Thermal-Driven Graupel Generation Process to Explain Dry-Season Convective Vigor over the Amazon

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Abstract. Large-eddy simulations (LESs) are conducted for each day of the intensive observation periods (IOPs) of the Green Ocean Amazon (GoAmazon) field campaign to characterize the updrafts and microphysics within deep convective cores while contrasting those properties between Amazon wet and dry seasons. Mean Doppler velocity (V_{dop}) simulated using LESs are compared with 2-year measurements from a Radar Wind Profiler (RWP) as viewed by statistical composites separated according to wet and dry season conditions. In the observed RWP and simulated LES V_{dop} composites, we find more intense low-level updraft velocity, vigorous graupel generation, and intense surface rain during the dry periods than the wet periods. To investigate coupled updraft-microphysical processes further, single-day golden cases are selected from the wet and dry periods to conduct detailed cumulus thermal tracking analysis. Tracking analysis reveals that simulated dry-season environments generate more droplet-loaded low-level thermals than wet-season environments. This tendency correlates with seasonal contrasts in buoyancy and vertical moisture advection profiles in large-scale forcing. Employing a normalized time series of mean thermal microphysics, the simulated cumulus thermals appear to be the primary generator of cloud droplets. When subsequent thermals penetrate the ice crystal layer, droplets within the thermals interact with entrained ice crystals, which enhances riming in the thermals. This appears to be a production pathway of graupel/hail particles within simulated deep convective cores. In addition, less-diluted dry-case thermals tend to be elevated higher, and graupel grows further during sedimentation after spilling out from thermals. Therefore, greater concentrations of low-level moist thermals likely result in more graupel/hail production and associated dry-season convective vigor.

44

1. Introduction

46

47 Deep convection is a fundamental process of turbulence that drives the Earth's general circulation
48 and regulates thermodynamic fields (Emanuel et al., 1994). Deep convection undergoes complex
49 dynamical and microphysical processes throughout its life cycle, which appear as towering clouds
50 visible from satellites in different parts of the world (Stephens et al., 2002). As a result, deep
51 convection generates significant amounts of atmospheric latent heat, surface precipitation, and
52 hydrometeors that reflect/absorb solar and infrared radiation, modifying atmospheric circulation
53 and surface energy and mass fluxes (Hartmann, 2016). These complexities in deep convection and
54 feedback processes pose significant challenges in predicting weather and climate using numerical
55 Earth system modeling across different scales (Grabowski and Petch, 2009; Sullivan and Voigt,
56 2021).

57

58 Characteristics of deep convection are unique in different seasons and geographic regimes affected
59 by the local environment. One of the most straightforward yet most robust regime separation
60 concepts is the land-ocean (L-O) contrast (Williams and Stanfill 2002). Solar radiation increases
61 the surface skin temperature over land more readily than over the ocean due to the smaller heat
62 capacity of soils and vegetation than deep water bodies, thus producing stronger surface infrared
63 flux and turbulent heat flux (Matsui and Mocko 2014). This greater surface energy deepens
64 planetary boundary layers that may trigger deeper convective clouds depending on the atmospheric
65 profiles (Pielke 2001). Overall, the continental environment tends to promote deeper convection
66 with stronger, wider convective cores (Lucas et al. 1994, Wang et al. 2019), with suppressed warm
67 rain and enhanced cold precipitation process (Williams et al. 2005), which often leads to unique
68 drop-size distribution characteristics and precipitation partitioning between convective and
69 stratiform process outcomes in different geographic regions (e.g., Tokay and Short 1996;
70 Giangrande et al. 2012; Dolan et al. 2018).

71

72 Satellite observations similarly depict continental convective invigoration as characterized by
73 more frequent lightning flashes and heavily rimed particles aloft over land than ocean (Williams
74 et al. 2004, Zipser et al. 2006, Stolz et al. 2015, Matsui et al. 2016). Takahashi et al. (2017 & 2021)

75 show that continental convection generally contains less diluted cores than their oceanic

76 counterparts, following an inverse relationship between convective core width and dilution rate.

77 Similarly, Jeyaratnam et al. (2020) recently suggested that convective updraft and mass flux

78 properties were distinctly different between tropical land and tropical oceanic convection using

79 methods to estimate those properties that blend satellite observations with plume models. Hereafter,

80 we define "convective vigor" by the enhanced cold-precipitation process characterized by larger

81 rimed particles (graupel/hail) and large and copious raindrops in convective cores.

82

83 Representation of deep convective cloud land-ocean contrasts is still an ongoing challenge for

84 global atmospheric models at storm-resolving resolution (a few km of horizontal grid spacing),

85 partially owing to the poor representation of cloud dynamics (Matsui et al. 2016). Robinson et al.

86 (2011) configured idealized simulation setups to investigate the "island" effect of convection with

87 finer grid spacing (500 m or 1 km) and successfully simulated convective vigor equivalent to the

88 observed microwave brightness temperature. Matsui et al. (2020) used a nested regional model

89 with 1 km grid spacing to compare mid-latitude continental versus tropical maritime storms and

90 successfully reproduced land-ocean contrasts of hydrometeor identification profiles from

91 polarimetric radars.

92

93 However, statistical evaluation of simulated vertical velocity and association with convective

94 vigor process (i.e., graupel/hail generation) have not yet been examined very well due to a lack of

95 observations and detailed process-oriented model investigation, respectively. For example,

96 mesoscale convective system (MCS) studies performed by Prein et al. (2022) and Ramos-Valle et

97 al. (2023) highlight the challenges when attempting to represent continental convection within the

98 constraints of limited observations while attempting to establish optimal configurations as a

99 function of model grid spacing for typical midlatitude (Oklahoma) and tropical continental

100 (Amazon) conditions.

101

102 The 2-year measurements from the Green Ocean Amazon (GoAmazon) campaign provide

103 unprecedented data on the vertical velocity of deep convection by the Atmospheric Radiation

104 Measurement user facility (ARM, ARM Mobile Facility (AMF), Martin et al. 2017, Giangrande

105 et al. 2017). Recently, Giangrande et al. (2023) contrasted the thermodynamics and lifecycle

properties, including the vertical air velocity within isolated convective clouds observed during the Amazon wet and dry seasons, and found that dry-season convection exhibited more intense low-level updrafts and larger reflectivity associated with smaller convective cell areas than wet-season counterparts. Dry-season convection also tended to exhibit a shorter life cycle and often achieved maximum updraft and precipitation intensity at earlier life cycle stages than wet-season storms. Pre-convective thermodynamics profiles from those events revealed that the dry season showed a stronger deficit of dew-point temperature in the middle troposphere and higher values of mean-layer convective available potential energy (MLCAPE) at lower levels.

