,



2015), as well as in closed-to-open cellular transitions in the midlatitude north Atlantic (Goren et al., 2019). Observations of MBL trajectories in the subtropical ocean basins show that transitions routinely occur from closed cell stratocumulus to both disorganized cumulus and to open cellular convective states under relatively similar meteorological conditions (Eastman et al., 2021), with the transition to disorganized cumulus convection favored by enhanced entrainment-drying and the transition to open cells by enhanced wind speed and precipitation (Christensen et al., 2020; Eastman et al., 2022).

The southeastern Atlantic (SEA) basin is an ideal region to study these different potential transition mechanisms because it experiences large intrusions of smoke during the southern African biomass burning season (July-October) that overlies and occasionally mixes into a large stratocumulus deck (Zuidema et al., 2016). Different LES modeling studies have come to differing conclusions about how this smoke affects the SCT (Baró Pérez et al., 2024; Diamond et al., 2022b; Yamaguchi et al., 2015; Zhou et al., 2017). Yamaguchi et al. (2015) found that smoke substantially delays the SCT by inhibiting precipitation formation whereas Zhou et al. (2017) found that smoke hastened the SCT due to enhanced entrainment, as increased N_c and smaller effective radius (r_e) values at cloud top lead to faster droplet evaporation timescales (Wang et al., 2003) and slower droplet sedimentation rates (Bretherton et al., 2007). Diamond et al. (2022b) found that FT semi-direct aerosol effects (cloud adjustments due to the large-scale thermodynamic and dynamic changes induced by smoke absorption) dominated over indirect aerosol effects [the Twomey effect of cloud brightening from greater N_c /lower r_e values (Twomey, 1977) along with the precipitation and entrainment adjustments discussed above] except when background aerosol concentrations were set to ultra-clean values, in which case precipitation was the most important factor driving the SCT. Importantly, Zhou et al. (2017) did not include a sink for aerosol concentration in their simulations, and thus were unable to simulate positive feedbacks like those that were shown important in Yamaguchi et al. (2015) and Diamond et al. (2022b). Absorption of smoke in the MBL, a local semi-direct effect, can decrease cloudiness and hasten the transition to trade Cu when drizzle is low in the background case (Baró Pérez et al., 2024; Yamaguchi et al., 2015).

The Southeastern Atlantic Stratocumulus Transitions with Aerosol-Rain-Radiation interactions (SEA STARR) LES intercomparison project described herein was initiated to better understand the factors driving the different LES results summarized above. The case is based on trajectories of MBL air advecting from the well-mixed stratocumulus region toward Ascension Island (8°S, 14.4°W) offshore during August 2017, and was chosen based on the availability of observations from several field campaigns taking place in the region during that time (Zuidema et al., 2016): NASA's ObseRvations of Aerosols above CLouds and their intEractionS (ORACLES) aircraft campaign (Redemann et al., 2021), the UK Met Office's and a consortium of British universities' CLOUD–Aerosol–Radiation Interaction and Forcing: Year 2017 (CLARIFY-2017) aircraft campaign (Haywood et al., 2021), and the US Department of Energy Atmospheric Radiation Measurement (ARM) Layered Atlantic Smoke Interactions with Clouds (LASIC) ground campaign (Zuidema et al., 2018). Section 2 describes the case setup in more detail and provides information about the models used in the intercomparison and the observations used for evaluation; Sections 3 and 4 describe the main results and sensitivity tests, respectively; and Section 5 concludes by identifying priorities for further research.



2 Data and methods

2.1 Case setup

As our base case, we develop a composite trajectory representative of conditions in the SEA during August 2017 in which cloud transitions clearly occurred as boundary layer air was advected from the overcast stratocumulus region west of the Southwestern African coast toward Ascension Island.

The trajectories used in this work are a subset of those computed for Painemal et al. (2018) and also formed the basis of individual LES cases presented in Baró Pérez et al. (2024). Horizontal and vertical wind data are taken from the Goddard Earth Observing System, Version 5 (GEOS-5) model (Molod et al., 2015) at a spatial grid resolution of 0.25° for latitude and 0.3125° for longitude with 72 vertical levels. The temporal interval between each adjacent output is 3 hours. The initial longitudes of the parcels range from 0 to 12°E , and their initial latitude is equal to 25°S . 5-day forward trajectories are run at a constant altitude of 250 m. Horizontal wind velocities are calculated by linearly interpolating values from 16 spatiotemporally adjacent points (x , y , z , and time). The equatorial and polar radii are set as 6378.137 km and 6356.752 km, respectively, to calculate the incremental changes of the parcel's location after each integration on the latitude/longitude coordinate. The model time step is 10 min, and we adopt the simple forward Euler method for time integration. The integration stops when the parcel gets too close to land to obtain the 250 m winds.

From this initial set of 744 trajectories for August 2017, we first filter trajectories to find those that pass within a 3° by 3° box centered on Ascension Island (8°S , 14.4°W), leaving us with 181 trajectories. Next, we select only the 89 trajectories that pass Ascension in a 3-hour window between 10:30 and 13:30 UTC. Finally, we only retain trajectories with cloud fractions (as measured by SEVIRI, see below) greater than 50% during the first 60 hours of the 5-day trajectories and below 50% during the final 24 hours. This leaves us with 40 trajectories reaching Ascension Island on the following dates: 6-8, 14-15, 17-21, and 27 August and 3 September 2017. These dates span both relatively clean and relatively polluted conditions at the LASIC ground site (Dobracki et al., 2025). Trajectories are temporally subset to include the 64 hours before and 3 hours after the noon (or closest available time) when the trajectory passes by Ascension Island. The end result is illustrated in Figure 1.

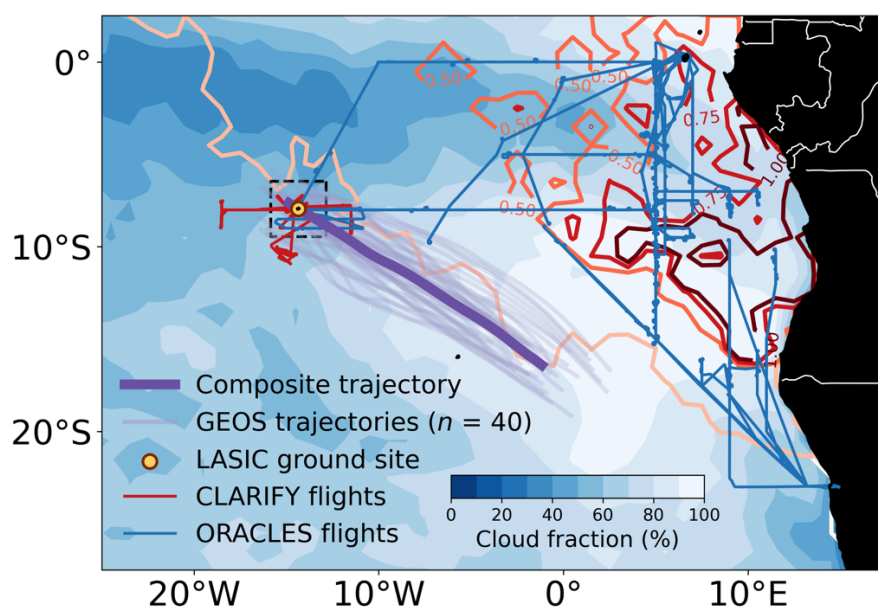
LES forcing files are created using the GEOS-5 outputs of temperature, specific humidity, vertical and horizontal winds, pressure, and, from the online Goddard Chemistry, Aerosol, Radiation, and Transport (GOCART) model, ozone and black carbon. Vertical velocity is smoothed by averaging over all times (Diamond et al., 2022b). An empirical fit between refractory black carbon mass concentration and accumulation-mode aerosol number concentration from ORACLES flight data (see below) is used to convert the GEOS-5 black carbon (BC) values into aerosol number concentration (N_a) estimates (see Figure S1 in the Supplement) as: $N_a = 100 + 750 \times \text{BC}$, where N_a is in units of mg^{-1} and BC in units of $\mu\text{g kg}^{-1}$.

Our modeling approach is to explicitly simulate marine boundary layer processes with the LES but rely on the large-scale meteorology from GEOS-5 to represent the free troposphere. In a similar procedure as used in Diamond et al. (2022b), FT values of temperature, specific humidity, aerosol number concentration, and ozone are extrapolated down to 500 m to avoid a situation in which an LES model simulates a boundary layer shallower than that simulated by GEOS-5 and then has its free



160 troposphere nudged with MBL-like values from GEOS-5. Values between 500 and 1800 m are set as the average value across all trajectories at 1800 m, excluding trajectories with MBL heights greater than 1800 m, and are then smoothed using a 3-hour rolling average. The first three hours (used for model spin-up) are set to have MBL heights of 1 km and constant values of 290 K for the liquid water potential temperature, 9 g kg^{-1} for specific humidity, and 100 mg^{-1} for aerosol number concentration.

Above 6500 m, the upper atmosphere is homogenized by imposing the composite time-mean value at all time steps. Below 6500 m, all values are linearly interpolated onto the LES grid (see below); below 65 m, horizontal winds are extrapolated to the surface using a log-layer profile assuming a surface roughness of $1 \times 10^{-4} \text{ m}$.



165 **Figure 1.** Map with individual and composite trajectories in the context of August 2017 observational campaigns in the southeastern Atlantic region. The sub-selected 40 individual GEOS trajectories are shown as thin purple lines and the composite trajectory as a thick purple line. The 3° by 3° box centered on Ascension Island is outlined in black for reference. The LASIC ground site on Ascension Island is shown as a yellow marker. Flight tracks are shown as blue lines for all three ORACLES deployments and red for lines for CLARIFY. Cloud fraction (blue filled contours) and aerosol optical thickness at 550 nm (red line contours) from the MODIS/Aqua MYD08 monthly Level 3 product (Platnick et al., 2017) are provided for reference.

175 Forcing files using all values taken from GEOS-5 (which includes smoke effects) are the basis for the LES control (CTRL) experiment. Two other experiments are run by modifying the aerosol values ($\sim 1000 \text{ mg}^{-1}$ in CTRL) to represent moderately and extremely “clean” background states: N100 and N030, in which all N_a values are set to 100 mg^{-1} and 30 mg^{-1} , respectively. CTRL and N100 are initialized with N_a values of 100 mg^{-1} in the MBL; N030 is initialized with 30 mg^{-1} . As such, differences in the cases should only be due to indirect and below-cloud semi-direct aerosol effects (at the 3-day timescale or less), not to above-cloud semi-direct effects including changes in subsidence and regional-scale air mass placement that were found to be important in Diamond et al. (2022b).