In addition to primary thermodynamic transitions between wet and dry season convective regimes (e.g., Giangrande et. al. 2020), the Amazon dry seasons may experience larger concentrations of aerosols due to biomass burning that have been recently associated with potential secondary contributions to changes in storm precipitation properties and convective vigor (e.g., Lin et al. 2006; Wang et al. 2018; Öktem et al. 2023). Moreover, the Amazon dry (wet) season has long been suggested to promote a continental (maritime) convection contrast for a given thermodynamic profile and background aerosols (Williams et al. 2002). Typical land-ocean contrast is characterized by a "hot" continental surface (Williams and Stanfill 2002) and sea-breeze type of mesoscale dynamics due to the thermal-patch effect (Robinson et al. 2011). Thus, instead of focusing on the complex nature of land-ocean contrast or other active versus break monsoonal contrasts performed globally (e.g., Holland et al. 1986, Keenan and Carbone 1992, Pope et al. 2009, Wu et al. 2009), the dry-wet season contrasts over the Amazon basin allows a unique emphasis on the impact of thermodynamic profiles and large-scale dynamics upon the formulation of convective vigor.

The main objective of this paper is to investigate dry-wet seasonal contrast and potential changes in the evolution of deep convection cloud processes using an LES model and forward simulations of Doppler radar observations. This attempts to reveal dynamical and microphysical processes that explain the observed dry-wet contrasts, focusing on the bulk controls imposed by the background thermodynamic profiles and large-scale forcing. The motivation for these efforts is the argument that an improved understanding of these dry-wet contrasts should facilitate untangling the more complex processes of land-ocean contrasts in deep convection. For this study, we employ a series

of daily large-eddy simulations (LESs) with bulk single-moment microphysics throughout the GoAmazon campaign dry and wet season intensive observation periods (IOPs) to characterize dry-wet season contrast in convection. These simulations are validated against the cumulative statistics of ground-based Doppler velocity measurements during those periods. A thermal tracking analysis is conducted to select golden cases from these dry- and wet-season LES runs to investigate the physical process of convective vigor further. This effort focuses on thermodynamic impacts and cloud dynamical roles in this manuscript, while the aerosol effects will be investigated in another study.

Section 2 describes the general methodology and tools, including radar profilers, LES, instrumental simulators, large-scale meteorological forcing, and thermal-tracking algorithms for this study. Section 3 shows the results of the dry-wet contrast of meteorological forcing, statistical composites of Doppler velocity, and thermal tracking analysis. Section 4 summarizes a thermal-driven process of dry-season convective vigor, its uncertainties, and future directions.

2. Methods

2.1 GoAmazon: RWP Observations

The primary datasets for this study are those collected by the 1290 MHz ARM Radar Wind Profiler (RWP) operated during the U.S. Department of Energy's ARM ARM facility deployment during its "Observations and Modeling of the Green Ocean Amazon 2014–2015" (GoAmazon) campaign near Manaus, Brazil, from March 2014 through December 2015 (e.g., Martin et al., 2017). The RWP was configured for precipitation sampling that included frequent vertical pointing to collect conventional radar reflectivity factor Z and mean V_{dop} profiles through deep convective cells to approximately 17 km in altitude (e.g., Giangrande et al. 2013, Giangrande et al. 2016, Wang et al. 2019, Williams et al. 2023). For measurements collected at these ultra-high frequencies and without expectations for larger hail in Amazon deep convective storms (Liu and Zipser 2015, Bang and Cecil 2019), all radar estimates are assumed as within Rayleigh scattering regimes, and measurements are unattenuated in rain. The RWP deployed during GoAmazon had a beam width

168   of approximately 10 degrees thus horizontal measurement resolution is typically less than 1 km,

169   with a 200 m vertical (bin, gate) resolution and 10-s intervals between consecutive radar profiles.

170   All radar measurements were calibrated against a reference laser disdrometer collocated at the

171   main AMF site during the campaign (e.g., Wang et al. 2018), and a detailed method is discussed

172   in Williams et al. (2023).

173

174   For observation and simulation comparisons, the deep convective core is defined by using

175   thresholds applied to the observed and simulated RWP profiles: 1) column-maximum reflectivity

176   is greater than 35 dBZ, and 2) column-maximum V_{dop} is greater than 5 m/s. The choice for these

177   criteria is admittedly flexible, as model-vs-observed Z thresholds, in particular, are not necessarily

178   well-posed for convective-stratiform segregation such as removing all stratiform cells (e.g., Steiner

179   et al. 1995). Still, the additional velocity constraint afforded by the vertically-pointing RWP and

180   statistical representation of convective and stratiform composites seems to be reasonable (not

181   shown here), noting what is important is an attempt to apply thresholds for both observations and

182   simulations. A slightly different threshold does not alter the conclusions. Note that events on

183   3/19/14, 3/20/14, and 3/23/14, as well as the 10/4/14 cases from the dry season IOP, are clear

184   examples of Amazon mesoscale convective systems (MCSs, e.g., Wang et al. 2019). Thus, these

185   cases have also been removed from our statistical analysis to focus on isolated convective days.

186

187

188   **2.2 GoAmazon LES, Forcing, and Simulator**

189

190   GoAmazon LES runs utilize the Goddard Cumulus Ensemble (GCE), a cloud-process model

191   developed and improved at NASA GSFC over several decades (Tao *et al.* 2014). The GCE is

192   driven by large-scale forcing (LSF) with cyclic boundary conditions to generate cloud dynamics

193   and microphysics processes in Cartesian grid coordinates. No additional heat, moisture, or

194   momentum enters the domain apart from that imposed by the LSF or solar/infrared radiative

195   processes. In addition, GCE's anelastic dynamic core option allows faster integration of finer-

196   resolution runs (up to 1.5~2 times) than its compressible dynamic core option.

197

198 GoAmazon LES runs use 200-m horizontal grid spacing with 512 x 64 x 128 grids (x-y-z cartesian

199 coordinates) with a 2-second model time step. Vertical grid spacings stretch from near surface

200 level (starting from 44 m) and reach 200m around 4 km level, not to exceed horizontal resolution.

201 Thus, the domain covers a 102 km x 12.8 km area; this "narrow channel" domain setup intends to

202 resolve three-dimensional large eddies (i.e., thermals) while minimizing computational cost in

203 order to run LES for the entire IOPs. In terms of model physics, the 1.5-order turbulent kinetic

204 energy (TKE) scheme is used for subgrid turbulent mixing, and the Goddard radiation scheme is

205 used for computing radiative flux and heating (Chou and Suarez 1999 & 2001, Matsui et al. 2018).

206 The Goddard bulk one-moment 6-class scheme (4ICE hereafter) has four ice classes and uses

207 preset size and density mapping for snow, graupel, and hail (Lang et al. 2014; Tao et al. 2016).

208 4ICE successfully generated a realistic L-O contrast of convective-core hydrometeor distributions

209 compared to polarimetric radar retrievals in the previous study (Matsui et al. 2020). Also, note that

210 the one-moment scheme is unaffected by the background aerosol concentrations to focus on the

211 impact of thermodynamic and large-scale forcing on convective vigor in this study.

212

213 The LSF is derived from the VARiational ANALysis (VARANAL) approach, which is a broadly

214 accepted method for generating large-scale forcing wherein data are collected and adjusted based

215 on the vertical integration of the atmospheric mass, moisture, dry static energy, and momentum

216 budgets (Zhang and Lin 1997, Zhang et al. 2001, Xie et al. 2004). The VARANAL approach is

217 applied to the GoAmazon field campaign using ERA-Interim reanalysis (Dee et al., 2011) and

218 constrained by radar-based surface precipitation rate (Tang et al. 2016). The horizontal/vertical

219 advective forcings, mean wind profiles, and surface heat fluxes from the GoAmazon LSF are used

220 to drive the LES. These fields are interpolated and imposed as tendency terms at every model time

221 step. Our previous research demonstrated that GCE reproduced the observed precipitation quite

222 well when forced by the GoAmazon LSF (Tao et al. 2022). GoAmazon LESs are run from

223 September 2014 to 10 October 2014, defined as the dry-season IOP, and also run from 14 February

224 2014 to 26 March 2014, defined as wet-season IOP, as suggested by thermodynamic behaviors

225 characteristic of larger dry and wet-season expectations, respectively (Giangrande et al. 2017,

226 2020). Each daily LES is initialized at 12 AM local time from the LSF and integrated just for 30

227 hours rather than continuously integrated during the entire IOPs because the convection life cycle

228 typically follows a strong diurnal cycle due to the solar heating cycle, excepting propagating

229 organized convection (Tang et al. 2016, Giangrande et al. 2017, 2020). As a default setting, hourly
230 LES outputs are used to analyze the mean seasonal behavior of LESs.

231

232 Hourly LES outputs include an additional Doppler velocity field, corresponding to an expected
233 RWP observation through a multi-instrumental simulator, Goddard Satellite Data Simulator Unit
234 (G-SDSU, Matsui et al. 2014a; Matsui et al. 2014b). In this study, a ground-based Doppler radar
235 simulator is implemented in the model to replicate RWP observable signals. Radar backscatter is
236 estimated from nonRayleigh calculations with a Maxwell-Garnett assumption of air-water-ice
237 mixtures at 1290 MHz frequency, though for the RWP frequency, vertical pointing, and media
238 type/size expectations therein, the forward modeling is more straightforward than most weather
239 radar wavelength applications and appropriate for Rayleigh scattering assumptions. Doppler
240 velocity is estimated using pressure-adjusted hydrometeor terminal velocities weighted by radar
241 backscatter spectrum for each particle size distribution (PSDs). All these single scattering
242 calculations follow the 4ICE microphysics calculation/assumptions of particle size, density, and
243 phase for each hydrometeor species for physics consistency (Matsui et al. 2014b). Finally,
244 simulated signals are averaged consistent with the RWP beamwidth (10 degrees). This beamwidth
245 implies different averaging at different heights, for example, corresponding to six horizontal grids
246 of the LESs being averaged for a representative output at the 15 km height. Overall, this beamwidth
247 averaging smear LES-scale Doppler velocity signal statistics closer to the anticipated observed
248 instrumental signals (Matsui et al. 2014b). However, it should be noted that the exact sampling
249 methods are different between observations and simulations. For example, the RWP observations
250 are vertical pointing measurements that collect profiles at 6-second ("instantaneous") intervals. In
251 contrast, the modeled RWP signals are drawn from a domain-wide sampling of hourly LES outputs.
252

253

254 **2.3 Thermal Tracking Algorithm**

255

256 The thermal tracking method used here is described in detail by Hernandez-Deckers and Sherwood
257 (2016), who improved the initial version used by Sherwood et al. (2013). It is an offline algorithm
258 that uses high temporal resolution output (~1 min) from LES to identify and track coherent rising
259 volumes of cloudy air, i.e., thermals. The algorithm first identifies all peak vertical velocities larger

260   than 0.8 m/s that have water condensate content of at least 0.01 g/kg at every available snapshot

261   of the simulation and matches peaks from successive snapshots to identify the available points of

262   the trajectories of rising cloudy air parcels. A third-order polynomial is fitted to these points to

263   reconstruct smooth trajectories and to allow a precise estimate of the ascent rate of the rising air

264   volume at each snapshot. Notice that this ascent rate differs from the actual vertical velocity at a

265   particular grid point since thermals develop internal toroidal circulations such that the peak vertical

266   velocity at their centers is higher than the actual ascent rate of the air volume (e.g., Blyth et al.

267   2005; Sherwood et al. 2013).

268

269   The extent of each rising air volume (the size of each thermal) is estimated assuming a spherical

270   shape centered at its smoothed trajectory, ensuring that the average vertical velocity of the enclosed

271   volume matches that obtained from the derivative of the trajectory. Tracked thermals must fulfill

272   certain requirements; for example, they must be tracked for at least three time steps, their radius

273   must be larger than twice the horizontal grid spacing, their time-average ascent rate must be at

274   least 1 m/s, their change in size in between successive snapshots must be less than 80% of the

275   smallest radius, and most importantly, their trajectories must be consistent with their vertical

276   momentum budget. The momentum budget of a tracked thermal is computed from its buoyancy

277   (obtained from the density field), the pressure gradient force (obtained by integrating the pressure

278   field over the entire thermal's surface), a "resolved mixing term" (obtained from the convergence

279   of vertical momentum flux across the thermal's surface), and an entrainment or detrainment

280   contribution due to the change in size between snapshots. This allows us to compute the expected

281   final position of each thermal based only on its initial ascent rate, which is compared with the

282   thermal's last tracked position. The distance between the actual and expected final positions must

283   be smaller than the average thermal diameter and smaller than 20 % of the vertical distance

284   traveled; otherwise, the thermal is discarded.

285

286   Once thermals are tracked with this algorithm, many properties can be studied based on all

287   available model variables of interest. For example, average values for each thermal, such as ascent

288   rate, size, altitude, entrainment rate, etc., are easily computed. Also, composites of different

289   quantities can be obtained for different "stages" of a thermal's lifecycle. Typically, thermals exhibit

290   one maximum ascent rate throughout their lifetime, which indicates their most vigorous phase.

291   This time step is used as a time reference common (t=0) to all thermals to create composites of
292   various properties at different stages of thermal lifetimes. Note that our tracking algorithm cannot
293   analyze merging or splitting thermals, regardless of their occurrence. This limitation requires
294   further study.

295

296   This thermal tracking algorithm was first used to study the main properties of cumulus thermals in
297   simulations of transient-growing convection (Sherwood et al., 2013; Hernandez-Deckers and
298   Sherwood, 2016) and provided strong evidence that thermals are typically small, short-lived (4-5
299   minutes on average), and mix vigorously with their environment. Also, Hernandez-Deckers and
300   Sherwood (2016) showed that the spherical shape approximation is generally valid and that
301   thermals, rather than plumes, are a more realistic building block for cumulus clouds. Hernandez-
302   Deckers and Sherwood (2018) used this algorithm to study the mixing properties of thermals in
303   more detail and contrast them with known parameterizations. Results from these studies have set
304   up the stage for a deeper understanding of cumulus dynamics and for further studies that use
305   different approaches (e.g., Gu et al., 2020; Morrison et al., 2020; Peters et al., 2020; Xu et al.,
306   2021; Morrison et al., 2023). Recently Hernandez-Deckers et al. (2022) used this algorithm to
307   study aerosol-deep convection interactions, highlighting the importance of the strong coupling
308   between microphysics and small-scale dynamics in convective clouds. Here we run this tracking
309   algorithm with the GCE model output for 5 hours starting at 1900Z (3 pm local time) on 09/07/14
310   (dry case) and 02/26/14 (wet case), using 1-minute interval output.