2.2 Large eddy simulation models

Five modeling groups participated in this phase of the intercomparison: versions of the System for Atmospheric Modelling (Khairoutdinov and Randall, 2003) were run at 1) NOAA's Chemical Sciences Laboratory (NOAA-SAM) and 2) the University of Washington (UW-SAM); the MISU-MIT Cloud and Aerosol (MIMICA) model (Savre et al., 2014) was run at 3) Stockholm University; the 3-D Distributed Hydrodynamic Aerosol and Radiative Modeling Application (DHARMA) model (Ackerman et al., 1995) was run at 4) the NASA Goddard Institute for Space Studies; and the Dutch Atmospheric Large-Eddy Simulation (DALES) model was run at 5) the Delft University of Technology. Temporal resolution is 1 s, horizontal resolution is 50 m, and vertical resolution is 10 m between the surface and 2500 m, then increasing by 10% each level above 2500 m until 6500 m is reached. The lateral boundary conditions are periodic. The simulations start at 21:00 UTC on 15 August 2017, with the first three hours used as spin-up, and end at 15:00 UTC on 18 August 2017 for a total runtime of 66 hours.

The standard cases of each model except MIMICA are run on a 19.2 km by 19.2 km horizontal domain; MIMICA is run on a 9.6 km by 9.6 km horizontal domain. Sensitivity tests are run with NOAA-SAM and DHARMA on a 9.6 km by 9.6 km domain to assess to what extent domain size differences may affect the comparison. NOAA-SAM is additionally run on a large 76.8 km by 76.8 km domain (with horizontal resolution of 200 m for computational efficiency) to test the importance of mesoscale convective circulations that are barely resolved on the 19.2 km by 19.2 km domain.

The simulations follow the “Lagrangian LES” approach (Diamond et al., 2022b; Goren et al., 2019; Kazil et al., 2021; Narenpitak et al., 2021) forced by the large-scale meteorology from GEOS-5. Free tropospheric values are nudged to the composite GEOS-5 profiles. Nudging is only performed above the domain maximum inversion height, as defined by the maximum gradient in liquid water potential temperature (potential temperature in the case of MIMICA), plus 100 m. A ramp-up of nudging follows the method discussed in Blossey et al. (2013) between the domain maximum inversion height and 200 m above the domain maximum inversion height. Nudging is applied to the following variables: temperature, moisture, aerosol number concentration, zonal wind, and meridional wind. Temperature, moisture, and aerosol number concentration have a nudging timescale of 30 minutes, and the meridional and zonal winds have a nudging timescale of 3 hours. Nudging the FT temperature prevents the simulation of FT semi-direct effects, which is appropriate as these should already be included in the GEOS-5 forcings (Diamond et al., 2022b). SST from the composite GEOS-5 trajectory is used for the surface forcing.

Aerosol properties follow those used in Diamond et al. (2022b), based on ORACLES-2017 measurements: single-scatter albedo (ω_0) of 0.85 at 550 nm (Pistone et al., 2019), geometric mean diameter of 185 nm, geometric standard deviation of 1.5, and kappa hygroscopicity parameter (κ) of 0.2 (Kacarab et al., 2020). A surface aerosol source is specified at $70 \text{ cm}^{-2} \text{ s}^{-1}$ following Yamaguchi et al. (2017). All models include a sink of aerosol number from cloud scavenging. Sensitivity tests are performed with NOAA-SAM and DHARMA for hygroscopicity (increasing κ to the ~ 0.65 value representative of ammonium sulfate) and with NOAA-SAM for aerosol absorption (decreasing ω_0 to 0.8).



Table 1 provides a summary of the models used and which cases they simulated, and Table 2 compares their microphysical schemes; further details of the individual LES model setups are provided in the subsections below.

Additional participation in the SEA STARR project is welcomed. Further instructions for interested modeling groups and the forcing files (following the DEPHY standard format for LES and single column models) needed to run the CTRL, N100, and N030 cases are publicly available at Diamond (2026a).

Table 1. Summary of horizontal resolution ($dx = dy$), number of horizontal grid points ($nx = ny$), hygroscopicity parameter (κ), and single-scatter albedo (ω_0) for the baseline configuration of each LES model (in bold) and any configurations for sensitivity tests and whether each model configuration ran the CTRL, N100, and/or N030 experiments (X indicates the experiment was run for that configuration).

Model (-variant)		dx (m)	nx	κ	ω_0	CTRL	N100	N030
NOAA-SAM	Baseline	50	384	0.20	0.85	X	X	X
	-10km	50	192	0.20	0.85	X	X	X
	-80km	200	384	0.20	0.85	X	X	
	-KAP06	50	384	0.65	0.85	X		
	-SSA08	50	384	0.20	0.80	X		
	-lowCO2	50	192	0.20	0.85	X		
UW-SAM	Baseline	50	384	0.20	0.85	X	X	X
MIMICA	Baseline	50	192	0.20	0.85	X	X	X
DHARMA	Baseline	50	384	0.20	0.85	X	X	
	-10km	50	192	0.20	0.85	X	X	X
	-KAP06	50	192	0.65	0.85	X		
	-highO3	50	192	0.20	0.85	X		
DALES	Baseline	50	384	0.20	0.85	X		X

2.2.1 NOAA-SAM

The NOAA-SAM configuration used here is nearly identical to that used in Diamond et al. (2022b). The System for Atmospheric Modelling is a large eddy simulation model with an anelastic dynamical core on an Arakawa C-type grid (Khairoutdinov and Randall, 2003). Version 6.10.10 of SAM is used for NOAA-SAM. Radiation is calculated every 12 s along the trajectory with the Rapid Radiative Transfer Model (Mlawer et al., 1997) modified to use the simulated properties below 6.5 km and a constant atmospheric profile above 6.5 km taken from the GEOS-5 composite. Cloud optical parameterizations are from the Community Atmosphere Model version 5 (Neale et al., 2012). The solar zenith angle varies diurnally and with the latitude and longitude of the Lagrangian trajectory. CO₂ is set to the August 2017 value of 405 ppm. Sub-grid turbulence closure is from a prognostic 1.5-order turbulent kinetic energy (TKE) scheme (Deardorff, 1980). Turbulent surface fluxes are computed prognostically following Monin–Obukhov similarity theory (Monin and Obukhov, 1954). Advection of scalars is performed with a monotonic multidimensional fifth-order conservative advection scheme (Yamaguchi et al., 2011) and momentum with a third-order Adams–Bashforth time integration method (Durran, 1991) coupled with the second-order centered advection scheme.



For aerosol and cloud microphysics, we use a bin-emulating bulk two-moment scheme
250 (Feingold et al., 1998; Wang and Feingold, 2009) with a cutoff radius between cloud droplets and rain
drops of 25 μm . Lognormal basis functions represent the aerosol, cloud droplet, and rain drop size
spectra and lookup tables based on a bin model are used to compute collection and sedimentation rates.
Aerosol particles above a critical dry diameter are activated following κ -Köhler theory (Petters and
Kreidenweis, 2007) based on the simulated supersaturation (i.e., without saturation adjustment).
255 Aerosol–radiation interactions are represented with a priori lookup tables of humidity-dependent optical
properties per unit aerosol number to calculate local heating rates as in Yamaguchi et al. (2015).

2.2.2 UW-SAM

The UW-SAM configuration used here is similar to that used in Erfani et al. (2022). Version
6.10.9 of SAM is used for UW-SAM. The treatment of sub-grid turbulence, turbulent surface fluxes,
260 and radiation, including aerosol-radiation interactions and the above-domain patch from GEOS-5, is
identical to that used in NOAA-SAM. Scalar advection is accomplished with a piecewise-parabolic
method that selectively preserves monotonicity (Blossey and Durran, 2008).

Aerosol and cloud microphysics follow Berner et al. (2013), as modified by Erfani et al. (2022).
Warm cloud microphysical processes are from the Morrison double-moment parameterization with
265 gamma functions to represent the cloud droplet and rain drop size distributions (Morrison et al., 2005;
Morrison and Grabowski, 2008) using the Khairoutdinov and Kogan (2000)-based precipitation
parameterization. The cloud droplet sedimentation flux is parameterized assuming a lognormal size
distribution of droplets falling in a Stokes regime (Ackerman et al., 2009; Bretherton et al., 2007).
Aerosols are represented by a single-mode bulk log-normal two-moment scheme that predicts the mass
270 and number of aerosol particles in three categories (unactivated, within-cloud-droplet, and within-rain-
drop) and calculates tendencies due to activation, accretion, autoconversion, interstitial scavenging,
sedimentation, and FT entrainment (Berner et al., 2013). While saturation adjustment is used, aerosol
activation follows Abdul-Razzak and Ghan (2000) using a diagnostic estimate of supersaturation
(Abdul-Razzak et al., 1998). Aerosol-radiation interactions are represented using the same lookup tables
275 as in NOAA-SAM.

2.2.3 MIMICA

The MIMICA configuration used here is identical to that in Baró Pérez et al. (2024). MIMICA is
an LES with an anelastic and non-hydrostatic dynamical core on an Arakawa C-grid (Savre et al.,
2014). Radiative transfer is calculated with a version of the four-stream Fu–Liou–Gu model (Fu and
280 Liou, 1992; Gu et al., 2003). The radiative fluxes are calculated for the simulated properties below 6.5
km and for a representative thermodynamic state of the tropical atmosphere above 6.5 km. Turbulent
surface fluxes are computed following the Monin–Obukhov similarity theory described by Garrett
(1994). Advection of scalars is performed with a coupling between the third-order Total Variation
Diminishing (TVD) flux-limited scheme described by Hundsdorfer et al. (1995) and the minmod flux
285 limiter (Roe, 1986). A conservative form of fourth-order central finite difference is used for momentum
advection, as described by Durran (2010).



Aerosol and cloud microphysics are from Ekman et al. (2006) and Seifert and Beheng (2006), respectively. The aerosol size distribution is represented by a bulk log-normal two-moment scheme that predicts the mass and number of aerosol particles. Aerosols can be scavenged by cloud processing and precipitation once activated and regenerated from hydrometeor evaporation and sublimation. Aerosol-radiation interactions are adapted from Slater et al. (2020). Here, aerosol is treated as an internal mixture of organic and black carbon with ratios (6.8% black carbon and 93.2% organic carbon) chosen to produce the desired hygroscopic and radiative properties. The aerosols are activated following κ -Köhler theory (Petters and Kreidenweis, 2007) based on the simulated supersaturation (i.e., without saturation adjustment); the aerosol activation spectrum is calculated following Khvorostyanov and Curry (2006) and Ghan et al. (2011).

2.2.4 DHARMA

The DHARMA configuration used here is very similar to that in Zhou et al. (2017), with the most important difference being the inclusion of sources and sinks of aerosol number; as reported (but not substantiated) in Diamond et al. (2022b), this change largely resolved the discrepancy in that study's results and Yamaguchi et al. (2015) in terms of qualitatively producing a drizzle-depletion-style SCT under low aerosol conditions. DHARMA (Ackerman et al., 1995) uses an anelastic dynamical core (Stevens et al., 2002) and the radiative transfer scheme of Toon et al. (1989). An isothermal layer for the radiative transfer calculations overlies the LES grid, with an ozone column following the specifications of de Roode et al. (2016).