311

312

313   **3. Results**

314

315   **3.1 Dry-Wet Contrast of Large-Scale Forcing**
316   Campaign atmospheric thermodynamic profiles and the typical variability observed during
317   GoAmazon dry and wet seasons have been previously depicted using composite radiosonde skew-
318   T log-P diagrams (e.g., Giangrande et al., 2017, 2020, 2023). These depictions often show very
319   similar temperature profiles between dry and wet seasons, whereas the moisture profiles indicate
320   apparent differences, highlighting the mid-level deficit of the dew-point temperature profile in dry-

321 season composites. Since this study utilizes LSF to drive LESs, seasonal thermodynamics and
322 dynamics are re-characterized by the LSF (Tang et al. 2016).

323

324 In Fig. 1, we plot a time series of apparent moisture sinks (Q2), vertical moisture advection, and
325 parcel potential buoyancy profiles with surface precipitation rate from GoAmazon LSF for the
326 IOPs. These time series of LSF profiles are integrated and contrasted in terms of Contoured
327 Frequency by Altitude Diagrams (CFADs, Yuter and Houze 1995) as the dry and wet season IOPs
328 (Figure 2).

329

330 Here, Q2 is the sum of changes in moisture content, horizontal moisture advection, and vertical
331 moisture advection (Yanai et al. 1973), balanced with net condensation rate and turbulent transport
332 of moisture vertical advection. Large Q2 corresponds to a large atmospheric moisture loss due to
333 net condensation loss (i.e., precipitation). Large Q2 is associated with intervals with heavier or
334 more widespread surface precipitation; thus, dry-IOP Q2 and surface precipitation are typically
335 smaller than wet IOP (Fig. 1a-b). Similarly, Figs. 1c-d shows that peaks of vertical moisture
336 advection term coincide with those peaks in the Q2 rate. Note that the Q2 rate in tropical
337 environments is mainly contributed by the vertical moisture advection term rather than the
338 horizontal advection term (not shown here). More importantly, positive (red shade) vertical
339 moisture advection of the wet IOP tends to be stretched up to higher altitude (up to 200 mb) than
340 the dry IOP (up to 600 mb) in most cases.

341

342 As previously discussed by Tang et al. (2016), the associated Amazon Q2 CFADs show the largest
343 positive Q2 between 700 and 400 mb, while the largest negative Q2 is around 800 mb (Figs. 2a-
344 b). The Dry-wet composite CFAD highlights more frequent positive Q2 values above the 800 mb
345 level during the wet IOP. In contrast, more frequent negative Q2 during the dry IOP (Fig. 2c).
346 Vertical moisture advection depicts similar CFAD shapes (Figs. 2d-e). Still, it highlights high
347 frequencies of low-level positive vertical moisture advection and mid-to-low-level negative
348 moisture vertical advection in the dry IOP in comparison with the wet IOP.

349

350 Finally, in Figs. 1e-f we plot the time series of parcel potential buoyancy profiles (positive
351 components only), computed from LSFs by lifting surface airmass dry and moist adiabatically.

352   These potential buoyancy magnitudes are not necessarily associated with precipitation intensity.

353   Potential buoyancy CFADs show peak forcing between the 600 mb and 200 mb levels (Figs. 2g,

354   h, & i). The wet IOP suggests a larger variability of potential buoyancy at the upper troposphere

355   than the dry IOP (Figs. 2g-h). Potential buoyancy appears to be slightly stronger in the dry IOP,

356   and concentrated in a relatively lower troposphere than its wet IOP counterpart (Fig. 2i), which

357   agrees with findings in Giangrande et al. (2023). These results will be further discussed along the

358   thermal concentrations in the latter section.

359

360

361   **3.2 Dry-Wet Composite of Doppler Velocity CFADs**

362

363   Giangrande et al. (2023) highlighted dry-wet seasonal characteristics of storm vertical air motions

364   retrieved using RWP. They found that daytime isolated dry season convective cells tend to have

365   stronger updrafts at altitudes below the melting level. Yet, unlike their wet-season counterparts,

366   updrafts do not increase in intensity much above the melting layer. However, dry-season

367   convective cores were also characterized by stronger downdrafts at all altitudes, especially when

368   compared to wet-season counterparts aloft. Our present study utilizes similar direct measurements

369   of the mean V_{dop} from RWP to characterize the dry-wet contrast of deep convective cores. The

370   advantage of using V_{dop} measurements is that the quantity is the direct radar measurement and

371   helps reduce uncertainties from retrieval assumptions, such as requiring hydrometeor

372   identification or associated terminal fall speed corrections if the intent was to retrieve the vertical

373   air motion (Giangrande et al. 2013, 2016). Here, vertically-pointing V_{dop} measurements contain

374   sufficient information to evaluate storm characteristics, with the understanding that these

375   measurements represent the terminal velocities of hydrometeors combined with the vertical air

376   motion.

377

378   In Fig. 3a, we provide the cumulative sample numbers of CFADs (for each bin of V_{dop} and altitude)

379   as simulated and subsampled from the LES hourly outputs from the combined dry and wet season

380   IOPs. If the sampling numbers are normalized for each altitude, the Vdop CFADs will be formed.

381   Fig. 3b shows the sum of hydrometeor mass concentrations from each V_{dop}-altitude bin. Namely,

382   each hydrometeor mass concentrations from "cloud", "rain", "graupel-plus-hail", or "ice-plus-

383 snow" are separately accumulated for each bin. The larger number of samples associated with a

384 larger accumulated mass concentration of hydrometeor can generate the "representativeness" of

385 the hydrometeor class for a given V_{dop}-altitude bin location. Because V_{dop} is the sum of the vertical

386 velocity of the air and the terminal velocity of hydrometeor particles weighted by their reflectivity,

387 this plot facilitates understanding V_{dop} CFAD.

388

389 As mentioned above, we defined four regimes based on the accumulated mass of each hydrometeor

390 category. The "cloud" category (CL) is centered around -5 m/s of V_{dop} and 4 km altitude, slightly

391 overlapping with other categories. A "rain" category (RA) is more narrowly concentrated around

392 -8 m/s of V_{dop} and below 4 km altitude. The "graupel-plus-hail" category (GH) is centered around

393 -14 m/s of V_{dop} at 5 km altitude. Finally, an "ice-plus-snow" category (IS) is narrowly concentrated

394 along -1 m/s of V_{dop} above 5 km altitude. These locations roughly correspond to each hydrometeor

395 category's altitude and terminal velocity when factoring in the background/ambient vertical air

396 velocity. Note that our "cloud" regime has no terminal velocity in GCE 4ICE microphysics, thus

397 V_{dop} represents or tracks the background vertical air velocity and overlaps with the other regimes.

398 Moreover, simulated V_{dop} and hydrometeor statistics are also sensitive to model physics and those

399 assumptions to some degree. For example, any real-world cloud regime may be extended to higher

400 altitudes, but the model 4ICE microphysics scheme tends to quickly convert cloud liquid to cloud

401 ice category due to saturation adjustment (See Figs. 14-16 of Matsui et al. 2023). Nevertheless,

402 this representative mapping will help discuss the variability of the V_{dop} CFADs between the dry

403 and wet season IOPs.

404

405 In Fig. 4, we provide an observed and simulated climatology of V_{dop} CFADs as sampled from deep

406 convective cores and summarized over the dry and wet season IOPs. In both the dry and wet season

407 IOPs, the observed CFADs depict a smoother transition of the V_{dop} at the freezing level into the

408 melting layer (4-5 km, Figs. 4a-b). At the same time, simulations show a more abrupt transition

409 around the freezing layer (Figs. 4d-e). This is primarily because bulk single-moment microphysics

410 more abruptly converts solid to liquid phases through autoconversion than explicit bin-resolving

411 microphysics (Iguchi et al. 2014). This rapid conversion also overestimates the terminal velocity

412 of raindrops near and just below the freezing level. Another possible reason is overestimating the

413 graupel/hail size, leading to larger melted raindrops with high terminal velocity.

414

415 The CFADs have been summarized according to dry and wet season IOPs to explore these seasonal

416 contrasts between the deep convective cores (Figs. 4c, 4f). In the R regime (green box), the dry

417 IOP suggests more prevalent samples in strongly negative V_{dop} for our observations and

418 simulations, indicating that deep convective cores during the dry season IOP tend to have more

419 vigorous, faster-falling (larger) raindrops. In the GH regime (purple box), the dry season IOP

420 dominates the sampling. The observations indicate this dominance (red shade) up to 10 km altitude

421 (the extent that observations were included), while the simulation shows this behavior up to 8 km,

422 suggesting LES underestimation in graupel/hail altitudes. In the CL regime, the observations and

423 the simulations agree well, except that some sampling is overwhelmed by the dry season IOP

424 behaviors in the overlapped area. This likely indicates a shift in the presence of stronger low-level

425 updraft velocities, consistent with the analysis in Giangrande et al. (2023).

426

427 When considering the IS regime, there are examples of agreements and discrepancies between the

428 observations and simulations. One key agreement is that the wet IOP dominates the samples in the

429 area of positive V_{dop} above 8 km altitude. This indicates that observations and simulations suggest

430 a shift towards stronger upper-level vertical air velocity for the wet season IOP examples than for

431 the dry season IOP. This is consistent with the absence of dry mid-levels and the stochastic updraft

432 model expectations from Giangrande et al. (2023). On the other hand, the observations indicate a

433 more dominant sampling of velocities during the wet season IOP at around -3 m/s of V_{dop}, whereas

434 simulations change the dominant sampling mode from wet to dry IOPs at around 7 km altitude.

435 This is a potential bias in single-moment bulk microphysics, which tends to glaciate cloud droplets

436 or raindrops more quickly into ice particles than double-moment schemes (e.g., Fig. 16 of Matsui

437 et al. 2023). The observed composite also shows more dry-season dominant frequencies in GH

438 zones than the simulation, indicating the underestimation (overestimation) of raindrop/graupel

439 (ice/aggregate) particles above 7 km height.

440

441 Excepting this discrepancy in the IS regime, dry-wet composites of V_{dop} CFAD agree well between

442 observations and simulations, suggesting that LES could successfully represent the important

443 nature of dry-wet contrast, i.e., dry-season convection tends to generate stronger low-level updraft

444   velocity, generating more graupel/hail, and vigorous raindrops accompanied with stronger low-

445   level downdraft than the wet season.

446

447   To further investigate these seasonal shifts in core properties, golden cases are selected to analyze

448   deep convection lifecycle and processes. Golden cases are two single-day simulation cases, one

449   for dry and one for wet season, representing V_{dop} CFADs of each season. For this, the V_{dop} CFADs

450   are constructed for each day during the wet and dry season IOPs, and these daily CFADs are

451   compared to the composites of seasonal CFADs (not shown here). After day-to-day analysis of

452   correlation and root-mean-square errors between daily and seasonal CFADs, the convective event

453   on the 2/26/14 case is selected to represent the wet IOP convections. In contrast, the 9/7/14 case is

454   chosen to represent dry IOP convection. Fig. 5 shows a dry-wet composite of V_{dop} CFAD using

455   these two case studies. This figure compares quite well with the seasonal composite of V_{dop} CFAD,

456   having the dry convective vigor signals and model biases of the seasonal composite (Fig. 4f).

457

458   In Fig. 6, we show a time series of domain-mean profiles of convective cores drawn from these

459   dry- and wet-season golden cases, highlighting from 1600Z (1200 local time) of the starting day

460   to 0400Z (0000 local time) of the next day. The dry season golden event shows a clear diurnal

461   convection cycle, peaking at 2100-2200Z (local 5-6 pm). In contrast, the wet season golden event

462   shows an already ongoing, continuous sequence of deep convection with several embedded strong

463   pulses. Convective top heights reach up to 17 km for both the dry and wet events (Figs. 6a-b).

464   Low-level positive upward vertical velocity is more ubiquitous in the dry case, while upward

465   vertical velocity of the wet case extends to the middle-to-upper troposphere up to 15km (Figs. 6c-

466   d).

467

468   Dry-case graupel-plus-hail (GH) mass concentrations peak around 2100-2300Z when the

469   convective clouds reach their deepest cloud top heights, and the maximum GH concentration

470   exceeds that of the wet case. Rain mass concentrations peak between 2200Z and 00:30Z on the

471   subsequent day for the dry case, and this appears to be slightly more intense than the rainfall

472   simulated for the wet cases. Note that precipitation areal fraction is expected to be larger for the

473   wet season (i.e., Giangrande et al. 2016, 2023), such that dry-season convection is often

474   characterized by narrow yet intense isolated convection, while wet-season convection is

16

475   characterized by widespread moderate to deep convection (although with higher domain mass

476   flux). The intense surface rainfall rates are generally correlated with the generation of graupel,

477   frozen drops, and/or small hail particles during the dry-season convection, but there are some time

478   lags from 21Z to 22:50Z in the dry-case convection. This is because the initial convective core is

479   much narrower, and near-surface relative humidity is slightly low (~80%) around 21Z, and later

480   convective area increases so as near-surface relative humidity (~96%) around 21:50Z. Thus, more

481   surface rain evaporation likely suppresses surface precipitation during earlier convective periods.

482   These time series behaviors are generally consistent with the observed characteristics in the time-

483   integrated V_{dop} CFADs (Fig. 5).

484

485   One key question is why larger or heavily rimed particles tend to be preferentially generated in

486   dry-season convection compared to wet-season convection, given that both seasons indicate

487   convection with intense updraft velocity. This question follows previous efforts of Williams and

488   Stanfill (2002) for simulations of deep convection that contrasted land and oceanic clouds. For

489   example, while land and ocean environments may have similar convective available potential

490   energy (CAPE), differences in detailed potential buoyancy and vertical velocity profiles enable

491   additional graupel/hail particles to form in continental deep convection when compared to the

492   maritime environments (Matsui et al. 2020). A Lagrangian tracking analysis is performed to

493   examine this question for Amazon dry and wet season contrasts to investigate the dynamics and

494   microphysics within cumulus thermals for these dry and wet golden events (Section 3.3).