The microphysical scheme combines aspects of Morrison et al. (2009), with a fixed cloud droplet dispersion of 0.3 (Geoffroy et al., 2010), and Seifert and Beheng (2006). Aerosol particles are represented as a single, solar-absorbing species with prognostic number concentration only. Activation follows Abdul-Razzak and Ghan (2000) but with the maximum supersaturation taken as the minimum value of prognostic supersaturation from equation A10 of Morrison and Grabowski (2008), as described in Section 5.1 of Vogelmann et al. (2015).

2.2.5 DALES

The DALES model (Heus et al., 2010; Nieuwstadt and Brost, 1986; Ouwersloot et al., 2016) is an LES with an anelastic dynamical core. Advection of scalars is performed with the Kappa advection scheme of (Hundsdoerfer et al., 1995). Radiative transfer is calculated using the toolbox of Pincus et al. (2019).

Its cloud and aerosol microphysics parameterizations are described in de Bruine et al. (2019). Warm cloud processes largely follow Seifert and Beheng (2006) and Seifert (2008). The aerosol scheme can represent several species (Vignati et al., 2004); here, aerosol is assumed to be primary organic matter. Activation is parameterized following an empirical approach, as implemented in Pousse-Nottelmann et al. (2015), and depends on the updraft velocity (calculated from the grid-scale velocity plus a turbulent component proportional to TKE) and the number concentration of aerosol particles with a wet radius greater than 35 nm.



325 **Table 2.** Summary of key cloud and aerosol microphysical processes represented in each LES model.

Model	Microphysics description		References
NOAA-SAM	<i>Cloud droplet and rain drop size distributions</i>	Double-moment bulk parameterization with lognormal distributions; rain cutoff at 25 μm radius	Khairoutdinov and Randall (2003), Feingold et al. (1998), Wang and Feingold (2009), Yamaguchi et al. (2015), Diamond et al. (2022b)
	<i>Autoconversion and accretion parameterization</i>	Bin-emulating lookup table approach of Feingold et al. (1998)	
	<i>Cloud droplet activation</i>	κ -Köhler theory with explicit supersaturation	
	<i>Aerosol</i>	Single-mode bulk lognormal two-moment scheme and absorption following Yamaguchi et al. (2015)	
UW-SAM	<i>Cloud droplet and rain drop size distributions</i>	Morrison and Grabowski (2008) bulk double-moment parameterization with gamma function distributions; rain cutoff at 25 μm radius	Khairoutdinov and Randall (2003), Berner et al. (2015), Erfani et al. (2022)
	<i>Autoconversion and accretion parameterization</i>	Precipitation parameterization of Khairoutdinov and Kogan (2000)	
	<i>Cloud droplet activation</i>	Abdul-Razzak and Ghan (2000) parametrization with diagnostic supersaturation	
	<i>Aerosol</i>	Single-mode bulk lognormal two-moment scheme of Berner et al. (2015) and absorption following Yamaguchi et al. (2015)	
MIMICA	<i>Cloud droplet and rain drop size distributions</i>	Seifert and Beheng (2006) bulk double-moment parameterization with gamma function distributions; rain cutoff at 25 μm radius	Seifert and Beheng (2006), Savre et al. (2014), Baró Pérez et al. (2024)
	<i>Autoconversion and accretion parameterization</i>	Precipitation parameterizations from Seifert and Beheng (2006)	
	<i>Cloud droplet activation</i>	κ -Köhler theory with explicit supersaturation	
	<i>Aerosol</i>	Two-moment scheme of Ekman et al. (2006) with internal mixture of organic and black carbon; radiation interactions modified from Slater et al. (2020)	
DHARMA	<i>Cloud droplet and rain drop size distributions</i>	Morrison et al. (2009) bulk double-moment parameterization with a lognormal distribution with fixed dispersion (Geoffroy et al., 2010) for cloud water and a gamma distribution for rain; rain cutoff at 40 μm radius	Ackerman et al. (1995), Vogelmann et al. (2015), Zhou et al. (2017)
	<i>Autoconversion and accretion parameterization</i>	Precipitation parameterizations adapted from Seifert and Beheng (2006) and Seifert (2008)	
	<i>Cloud droplet activation</i>	Abdul-Razzak and Ghan (2000) parametrization with the minimum value of prognostic supersaturation from Morrison and Grabowski (2008), as described in Section 5.1 of Vogelmann et al. (2015)	
	<i>Aerosol</i>	Single species of solar-absorbing aerosol with prognostic number concentration only	
DALES	<i>Cloud droplet and rain drop size distributions</i>	Seifert and Beheng (2006) bulk double-moment parameterization with gamma function distributions; rain cutoff at 40 μm radius	Nieuwstadt and Brost (1986), Heus et al. (2010), Ouwersloot et al. (2016), de Bruine et al. (2019)
	<i>Autoconversion and accretion parameterization</i>	Precipitation parameterizations from Seifert and Beheng (2006) and Seifert (2008)	
	<i>Cloud droplet activation</i>	Empirical formula of Pousse-Nottelmann et al. (2015) based on grid-scale w , TKE, and N_a with wet radius greater than 35 nm	
	<i>Aerosol</i>	Adaptation of Vignati et al. (2004) multimodal scheme treating aerosol here as particulate organic matter	



2.3 Observations

2.3.1 SEVIRI

Cloud properties (cloud fraction, cloud top height, and N_c) from the Spinning Enhanced Visible and Infrared Imager (SEVIRI) aboard the geostationary Meteosat-10 satellite were retrieved by the
330 NASA Langley Research Center using the Satellite Cloud and Radiation Property retrieval System (SatCORPS) algorithms (Minnis et al., 2008; Painemal et al., 2012; Painemal et al., 2015); N_c was calculated from r_e and cloud optical depth assuming an adiabatic profile (Grosvenor et al., 2018). SEVIRI retrievals are averaged in boxes with diameter 0.185° around the GEOS-5 trajectories and are temporally collocated with each trajectory data point within 15 minutes. Retrievals are screened to only
335 include data with solar zenith angle values below 70° and cloud fraction within the 0.185° by 0.185° boxes greater than 90%.

2.3.2 ORACLES

The ORACLES campaign consisted of three separate NASA P-3 Orion deployments to the southeastern Atlantic: September 2016 based out of Walvis Bay, Namibia; August 2017 based out of
340 São Tomé, São Tomé e Príncipe; and October 2018 again based out of São Tomé (Redemann et al., 2021). We focus on the August 2017 deployment (ORACLES-2017) for aerosol properties. Refractory black carbon (rBC) from 53 to 524 nm mass equivalent diameter was measured using a Droplet Measurement Technologies (DMT) Single Particle Soot Photometer (SP2) with a solid diffuser inlet (Schwarz et al., 2006; Stephens et al., 2003) and accumulation mode aerosol number was measured
345 using a DMT Ultra-High Sensitivity Aerosol Spectrometer (UHSAS). Reported UHSAS values are for dry diameters between 60 and 600 nm, which is the size range covered by the sizing correction from Howell et al. (2021). The majority of the ORACLES-2017 observations took place well to the east of Ascension Island and are thus used to characterize the FT aerosol properties but not to assess the LES model output on Day 3. ORACLES-2017 measurements informing the aerosol size distribution,
350 hygroscopicity, and optical properties applied in the LES models are described by Diamond et al. (2022b) and further information about the full suite of available ORACLES data is available in Appendix B of Redemann et al. (2021).

Given the large amount of sampling throughout the three years of the ORACLES campaign, we further analyze cloud processes in a more statistical sense by compositing values in a state space of
355 cloud water-cloud droplet number concentration. In situ cloud observations are from the merged cloud physics product (Gupta et al., 2021; Gupta et al., 2022a; Gupta et al., 2022b) that combines measurements from the DMT Cloud Droplet Probes (Lance et al., 2010) and Cloud, Aerosol and Precipitation Spectrometer (Baumgardner et al., 2001) for droplets from 3-50 μm in diameter; 2D-S Stereo Probe (Lawson et al., 2006) for drizzle drops from 50-1,300 μm in diameter; and High Volume
360 Precipitation Sampler (Lawson et al., 1998) for raindrops with diameters exceeding 1.3 mm to create a best estimate cloud droplet size spectrum (O'Brien et al., 2021). For instantaneous 1 Hz measurements, liquid water content (LWC) [and its cloud water content (CWC) and rain water content (RWC) components] is calculated by integrating the mass size spectrum and N_c (and rain number N_r) as the



365 zeroth moment (count) of the size distribution. We also utilize flight legs identified as “sawtooths”
(sampling above, within, and below clouds in a sawtooth pattern), “square spirals” (ascents or descents
over a fixed geographical point), and “ramps” (ascents or descents while travelling in one direction
only) based on the flags from Diamond et al. (2018) to analyze vertically-integrated cloud profiles. In-
cloud liquid water path ($\mathcal{L}_c$) and column-average N_c are calculated by first creating vertical profiles of
mean LWC and LWC-weighted N_c in bins of 50 m altitude and then vertically integrating for $\mathcal{L}_c$ and
370 averaging by LWC for N_c . As for the LES models, cloud droplets with radii below 25 μm are treated as
“cloud” and those larger as “rain”. Valid “in cloud” observations are defined as those with LWC values
exceeding 0.01 g m^{-3} and $N_c + N_r$ values exceeding 10 mg^{-1} . Only observations taken below 3,000 m
altitude are included to represent low cloud properties.

2.3.3 CLARIFY

375 The CLARIFY campaign deployed the Facility for Airborne Atmospheric Measurements
(FAAM) BAe-146 aircraft out of Ascension Island during August and September 2017 (Haywood et al.,
2021). Cloud droplet number concentration for droplets with diameters between 2 and 50 μm was
measured using a DMT Cloud Droplet Probe (CDP) and aerosol number concentration for particles with
aerodynamic diameters between 100 nm and 3 μm with a DMT Passive Cavity Aerosol Spectrometer
380 Probe (Cai et al., 2013). Five CLARIFY flights took place on days with valid trajectories and are thus
used to evaluate the LES model output: C028 (16 August), C029 (17 August morning), C030 (17
August afternoon), C031 (18 August), and C032 (19 August). Further information about the full suite of
available CLARIFY data is available in Table 1 of Haywood et al. (2021).

385 Intercomparison flights with ORACLES-2017 and sampling around the LASIC ground site
show generally good agreement between measurements from the various campaigns’ instruments
(Barrett et al., 2022).

2.3.4 LASIC

390 The LASIC campaign deployed the ARM Mobile Facility 1 (AMF1) to Ascension Island from 1
June 2016 to 31 October 2017 (Zuidema et al., 2018). We focus on observations from August 2017 and
3 September 2017 (based on trajectories that started in August 2017 but only reached Ascension Island
in early September) here. Inversion heights for dates with valid trajectories (6-8, 14-15, 17-21, and 27
August and 3 September 2017) are calculated as the greatest altitude below 3 km with a relative
humidity above 70% using profiles from Vaisala RS-92 radiosondes (ARM user facility, 2016b) that
were launched from the Ascension Island airport (near sea level) at 12:00 UTC and swiftly blown over
395 the ocean (Zhang and Zuidema, 2019). Accumulation-mode aerosol number concentration is from a
DMT UHSAS at the AMF1 site. The observations from 6-8, 14-15, and 17 August 2017 correspond
with Plume 8 (Regime 2) and those from 27 August 2017 with Plume 9 (Regime 3) in Dobracki et al.
(2025).