495

496

497   **3.3 Thermal Tracking Analysis**

498

499   Thermal tracking analysis (Section 2.3) was conducted over 5-hour periods from 1900Z to 0000Z

500   for the dry and wet season events using 1-minute LES outputs. Fig. 7 depicts normalized x-z cross-

501   sections of thermal properties at the moment of maximum vertical velocity in the dry and wet cases

502   and dry-wet differences. Thermals typically experience development and decaying stages in their

503   lifetime. During development, moist thermals increase their vertical velocity and size by releasing

504   latent heat and entraining surrounding air (Morrison et al. 2021). After defining and tracking each

505   thermal from the LESs, our normalizing procedure first defines the reference time from each

506 thermal's lifetime based upon peak vertical air velocity (denoted as thermal maxima) and then
507 conducts a weighting average of each thermal property at the thermal maxima only. Our weights
508 are based on the magnitude of thermal mass flux to avoid under-representing properties of less-
509 populated but vigorous thermals. Because these heights at thermal reference time are different for
510 each thermal in dry and wet case studies, averaging properties are somewhat biased toward thermal
511 vertical distributions (discussed later).

512

513 For example, in Fig. 7a we plot the weighted-average peak vertical air velocity (W) for the dry-
514 case thermal (9.6 m/s) and the wet-case thermal (10.6 m/s). Perhaps surprisingly, the flux- and
515 radius-weighted average dry-case thermal is slightly slower in W than that found for the average
516 wet-case. Here, we find that the vertical air velocity of the wet-case thermal is more
517 homogeneously distributed than its counterpart for the dry-case thermal, leading to higher
518 weighted-mean W despite weaker values at thermal centers (red shade in Dry-Wet plot, Fig. 7a).
519 Also, unexpectedly, supersaturation and cloud droplet mixing ratio (Qc) of the dry-case thermal
520 are elevated compared to the wet-case thermal (Fig. 6b-c), since wet-case thermals may be
521 expected to instead have higher supersaturation and/or more condensation owing to the higher
522 availability of water vapor (e.g., Giangrande et al. 2023).

523

524 Exploring the other classes, the rain mixing ratio (Qr) is similar between the dry-case and wet-case
525 thermals (0.17 g/kg), but graupel-hail concentrations (Qg+h) are significantly larger in the dry-
526 case thermals (0.95 g/kg) compared to the wet-case thermals (0.79 g/kg); this latter result is
527 consistent with previous discussions from event time-series in Fig. 6e. Cloud ice and snow mixing
528 ratio (Qi+s) values are slightly larger in the wet-case thermal (3.5 g/kg) than in the dry-case thermal
529 (3.2 g/kg). While this difference is not significant, this is also potentially a surprising outcome
530 since dry-case deep convective clouds might otherwise be expected to be deeper/stronger and thus
531 characterized by additional ice hydrometeor concentrations. However, some absence of these
532 media may be partially explained by following Giangrande et al. (2020; 2023) suggestions that
533 drier mid-to-upper levels in the dry season may limit periphery precipitation aloft (i.e., enhanced
534 evaporation). Overall, Qr and Qg+h seem to be concentrated in these composite averages
535 downward from the thermal core due to the gravitational sedimentation process. Supersaturation
536 and Qc, however, are also more vertically elongated than thermal properties established by

537   Hernandez-Deckers et al. (2022) using the Weather Research and Forecasting (WRF) model for a

538   case of scattered convection over Houston, Texas. Qi+s is more homogeneously distributed across

539   the defined borders of thermals. Also, dry-wet differences show slight asymmetric results,

540   particularly in W, Qr, and Qg+h. These could be attributable to differences in horizontal wind

541   shear, evidenced by a greater tilt in the thermal centerline flow in the dry case (gray streamlines),

542   leading to greater concentrations in the tilt direction of more rapidly sedimenting quantities that

543   are formed within thermals (i.e., Qr and Qg+h); since thermal composites are not aligned with the

544   mean wind, such preferential outflow may not be fully captured by this analysis (i.e., asymmetric

545   signatures could be greater or lesser along other directions than X alignment).

546

547   An initial leading question is why the dry-case thermals have greater cloud water and

548   supersaturation on average. To further untangle these results in Fig. 7b-c, we derive the vertical

549   profiles of flux-weighted mean thermal states, now including all thermal times (Fig. 8a-g).

550   Immediately, these plots reveal striking differences between the thermal number concentration

551   (N) profiles for dry-case and wet-case examples (Fig. 8a; the number of thermals per km height

552   within the 102 km x 12.8 km domain). For instance, dry-case convection shows a larger

553   concentration of thermals below the 8 km height, while wet-case convection promotes a more

554   homogeneous thermal concentration that extends across most heights. This behavior is somewhat

555   reminiscent of the distribution for the difference in vertical moisture advection and potential

556   buoyancy profiles between the parent dry and wet season conditions (e.g., Fig. 1 and 2, discussions

557   in Section 3.1). Moreover, thermal generation in our LES responds to these terms partially from

558   the seasonal large-scale forcing.

559

560   According to the classic similarity theory of Morton et al. (1956), the width of dry/moist thermals

561   should increase with increases in the boundary layer depth (William and Stanhill 2002). For the

562   Amazon basin, previous GoAmazon studies such as Giangrande et al. (2017, 2023) showed that

563   dry season boundary layer height is generally deeper than that of the wet season, potentially on the

564   order of 200 m deeper for isolated deep convective events they tracked. Following this logic, dry-

565   case convection may anticipate larger thermals. However, LES thermal tracking analysis suggests

566   that the sizes (R) of thermals upon initiation appear to be quite similar between the wet and dry

567   events and then appear to grow at similar rates for several km before the dry-case thermal size

568　catches up with the moist size around 6 km in height, only to be overtaken again by the deeper

569　wet-case thermals around 9 km (Fig. 8b). Further, Fig. 8c shows the mean vertical velocity of

570　thermals, showing nearly identical updraft velocity below 4 km. However mean updraft velocity

571　profiles above 4 km are quite different between the dry and wet cases; e.g., the dry case peaks

572　around 8 km, while the wet case peaks at 6 and 10 km. This result implies that differences in moist

573　convection between dry and wet cases are poorly characterized by thermal sizes.

574

575　Qc in thermals also shows very similar profiles between the dry and wet cases (Fig. 8d). However,

576　because thermal numbers of the dry case are more concentrated at the lower troposphere (Fig. 8a),

577　all-height mean properties of dry-case thermals are characterized by more Qc (Fig. 7c). Qr of the

578　wet case is nearly twice as large as the dry case (Fig. 8e); however, normalized x-z cross-section

579　(Fig. 7d) does not show such a large difference (explained below). Qi+s also shows similar

580　distributions (Fig. 8f). Still, total x-z mean Qi+s is larger in the wet case than the dry case due to

581　larger thermal numbers in the upper troposphere (Fig. 7e). Uniqueness appears in thermal Qg+h

582　(Fig. 8g). While both dry and wet cases show similar magnitude of the peak values (~0.9 g/kg),

583　the peak height in the dry case is approximately 3 km higher than the wet case. This Qg+h peak of

584　the dry case coincides with the peak of vertical velocity (Fig. 8c).