3 Results for the baseline simulations

3.1 Cloud macrophysics and boundary layer evolution

Figure 2 provides an overview of the CTRL, N100, and N030 experiments as simulated by NOAA-SAM. Under polluted, smoky conditions, the overcast, closed-cell stratocumulus clouds break up into scattered trade cumulus with thin anvils (Fig. 2a); as aerosol concentrations decrease, however, the overcast stratocumulus break up rapidly (Fig. 2b, hours 18-24) into precipitating open cells. Under ultraclean aerosol conditions (Fig. 2c), the closed cells break up immediately once collision-coalescence is allowed after the 3-hour spin up period.

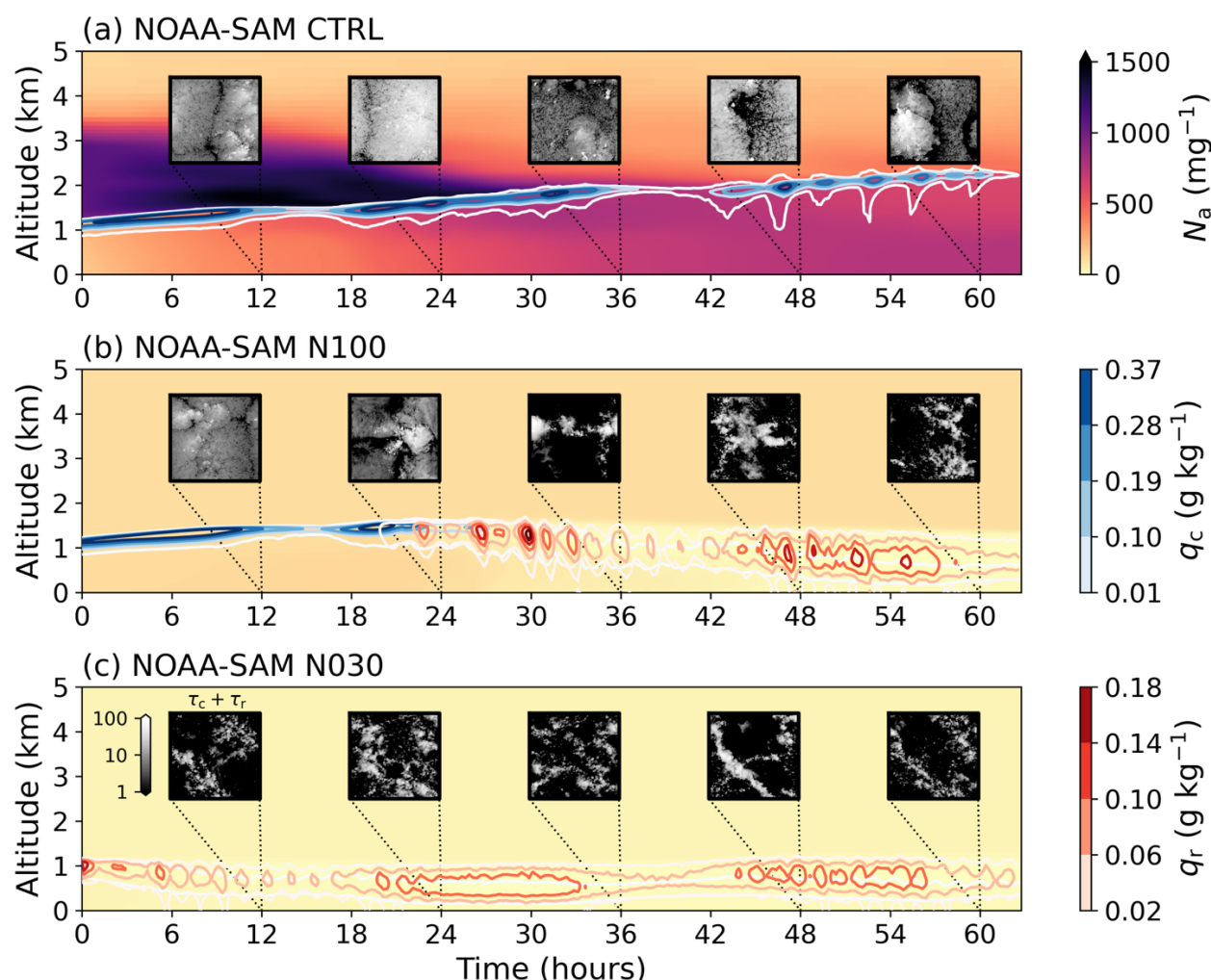


Figure 2. Summary of the stratocumulus-to-cumulus transitions simulated by NOAA-SAM under the (a) highly polluted CTRL, (b) cleaner N100, and (c) ultraclean N030 experiments. Peach-purple shading indicates the domain-averaged total (dry and activated) aerosol number concentration and contours indicate domain-averaged specific cloud (blue) or rain (red) water concentrations. Insets (black-and-white shading) every 12 hours provide snapshots of the horizontal distribution of column cloud and rain optical depth.



Cloud fraction evolution over the course of the simulations is shown for all five LES models in Figure 3. Cloud fraction was defined as the coverage of columns with cloud and rain optical depth exceeding one in all models except DALES, for which it was defined as the fraction of columns containing any cloud water. In the CTRL run, all models show qualitatively similar behavior: mainly overcast with limited breakup during the first day (6-18 hours), full recovery over the second night (18-30 hours), greater breakup during the second day (30-42 hours), at least partial recovery at night (42-54 hours), and extensive breakup over the final day near Ascension Island. This pattern fits the SEVIRI observations qualitatively well, albeit with a generally stronger nocturnal recovery before Day 3. Note that, as we are simulating an idealized composite case, we do not expect strict agreement with observations from any given day but instead are interested in whether the models produce values within the typical range of that observed over the relevant time period. Larger model discrepancies arise in the cleaner N100 and N030 experiments. NOAA-SAM and DHARMA undergo rapid breakup to open cells during the second night in N100 and almost immediately during the first night in N030 whereas MIMICA and DALES simulate deepening transitions to trade Cu regardless of the aerosol background. UW-SAM is somewhere in between, without a rapid breakup in N100 but a prolonged breakup over the first day and a half in N030. Note that results from the model variants used for the sensitivity tests (see Table 1) are discussed in Section 4.

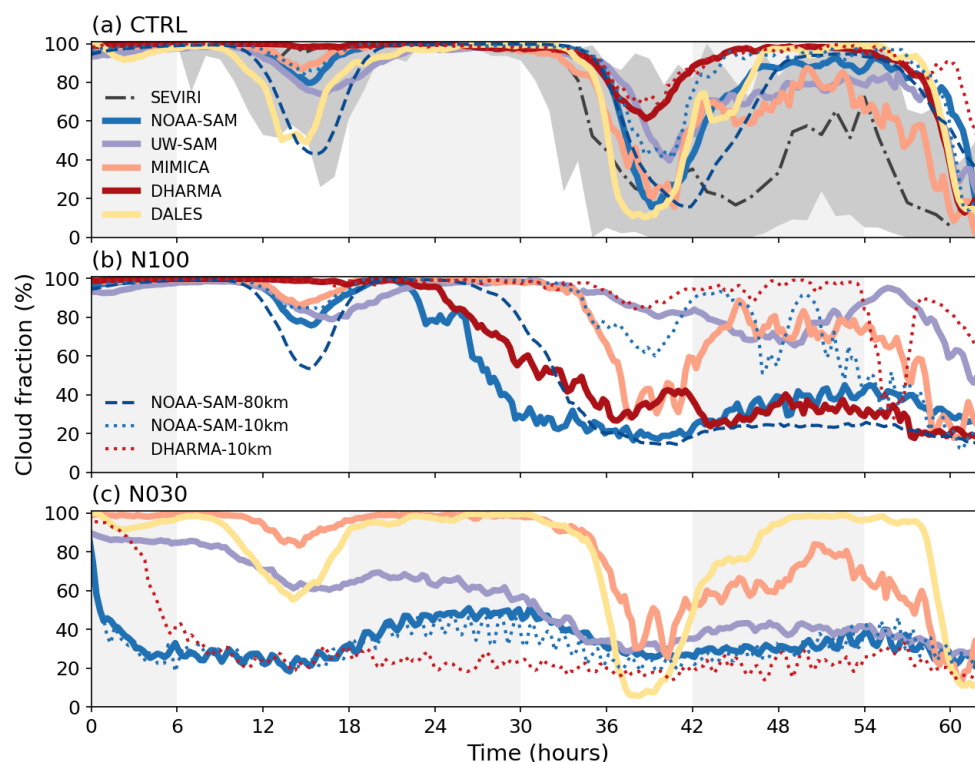


Figure 3. Cloud fraction evolution over the composite trajectory. LES model results are shown as colored lines (blue for NOAA-SAM, purple for UW-SAM, pink for MIMICA, red for DHARMA, and yellow for DALES) for the (a) CTRL, (b) N100, and (c) N030 experiments. Baseline model configurations are shown as solid lines; sensitivity tests using 80 km by 80 km and 10 km by 10 km domains are shown as dashed and dotted lines, respectively. SEVIRI median values and interquartile range of cloud fraction between the trajectories are shown as a dot-dashed black line and grey shading, respectively. Light gray background shading indicates nighttime.



Figure 4 shows the evolution of inversion height (LES models and radiosonde and in-situ aircraft data) and cloud-top height (SEVIRI retrievals and in-situ aircraft data). In the CTRL run, all LES models except DALES deepen more rapidly than the clouds tracked by SEVIRI, although it is worth noting that the SEVIRI retrieval filtering may systematically bias the observations toward shallower and better-mixed MBLs. The models trend on the high end of the radiosonde observations from LASIC, with DALES falling comfortably and MIMICA just within the observed envelope and the SAMs lying just above; DHARMA deepens well beyond what would be expected from the LASIC observations, but at least one CLARIFY flight sampled similar boundary layer depths nearby (Fig. 4a). For NOAA-SAM, the rapid cloud breakup events in N100 and N030 also lead to a break in MBL growth and even shoaling such that the inversion is at the low end (N100, Fig. 4b) or well below (N030, Fig. 4c) the observed values from LASIC and CLARIFY. DHARMA also shoals after breaking up into open cells while UW-SAM does not shoal during its breakup in N030 but does deepen at a markedly slower pace; both end up squarely within the SEVIRI and LASIC observations, although is likely a coincidence as the N030 case is much cleaner than typical conditions over the SEA.

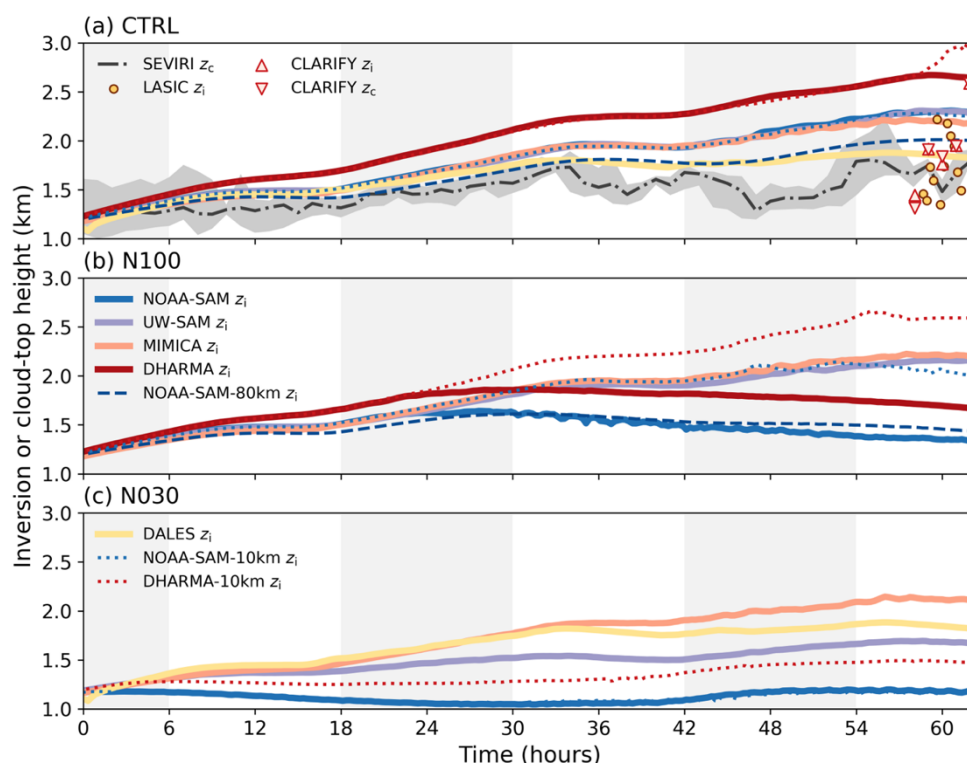


Figure 4. Inversion and cloud-top height evolution over the composite trajectory. LES model results and SEVIRI observations as in Figure 3. LASIC radiosonde observations at 12:00 UTC for available dates with valid trajectories and CLARIFY observations for flights on days with valid trajectories are shown as yellow circles and red triangles, respectively (abscissa placement in chronological order with arbitrary time offset).



3.2 Cloud microphysics, aerosol concentrations, and activation

More striking model biases are apparent in the in-cloud cloud droplet number concentration evolution, shown in Figure 5. A representative N_c is calculated as the LWC-weighted column average, as for the in-situ data (Section 2.3.2). As N_c is roughly constant with altitude (Martin et al., 1994; Painemal and Zuidema, 2011) and satellite retrievals are most representative of the high-LWC cloud top, these in-cloud column N_c values should be reasonably comparable to the SEVIRI observations. All LES models simulate cloud droplet number concentrations of several hundred mg^{-1} (maximum values of 716 mg^{-1} for NOAA-SAM, 573 mg^{-1} for UW-SAM, 588 mg^{-1} for MIMICA, 423 mg^{-1} for DHARMA, and 542 for DALES), whereas the observed clouds had typical N_c values closer to 100-200 mg^{-1} and infrequently exceeded 300 mg^{-1} . Note that the N_c calculation becomes unreliable when cloud fraction is particularly low, as during the Day 2 and Day 3 afternoons in DALES. Differences in the aerosol number concentration in the MBL between the models and observations are not nearly as large, with the models falling within the upper range of values observed during LASIC and CLARIFY (Fig. 6a).

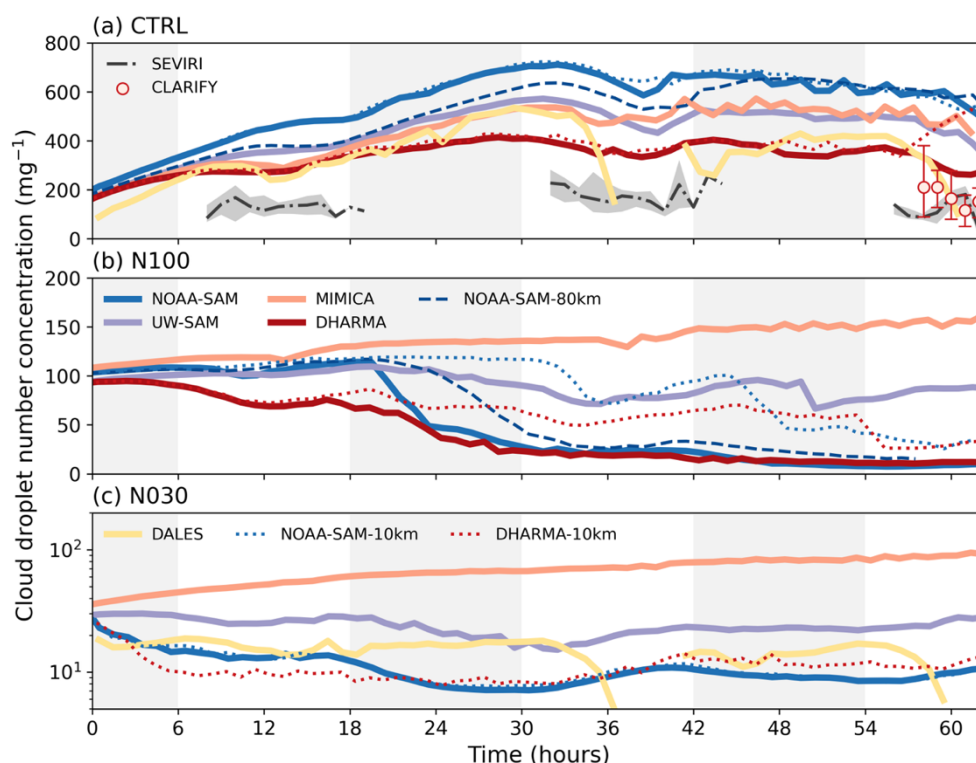


Figure 5. Cloud droplet number concentration evolution over the composite trajectory. LES model results and SEVIRI observations as in Figure 3. Note that shading for SEVIRI represented trajectory variability; retrieval uncertainty can be much larger (Grosvenor et al., 2018). CLARIFY median and interquartile range observations for flights on days with valid trajectories are shown as pink circles and red error bars, respectively (abscissa placement in chronological order with arbitrary time offset). Note that y-axis scale and transform differ between rows to highlight key features.

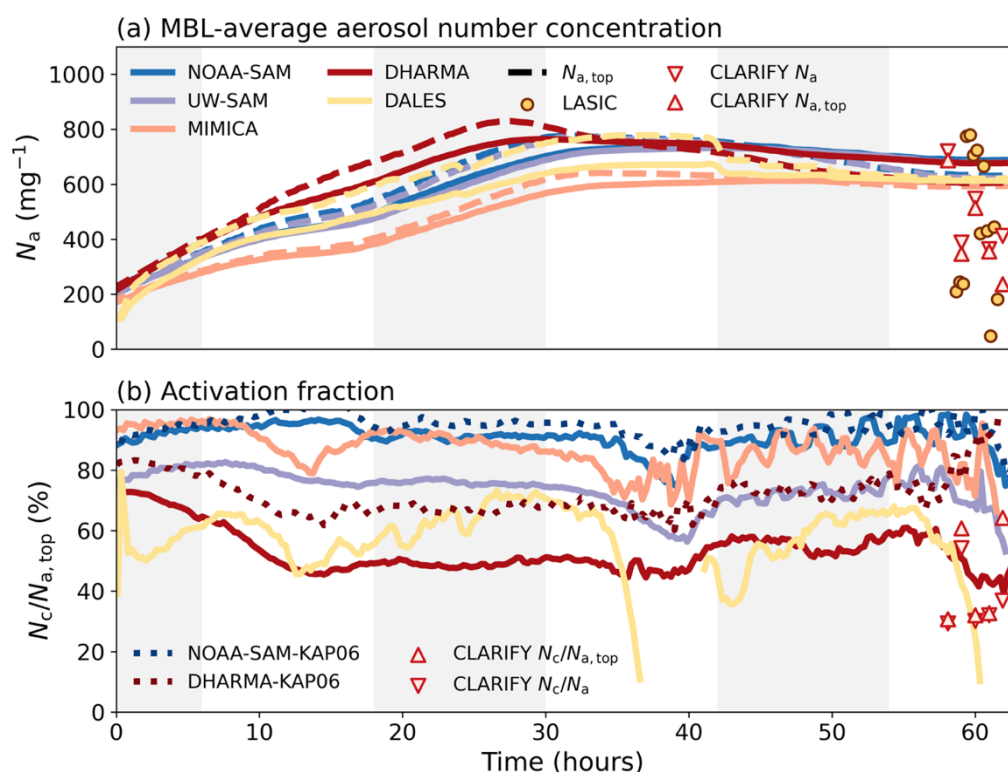


Figure 6. Aerosol number concentration and activation fraction over the composite trajectory. LES model results from the CTRL experiment are shown as colored lines. (a) For N_a , lines are solid for the full MBL average and dashed for aerosol averaged over the top 25% of the MBL. LASIC values (yellow markers) are representative of 340.8 m above sea level and CLARIFY values (red triangles) are defined in the same way as the LES values for the full MBL (downward-pointing markers) and top 25% (upward-pointing markers). (b) For activation fraction (defined using aerosol at MBL top), baseline LES model configurations are shown as solid lines; sensitivity tests using a hygroscopicity parameter representative of ammonium sulfate instead of smoke are shown as dotted lines. CLARIFY values are shown for both activation fractions defined like the LES (upward-pointing markers) and with the MBL-average aerosol (downward-pointing markers).

We can approximate an activation fraction that can be compared fairly between the models and CLARIFY observations by comparing the modeled or observed N_c with the boundary layer aerosol concentration (Fig. 6b). For the models, we consider only aerosol values from the top 25% of the MBL to avoid unphysical activation fractions greater than 100% in the middle of the simulations, when the combination of strong entrainment of above-cloud smoke and a weakly stratified MBL make the MBL-average underestimate the aerosol available at cloud base; we calculate CLARIFY estimates using both the MBL-average and the MBL-top only.

NOAA-SAM and MIMICA activate a large majority of the available aerosol, despite the relatively low hygroscopicity; DHARMA hovers around an activation fraction of 50%; and UW-SAM and DALES generally fall in between. (Very low trailing values for DALES correspond to essentially cloud-free conditions with unreliable values.) CLARIFY observations cluster between 30-40%,



495 although one flight (C029 on the morning of 17 August 2017) sampled conditions with an activation fraction around 60% regardless of calculation method. The CLARIFY flights with higher activation fractions (C029 and C32 on 19 August 2017) correspond with lower N_a values.