585

586　Fig. 8h-k displays these hydrometeor mixing ratios averaged over the same periods, including all

587　convective grids defined by vertical velocity greater than 1 m/s. Vertical profiles and dry-wet

588　differences are similar to the results in Fig. 6. However, compared with the in-thermal profile

589　results (Fig. 8d-g), it facilitates understanding of the convective core microphysics process. First,

590　mean in-thermal convective-grid hydrometeor concentrations are smaller than in-thermal profiles;

591　particularly in-thermal Qc values are roughly six times larger than convective-grid average Qc

592　(Figs. 8d & 8h), suggesting that thermals are major cloud droplet generators (Hernandez-Deckers

593　et al. 2022).

594

595　The convective-grid Qg+h of the dry case is nearly twice as high as that in the wet case, peaked

596　around the melting layer (Figs. 8g & 8k), whereas in-thermal Qg+h shows similar peak values

597　between the dry and wet cases. As indicated by Fig. 7g, these larger and heavier rimed particles

598　sediment from thermals and further collision with supercooled liquid must enhance the graupel

599 growth during the sedimentation process, as suggested from aircraft measurements (Blyth and
600 Latham 1993). Thus, elevated in-thermal $Qg+h$ in dry-case convection can have further riming
601 growth after falling out from thermals. This vigorous growth of $Qg+h$ in dry-case convection
602 eventually generates vigorous raindrops after the melting process. This could explain why
603 convective-grid Qr in the dry case is larger than that in the wet case (Fig. 8i), opposite from the
604 result of in-thermal Qr (Fig. 8e). Thus, in-thermal Qr values are not directly related to total Qr in
605 the convective core (or surface precipitation rate) because of this cold precipitation microphysics
606 process in deep convection.

607

608 A second leading question is why the height at the peak value of dry-case in-thermal $Qg+h$ is more
609 elevated than the wet-case thermal (Fig. 8g). Fig. 9 shows histograms of thermal properties from
610 the dry and wet cases. Consistent with the mean vertical profiles (Fig. 8a), more thermals are
611 initiated below 7 km in the dry case than in the wet case (Z0, Fig. 9d). Thermal radius in the wet
612 case is also larger than the dry case regardless of shallower boundary layer depths in the wet case
613 (Fig. 9a), consistent with R in thermal vertical profiles reaching larger sizes at most elevations in
614 the wet case (Fig. 8b). However, here we see that thermal vertical velocity (W, Fig. 9b), travel
615 distance (dZ, Fig. 9c), and lifetime (Fig. 9e) in the dry case are all greater than in the wet case.
616 Thermal entrainment rate is smaller in the dry case than the wet case. These results indicate that
617 the thermals in the dry-case deep convection can travel longer distances with an extended lifetime
618 due to a lesser dilution.

619

620 Interestingly, slightly smaller thermal radii in dry-case convection can have a lower entrainment
621 rate than in wet-case convection. Hernandez-Deckers and Sherwood (2018) also found that the
622 variability of thermal radius can only account for 20% of the total variance of thermal dilution rate,
623 i.e., larger thermal tends to have a lesser dilution rate. This was concluded through similar thermal
624 tracking analysis from different LESs. Therefore, thermal size is not the sole parameter for
625 determining dilution rate.

626

627 Giangrande et al. (2022) suggest that the convective area is smaller in dry-season convection over
628 this region. Thus, this indicates that stronger low-level buoyancy in dry-season environments can
629 more narrowly concentrate updraft and low-level thermals in the area, thus creating less diluted

630 environments probably due to the impact of thermal drag (Romps and Charn 2015). This is merely

631 speculative and requires further investigation to confirm or refute. Takahashi et al. (2022)

632 investigated cloud-scale entrainment between continental and maritime environments and found a

633 larger dilution rate in maritime convection than in continental convection. Our results suggest that

634 this difference in cloud dilution happens from the thermal-process level. These conditions elevate

635 dry-case thermals and graupel peak concentration toward higher altitudes than the wet-case

636 convection (Fig. 7f), leading to greater graupel production.

637

638 Finally, time series of thermal properties in the x-z cross-section are constructed for the dry case.

639 For this, each thermal at its maximum w value is centered and defined as the time of zero, and

640 prior (later) steps are represented in negative (positive) time steps. Because of the 1-minute LES

641 output, the time series from -3 to 3 encompasses 7 minutes of time steps. This averaging process

642 also weighs upon the magnitude of the thermal mass flux (Hernandez-Deckers et al. 2022); thus,

643 thermals at larger values in positive and negative time steps tend to have a fewer sampling numbers.

644 Also, to make the composites, equal-sized thermals are sampled to characterize the mean time

645 series of thermal properties, avoiding sampling too small thermals, which often has no

646 supersaturation (Hernandez-Deckers and Sherwood. 2016). This normalization procedure ends up

647 with the result that maximum W values do not appear at reference time (t=0), but better capture

648 the evolution of the largest flux-bearing thermals (Fig. 10). We also note that a typical thermal

649 travel distance is 1.3 km (Fig. 9c) and a minority of dry-case thermals therefore contain either no

650 ice phase (Fig. 8e-f) or no liquid phase (Fig. 8c-d), but most contain both phases between 3 and 7

651 km. Note that this flux-weighting is the one way to present the results, while simple non-weighting

652 averaging can also show similar results.

653

654 In the dry case (Fig. 10), within thermals that experience an extended peak in W (6–11 m s^{-1}), the

655 average supersaturation, cloud, and rain mixing ratio peaks at the earlier steps and decreases

656 toward the end of the time steps. This indicates that a chunk of condensation heating is the main

657 initial driver of moist thermal growth. These thermal properties are typically centered around the

658 thermal core. By contrast, Qi+s properties are more homogeneous and less concentrated at the core

659 of thermals, and they tend to increase toward the end of the time series. Especially, the early stages

660 (t=-3, -2, & -1) indicate thermals are approaching an existing ice layer rather than generating ice

661   around the thermal core. In the later stages (t=1, 2, & 3), the Qi+s is weakly concentrated toward

662   the upper thermal cores. This evolution of Qi+s suggests that thermals are not the main initiator of

663   Qi+s at the beginning, while Qi+s is rather entrained into the thermal within the early stages of the

664   mixed-phase zone, at least using the single-moment bulk microphysics. On the other hand, after

665   liquid saturation is no longer contributing substantially to Qc, Qi+s becomes a leading destination

666   of the overall transfer from vapor to hydrometeor phases within thermals that remain vigorous,

667   probably due to the Bergeron process (Bergeron 1935). Further research is needed to investigate

668   the ice nucleation and growth process in greater detail throughout the different stages of thermals'

669   lifecycle.

670

671   On the other hand, Qg+h increases toward the peak time of thermals (t=0), and starts decreasing

672   toward the later time steps (t=3). The spatial concentration of Qg+h is also peaked around the

673   thermal cores, similar to W, rh, Qc, and Qr. The increase of Qg+h coincided with the timing of

674   thermal entrainment of Qi+s and a reduction in Qc and Qr for time steps between -3 and 0. This

675   suggests that large concentrations of in-thermal Qc and Qr collide with entrained Qi+s to enhance

676   the riming process, generating graupel and hail particles at the thermal core. Note that the 4ICE

677   scheme only allows wet growth (collecting supercooled liquid) of graupel, while dry growth

678   (collecting ice and aggregate) of graupel has been suppressed due to unrealistic graupel in

679   convective anvil (Lang et al. 2014). After the reference time step (t=0), Qg+h decreases, most

680   likely due to sedimentation exceeding production. As indicated by Fig. 8g & 8k, this spilled

681   graupel and hail can further grow by colliding with supercooled liquid particles until melting.