The counterfactual “clean” N100 case produces N_c values closer to observed for UW-SAM and MIMICA (Fig. 5b), despite the fact that smoke aerosol was abundant over the SEA at that time in reality (Haywood et al., 2021). When undergoing rapid precipitation-mediated breakup (Fig. 5b-c), 500 NOAA-SAM and DHARMA reach N_c levels as low as several mg^{-1} . UW-SAM reaches values as low as 14 mg^{-1} in the N030 case before recovering to approximately 30 mg^{-1} by the end of the simulation (Fig. 5c); DALES hovers around $10\text{--}20 \text{ mg}^{-1}$ without ever breaking up into precipitating cells. MIMICA, surprisingly, ends up with N_c of $\sim 100 \text{ mg}^{-1}$ in N030, retaining much of the aerosol generated by the 505 surface source against entrainment of ultraclean FT air and any cloud processing.

3.3 Drizzle production in cloud state spaces

Analyzing cloud evolution in terms of an N_c -LWP “state space” has proven helpful to elucidate key processes (Feingold et al., 2025; Glassmeier et al., 2019; Glassmeier et al., 2021; Gryspeerd et al., 2019; Hoffmann et al., 2020; Zhang et al., 2022). In Figure 7, the fraction of total condensate in the 510 precipitation mode as a function of the N_c - $\mathcal{L}_c$ state space is presented for each model (in its baseline configuration) and the three main experiments (CTRL, N100, N030). NOAA-SAM, UW-SAM and DHARMA show a clear separation between non-precipitating and precipitating clouds with a transition located in the region of the state space in which the cloud-top effective radius for an adiabatic cloud grows between 12 and $16 \mu\text{m}$, which are commonly used as thresholds to separate precipitating and 515 non-precipitating clouds (Gerber, 1996; vanZanten et al., 2005). NOAA-SAM and DHARMA produce substantially stronger precipitation with higher $\mathcal{L}_c$ than UW-SAM, which could plausibly be related to more condensate-laden clouds producing stronger precipitation, stronger precipitation producing a strongly open cellular mesoscale oscillatory state (Feingold et al., 2010), or some interaction thereof. MIMICA and DALES produce the least precipitation and also do not exhibit a clear relationship in N_c - 520 $\mathcal{L}_c$ space.

Figure 8 places the LES model results from Figure 7 (subset to every 12 hours) in the context of ORACLES campaign values (see Section 2.3.2). The ORACLES observations, particularly the sawtooth legs (which feature more cloud sampling than ramps or square spirals), largely follow the precipitation ratio pattern of NOAA-SAM, UW-SAM, and DHARMA, although no observations were as clean as 525 those simulated by the NOAA-SAM and DHARMA N030 cases. MIMICA produces rain ratios that are low but still plausible as compared to the ORACLES data. No clouds were sampled with the combination of low- N_c /low- $\mathcal{L}_c$ produced by DALES in N030. No model besides DALES and none of the ORACLES observations show rain ratios below a few percent past the $r_e > 16 \mu\text{m}$ threshold.

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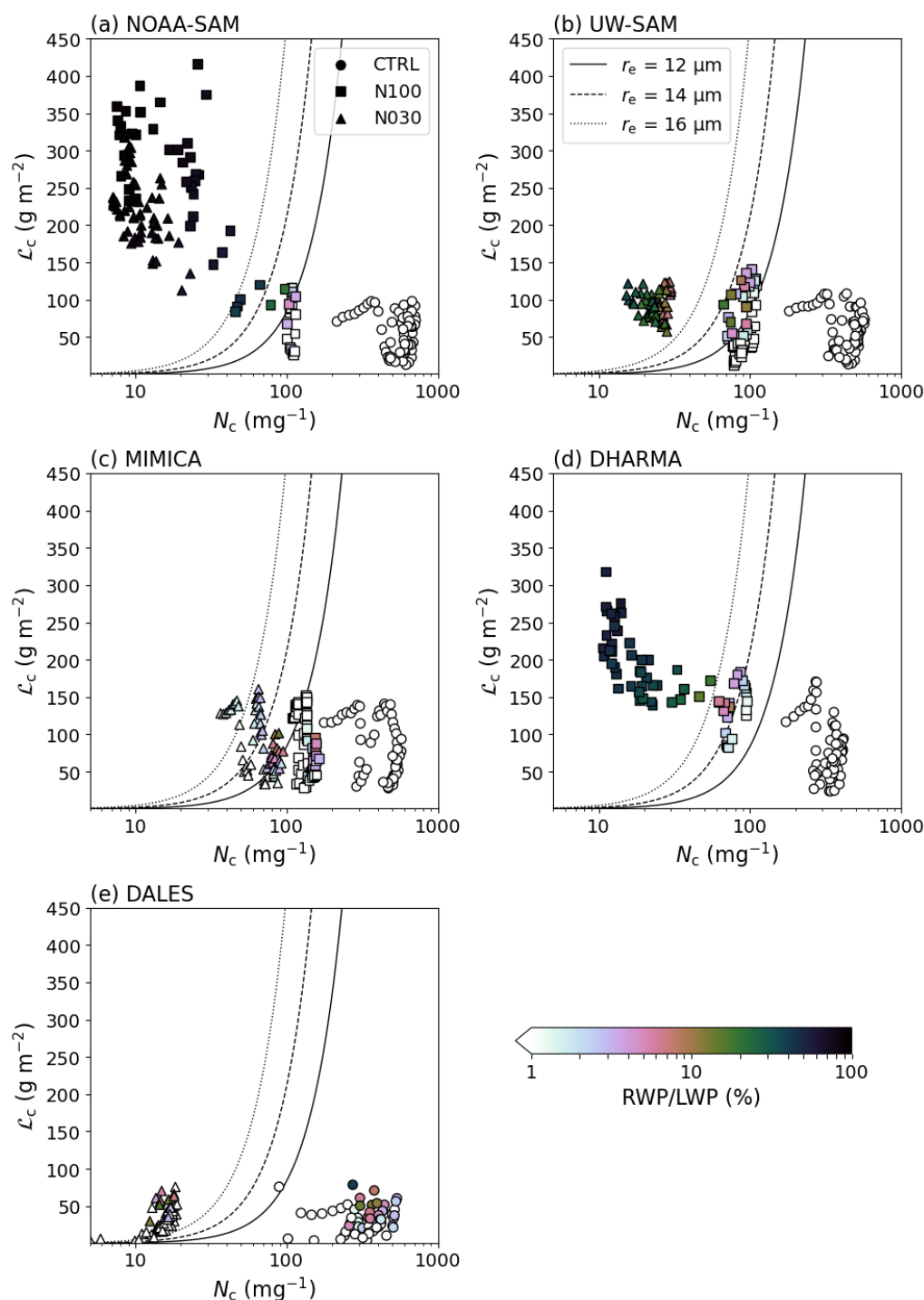


Figure 7. Fraction of total condensate in the rain mode as a function of LWC-weighted N_c and in-cloud LWP as simulated by the LES models. For each LES model (a-e), markers are plotted every hour for the CTRL (circle), N100 (square) and N030 (triangle) simulations and shaded by the ratio of rain to total liquid water. Adiabatic cloud-top effective radius values of 12 (solid line), 14 (dashed line), and 16 (dotted line) μm are shown for reference.

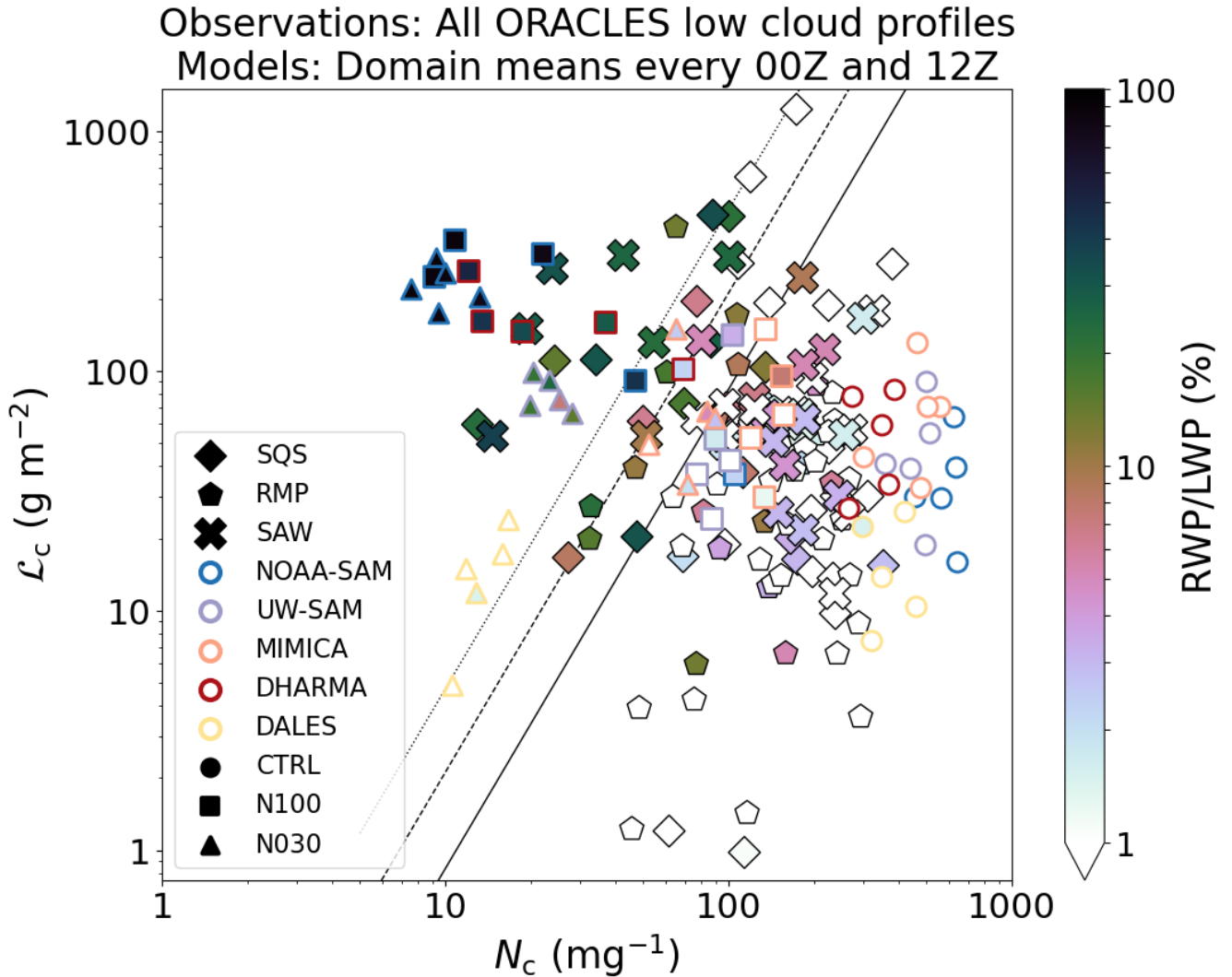


Figure 8. Fraction of total condensate in the rain mode as a function of N_c and in-cloud LWP as observed during ORACLES and simulated by the LES models. Square spiral (SQS, diamond markers), ramp (RMP, pentagon markers), and sawtooth (x markers) flight legs including low cloud profiles from all three ORACLES deployments are included and are shaded by the ratio of rain to total liquid water. LES model values follow Figure 7 but are only shown every 12 hours. Adiabatic cloud-top effective radius values of 12 (solid line), 14 (dashed line), and 16 (dotted line) μm are shown for reference.

Unfortunately, no flights sampled in the region of greatest interest for breakup here (see trajectories in Fig. 1); however, many stratocumulus clouds were sampled during the ORACLES campaign whose statistics are likely representative of those in the more eastern portion of the deck. Figure 9 utilizes the full ORACLES record, considering the rain fraction observed in all valid in-cloud measurements taken below 3 km altitude regardless of aircraft maneuver. Values are averaged over logarithmically spaced bins (20 x 20) of total cloud and rain number concentration and LWC (total mass of rain and cloud water per volume). We sample the LES models at their altitude of maximum domain-



mean cloudiness at midnight on the second day, which is the approximate time that NOAA-SAM and DHARMA transition to open cells while the other models continue on a deepening-warming trajectory in N100 (Fig. 2b, 3b). NOAA-SAM appears to generate rain too efficiently compared to the observations (N030 and N100); interestingly, DHARMA, which also undergoes a rapid transition to open cells, seems to underpredict rain fraction (N100). UW-SAM generates non-negligible rain in the N100 and N030 experiments but is noticeably lower than the mean observations and NOAA-SAM and DHARMA. MIMICA and DALES stand out as generating almost no rain under situations in which the observations suggest that more than 10% of the liquid mass should be in the rain mode, at least.

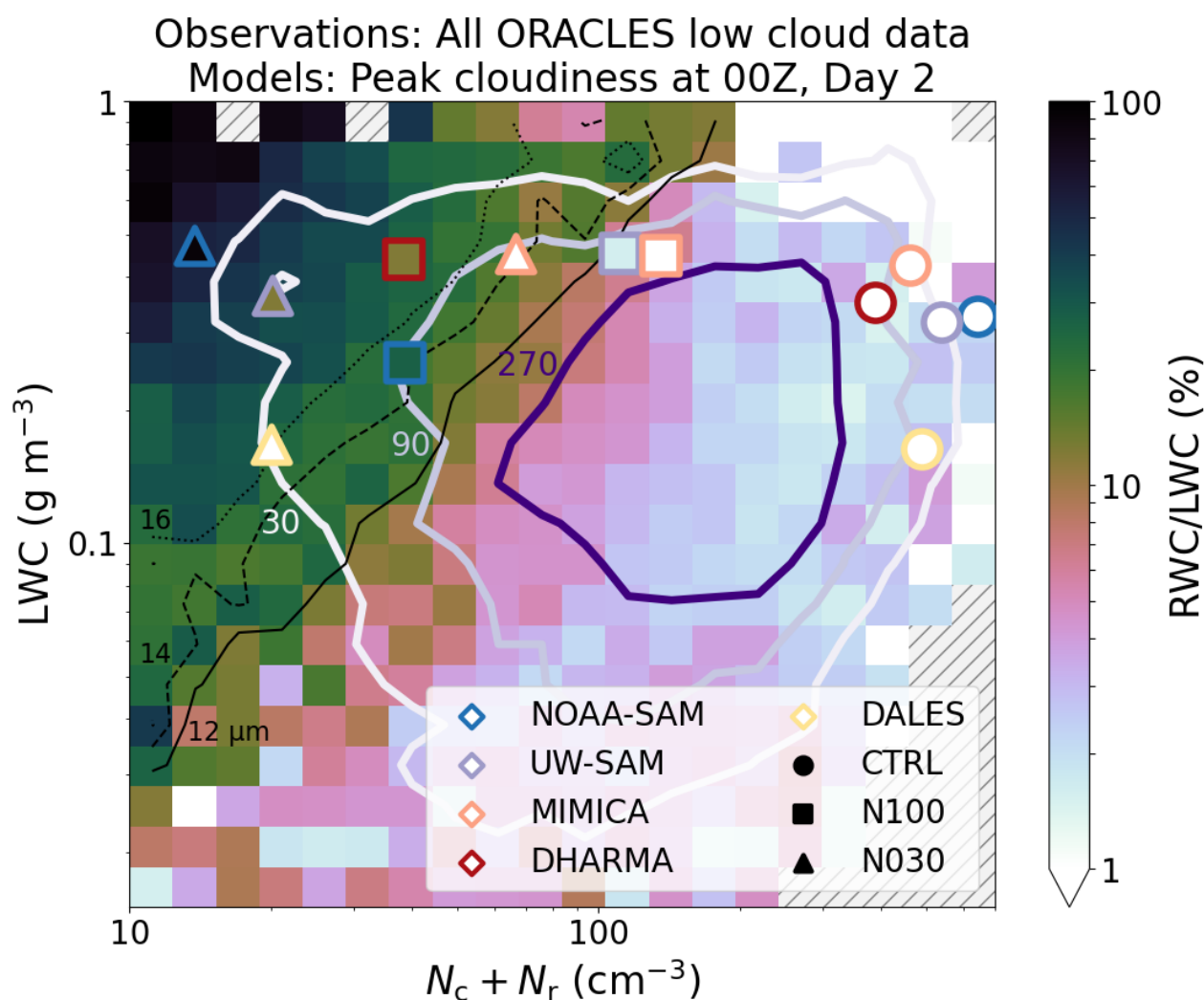


Figure 9. Fraction of condensate in the rain mode in a given volume of cloudy air as a function of cloud and rain droplet number and liquid water content as observed during ORACLES and simulated by the LES models. Shading represents the mean value in each bin of $N_c + N_r$ and LWC considering all ORACLES cloud observations taken below 3 km altitude. Black contours of 12 (solid), 14 (dashed), and 16 (dotted) μm mean effective radius values are plotted for reference. Purple contours represent the sampling probability distribution; stippling represents unsampled state spaces. Markers indicate the baseline LES model outputs sampled at the altitude of peak domain-mean cloudiness at midnight on the second day; colors indicate the different models and shapes the experiments.



4 Sensitivity tests

570 4.1 Domain size

To assess whether the smaller domain size could be responsible for the lack of precipitation in MIMICA, additional runs of NOAA-SAM and DHARMA were performed with the smaller 9.6 km by 9.6 km (“-10km” variants) for the CTRL, N100, and N030 experiments (Table 1). For N100 (Fig. 2-4b), the smaller domain in NOAA-SAM-10km delays the transition to broken open cells by approximately 575 12 hours, qualitatively consistent with the behavior in Yamaguchi et al. (2017) and Erfani et al. (2022); for DHARMA-10km, the breakup never occurs despite the cloud droplet number concentration dropping to a few dozen mg^{-1} . In N030 (Fig. 2-4c), however, the transition to open cells starts essentially immediately in both NOAA-SAM-10km and DHARMA-10km. These results suggest that the smaller domain size used in MIMICA is not sufficient to explain the difference in simulated 580 transition mechanisms.

Even the 20 km by 20 km domains are too small to resolve mesoscale cellular convection well, as a single cell can easily dominate the full domain. To assess the robustness of the cloud morphology inferences, we ran additional simulations with NOAA-SAM using an approximately 80 km by 80 km domain by reducing the horizontal resolution by a factor of four (Table 1). Results qualitatively track 585 those from the standard domain and resolution (Figs. 3-5). In N100, the oscillations apparent in the smaller domains are smoothed out in NOAA-SAM-80km, as would be expected if we were more robustly capturing multiple cells simultaneously within the domain.

Figure 10 shows snapshots of the cloud field organization at midnight on the third day for CTRL and N100 for NOAA-SAM and NOAA-SAM-80km. CTRL features isolated cumuli with thin stratiform 590 anvils while N100 features clearly defined open cellular structures in the large domains, agreeing with our inferences from the more compressed picture from the smaller domains (Fig. 2ab). We thus conclude that the 20 km by 20 km domain size is sufficiently large to capture the fundamental differences between the disorganized and open cellular cumulus states even if they cannot resolve the mesoscale morphology in detail.

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NOAA-SAM, 00Z on day 3

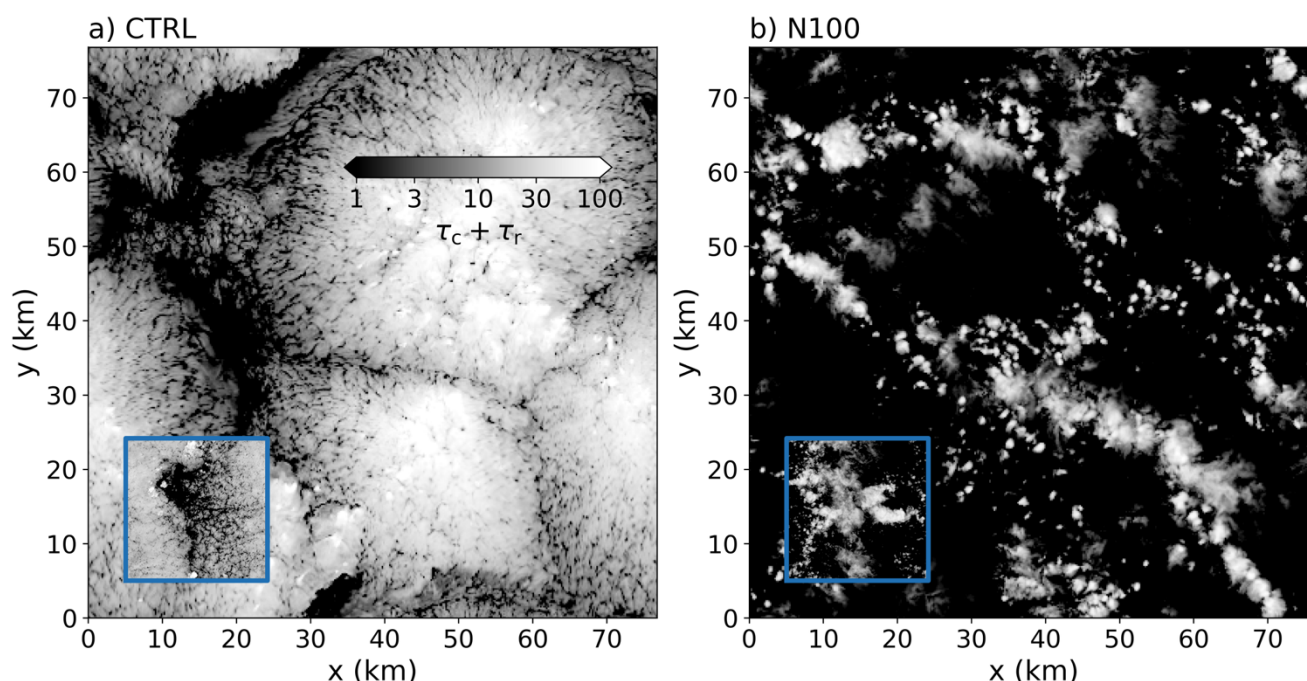


Figure 10. Snapshots of cloud morphology at midnight on the third day of the NOAA-SAM simulations as revealed by cloud and rain optical depth. CTRL experiment values are shown in (a) and N100 in (b). For ease of comparison, the 20 km by 20 km domains are shown to scale as insets (blue borders) at an arbitrary offset within the 80 km by 80 km domains.

4.2 Aerosol hygroscopicity

The apparently over-active activation in the LES models compared to observations is especially surprising given the very low hygroscopicity (0.2) prescribed for the smoke aerosol. Sensitivity tests were also run with NOAA-SAM and DHARMA with a hygroscopicity representative of ammonium sulfate (~ 0.65), a common default (Table 1). Unsurprisingly given the nearly complete activation of the less hygroscopic smoke, NOAA-SAM-KAP06 only minimally enhances the activation fraction (Fig. 6); DHARMA-KAP06 produces a more pronounced increase (~ 10 - 20%) in activation over DHARMA. These sensitivity tests suggest that the activation bias may be, if anything, worse than suggested in Figures 5-6.

4.3 Aerosol-radiation interactions

Baró Pérez et al. (2024) conducted a more in-depth exploration of the effects of smoke absorption in MIMICA, finding that below-cloud semidirect effects noticeably sped the SCT as compared to the minimal influence of indirect effects in that model. Here, we see that MIMICA's lack of rain production is likely responsible for the muted indirect aerosol effects on SCT type. To investigate the relative importance of absorption in a model that does readily undergo a drizzle-driven closed-to-open transition in the right conditions, we run a sensitivity test for the CTRL case with



NOAA-SAM, lowering the single-scatter albedo to 0.8 (Table 1). Figure S2 in the Supplement shows the resulting evolution in terms of cloud fraction and MBL deepening. The $\sim 1 \text{ K day}^{-1}$ peak absorption difference in NOAA-SAM-SSA08 amplifies the diurnal cycle, consistent with LASIC observations (Zhang and Zuidema, 2019), but does not fundamentally change the pacing of the SCT. It does, however, prevent $\sim 100\text{--}200 \text{ m}$ of MBL growth. Giuffrida et al. (2025) also find that forecasts of 3 days or less do not produce clear cloud property differences attributable to the boundary-layer semi-direct effect. While subcloud semidirect effects can clearly influence the nature of the transition between closed-cell stratocumulus and trade cumulus cloud scenes (Baró Pérez et al., 2024), their importance pales in comparison to the secondary indirect effect of precipitation suppression in the models that undergo drizzle-depletion SCTs.

4.4 Downwelling longwave radiation

In the course of investigating the several hundred meter difference in MBL deepening between NOAA- and UW-SAM and DHARMA in the CTRL case (Fig. 4a), a large ($>10 \text{ W m}^{-2}$) discrepancy in downwelling longwave radiation at model-top (6.5 km) produced by the SAM and DHARMA radiation codes was identified. Although a full diagnosis is outside the scope of this work, simulations were run increasing stratospheric ozone by a factor of 10^6 in DHARMA (DHARMA-highO3) and decreasing CO_2 from 405 ppm to 125 ppm in NOAA-SAM (NOAA-SAM-lowCO2) to narrow the gap (Table 1). Figure S3 in the Supplement shows that increasing the downwelling longwave in DHARMA and decreasing it in NOAA-SAM largely, but not entirely, closes the gap in terms of boundary layer growth. The model variants with greater downwelling longwave break up more during the day but otherwise follow a similar deepening-warming trajectory as those with less downwelling longwave. Given variability in free tropospheric water vapor (Pistone et al., 2021) and the occasional presence of midlevel clouds (Adebiyi et al., 2020), the influence of downwelling longwave radiation on the SCT in the southeastern Atlantic basin could be a useful avenue of future work.

5 Discussion and conclusions

The SEA STARR LES intercomparison project simulated stratocumulus boundary layer transitions in the presence of smoke along a composite trajectory representing conditions during August 2017 in the southeastern Atlantic (Fig. 1) and compared the results with observations from aircraft and ground-based campaigns that took place in the region during August 2017 and geostationary satellite retrievals. Simulations were conducted including smoke aerosol and under two different lower aerosol background conditions (Table 1, Fig. 2).

In the presence of substantial smoke, all of the LES models simulate a deepening-warming-style transition with substantial boundary layer deepening (Figs. 3–4) that qualitatively matches the cloud fraction evolution along the SEVIRI trajectories. However, the models overestimate the cloud droplet number concentrations near Ascension Island as measured during the CLARIFY campaign (Fig. 5), despite not overestimating MBL-average aerosol number concentrations (Fig. 6a). These high N_c values are consistent with what has been simulated by previous LES studies with SEA-like smoke conditions (Diamond et al., 2022b; Yamaguchi et al., 2015; Zhou et al., 2017) and inconsistent with typical values



observed across the SEA (Barrett et al., 2022; Diamond et al., 2018; Gupta et al., 2022a). Future work should focus on understanding why the models' diverse activation schemes (Table 2) simulate higher activation fractions than observed (Fig. 6b) and expected based on the highly polluted conditions (Kacarab et al., 2020). DALES, which uses an empirical approach, comes closest to matching the CLARIFY values. High activation fractions may be particularly surprising from the UW-SAM and DHARMA schemes using Abdul-Razzak and Ghan (2000), which has been shown to underestimate activation from Aitken-mode particles (Ghosh et al., 2025); the relevance of Aitken-mode biases may be limited for this case given the dominance of relatively large accumulation mode particles, however. The 1 s timestep used may be too coarse to resolve relevant microphysical processes under high aerosol concentrations (Schwarz et al., 2024), where competition for water vapor is important (Dedrick et al., 2025; Feingold et al., 2001). As high number concentrations, albeit of more hygroscopic aerosol, are envisioned for hypothetical marine cloud brightening interventions using sea salt spray to offset some impacts from greenhouse warming (Feingold et al., 2024; Latham, 1990), proper representation of activation will be critical for assessing the feasibility of marine cloud brightening at local to planetary scales (Diamond et al., 2022a).

Major differences emerge under cleaner free tropospheric aerosol concentrations. NOAA-SAM and DHARMA simulate rapid transitions between overcast stratocumulus and broken open cellular convection driven by a strong positive feedback between drizzle formation and the depletion of boundary layer aerosol concentrations. UW-SAM simulates a deepening-warming transition to scattered cumulus under the N100 case but does break up into open cells in the N030 case, albeit at a much more gradual pace than in NOAA-SAM and DHARMA. MIMICA and DALES maintain a deepening-warming transition regardless of the aerosol conditions.

The differences in transition nature and timing are linked to large LES model differences in the production of drizzle for a given liquid water path and cloud droplet number concentration (Figs. 7-8). NOAA-SAM exhibits a nearly complete transition from all condensate being in cloud droplets to all condensate being in rain drops as LWP increases and N_c decreases, with a sharp gradient in the location of the LWP- N_c state space associated with adiabatic cloud-top effective radius values between 12 and 16 μm . DHARMA and UW-SAM display qualitatively similar albeit gentler transitions between cloud and rain dominated states. MIMICA and DALES show no clear relationship in the LWP- N_c state space. Compared to in-cloud observations aggregated across all three years of the ORACLES campaign (Fig. 9), NOAA-SAM produces rain more readily while UW-SAM and DHARMA produce rain less readily than the observed average for a given cloud state; MIMICA and DALES produce essentially no rain under conditions in which the observed clouds would be expected to contain a substantial rain water content. These model differences do not track any obvious divide in the bulk microphysical specifications (Table 2), with a partial exception of the bin-emulating scheme of Feingold et al. (1998) producing noticeably more rain than the more traditional bulk schemes. DHARMA, MIMICA, and DALES all use variations of the Seifert and Beheng (2006) warm rain parameterizations with gamma function size distributions (although DHARMA uses a lognormal distribution for its cloud mode and MIMICA uses a rain cutoff of 25 μm rather than 40 μm) and end up on opposite ends of the spectrum in terms of producing drizzle-depletion type transitions under moderate to ultraclean aerosol conditions. Microphysical scheme differences are thus the most likely factor behind the difference in importance of drizzle between prior work using the NOAA-SAM bin-emulating scheme (Diamond et al., 2022b; Kazil



et al., 2021; Yamaguchi et al., 2015) or, in the northeast Pacific, the UW-SAM Morrison-based bulk scheme (Erfani et al., 2022), which simulated strong drizzle-driven cloud transitions under clean conditions, and that using the version of MIMICA Seifert-based bulk scheme evaluated here (Baró Pérez et al., 2024) and an earlier version of the DHARMA hybrid Morrison-Seifert scheme without prognostic aerosol (Zhou et al., 2017), which simulated absent or weak drizzle influence on the SCT compared to entrainment. Further work is needed to understand the source of the differences between the different applied model microphysical schemes and constrain model behavior using observations.

Modeling groups that are interested in contributing LES or single column model to future analyses of the SEA STARR dataset are invited to participate following the protocols at Diamond (2026a).

Code and data availability

Source code for SAM is available at Khairoutdinov (2004); for MIMICA, at Brakebusch (2026); for DALES, at Arabas et al. (2024). DHARMA source code is maintained at NASA GISS and can be made available upon request. Code to reproduce the analyses presented in this paper is available at Diamond (2026b).

Forcing files following DEPHY standards and GEOS-5/SEVIRI trajectory data are available at Diamond (2026a). Official SEA STARR output data following DEPHY and CF standards are available at Diamond (2026c) for NOAA-SAM, Diamond and Erfani (2026) for UW-SAM, Diamond and Baró Pérez (2026) for MIMICA, Diamond et al. (2026) for DHARMA, and Diamond and Jungbacker (2026) for DALES.

ORACLES data are available at ORACLES Science Team (2020a) for 2016, ORACLES Science Team (2020b) for 2017, and ORACLES Science Team (2020c) for 2018. CLARIFY data are available at Facility for Airborne Atmospheric Measurements et al. (2017). LASIC aerosol and sonde data are available at ARM user facility (2016a) and ARM user facility (2016b), respectively. MODIS/Aqua MYD08 data are available at NASA LAADS DAAC (2019).

Author contributions

MSD, ASA, AMF, GF, RW, TY, and PZ conceived the SEA STARR intercomparison project. HL and DP created and analyzed the GEOS and SEVIRI trajectories. MSD ran the NOAA-SAM simulations with contributions from GF, TY, JZ, and XZ. EE ran the UW-SAM simulations with contributions from RW. ASA and AMF ran the DHARMA simulations. ABP ran the MIMICA simulations with contributions from FAMB, AMLE, and MS. CJ ran the DALES simulations with contributions from FG and FRJ. MSD and DAJ analyzed the LASIC, CLARIFY, and ORACLES data. MSD wrote the original draft of the manuscript and all authors contributed to review and editing.



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Competing interests

Some authors are members of the editorial board of *Atmospheric Chemistry and Physics*. The authors declare that they have no other conflicts of interest.



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