682   Taken together, this analysis also suggests that this vigorous Qg+h-generation process in the

683   convective core *does not* occur through the classic parcel-driven convection. Instead, these graupel

684   and hail generations are most likely driven by sequential interactions of thermal ensembles and

685   microphysical processes. Note that the time series of the wet case also shows a similar finding but

686   is biased toward the thermals in the upper atmosphere (not shown here).

687

688   In addition to reference time, we composited thermal properties at different altitude levels (Fig.

689   11). The method for sampling and compositing is the same as in Fig. 10. However, it characterizes

690   vertical profiles of thermal composites using altitude references from 2.5km up to 10.5km,

691   including the mean air temperature. Despite of different reference methods, altitude-reference plots

692   appear to be similar patterns to time-reference plots. Vertical velocity (W) increases toward the

693   peak level at 8.5 km, similar to the mean profile in Fig. 8c. There is strong supersaturation (S)

694   between 4.5 km and 6.5 km, which rapidly decreases above 8.5 km. Qc, Qr, Qi+s, and Qg+h

695   profiles also resemble thermal-mean profiles in Figs. 8d, 8e, 8f, and 8g, respectively. In thermal

696   cores, Qc, Qr, and Qg+h are initially concentrated but sediment as thermals ascend. Even

697   compared with the lifetime composite in Fig. 10, Qi+s are more stratified horizontally rather than

698   toward thermal cores, particularly from 3.5 km to 6.5 km, suggesting entrainment of Qi+s within

699   thermals at these altitudes. Simultaneously, Qc and Qr decrease while Qg+h increases at these

700   altitudes. Because wet growth (ice collecting supercooled liquid) is the primary graupel growth

701   process within 4ICE microphysics in the GCE (Lang et al. 2014), the droplet-loaded thermal

702   penetration toward ice layers appears to be the important graupel/hail generation process within

703   tropical deep convection.

704

705   **4. Conclusion: Thermal-driven Convection Invigoration Process**

706

707   We have investigated seasonal differences of the measured and simulated V_{dop} between the dry

708   and wet seasons to confirm dry-season convective vigor associated with enhanced cold

709   precipitation (graupel and hail) processes. Tracked thermal properties from the selected case

710   studies reveal unique updraft microphysics processes in the convective core that explain the dry-

711   wet contrast in deep convection. To summarize our findings in graupel-hail development

712   sequences, a thermal-driven process is proposed in the following steps (Fig. 12a).

713

714   1. Where condensation may occur within moist turbulent structures in the lower atmosphere,

715   local moist thermals may be initiated, which are characterized by dipole vortex rings with

716   intense vertical velocity, supersaturation, cloud droplets, and raindrops around the thermal

717   core.

718   2. When moist thermals penetrate the 0°C isothermal layer and dissipate in the mixed-phase

719   zone, cloud droplets are detrained and gradually glaciated to form ice-particle layers.

720   3. As additional thermals fill with droplets at the thermal core and penetrate the glaciated

721   mixed-phase zone, they entrain ice particles and collide with each other, generating graupel

722   and hail embryos.

4. Once graupel and hail particles grow sufficiently large, they start falling out from thermals and develop further by collecting supercooled droplets and ice particles during sedimentation.

The process of generating ice layers (Step 3) could be the largest source of uncertainty in this study. To prove the convective vigor process, this study used the simple bulk single-moment microphysics parameterization (Lang et al. 2014, Tao et al. 2016). This parameterization tends to convert droplets into ice particles through the saturation adjustment process. Cloud droplets are glaciated much more quickly when compared to two-moment microphysics (e.g. Matsui et al. 2023). Time series as well as altitude reference composite also shows some ice generation within the thermal core in later lifecycle stages (~10 km altitude), which may be associated with the Bergeron process. Yet, ice crystal formation processes remain one of the largest sources of microphysics uncertainty (Kanji et al. 2017; Korolev and Leisner 2020) and need further investigation to establish with adequate parameterizations. Furthermore, updrafts passing through the melting layer containing both large drops and ice crystals (which are identified here as a source of graupel) have also been pinpointed as a leading source of secondary ice production in oceanic convection sampled extensively via aircraft (Korolev et al. 2020). Thus, all quantitative components of the proposed ice-graupel generation process described here remain uncertain and subject to future investigations via instrumental observations and more detailed numerical simulations.

Nonetheless, building on the ability of existing knowledge and simulations to reproduce some basic features of observations during GoAmazon, Fig. 12b shows a newly proposed process that can explain why dry-season convection has more graupel and intense precipitation than wet-season counterparts in the following steps.

1. Dry-case (wet-case) convection tends to generate more (less) numbers of droplet-loaded thermals from the lower atmosphere because of larger potential buoyant energy at a low level in the dry season.

2. Once an ice layer is built from initial cumulus thermal ensembles (Fig. 11a), more (less) numbers of droplet-loaded thermals penetrate ice layers to generate more (less) graupel and hail embryos in dry-case (wet-case) convection.

3. Individual dry-case (wet-case) thermals can rise to higher (lower) elevations via weaker (stronger) dilution with faster (slower) updraft, elevating in-thermal graupel at higher (lower) altitudes.

4. During sedimentation, graupel in dry-case (wet-case) thermals has a higher (lower) chance to grow due to the longer (shorter) distance toward the melting level.

These new processes are proposed from the "golden" cases from the dry and wet seasons. Further investigation with more case studies will augment our hypothesis in the future.

The "hotter" surface in the dry season must be the physical origin of step 1, similar to L-O contrast (William and Stanfill, 2002). The dry season typically has clearer skies, less soil moisture, and stronger surface heating, leading to more turbulent heat flux and energy at the lower troposphere even during GoAmazon experiment (Biscaro et al., 2021; Ghate and Kollias, 2016). In contrast, the wet season is characterized by frequent precipitation and increased release of atmospheric latent heat with the weak surface sensible heat flux caused by wet soil moisture (Rocha et al., 2004). As a result, the entire troposphere experiences upward motion during the wet season, unlike its dry season counterpart (Tang et al., 2016).

Contrary to the speculation made by William and Stanfill (2002), it has been found that stronger surface heating and deeper PBL during the dry season do not increase the thermal "size" based on the classic similarity theory of Morton et al. (1956). Instead, our analysis of simulations indicates that the numbers and updraft velocity profiles of cumulus thermals become more important, particularly those initiated in the lower troposphere. Even for similar CAPE, the concentration of potential buoyancy profiles in the lower troposphere can trigger more vigorous convection. This is similar to the difference between mid-latitude continental and tropical maritime environments, where the mid-latitude continental environment tends to have more potential buoyancy in the mid-to-lower troposphere, leading to continental convective vigor (Matsui et al., 2020). For this, we need to investigate boundary layer dry thermals and deep-convective moist thermal seamlessly between various continental and maritime environments.

It is also hypothesized that the low-altitude concentrated cumulus thermal trains could additionally enhance the cold precipitation process by improving the residence time of graupel and hail within

785   the mixed-phase zone if thermal-spilled graupel and hail encounter subsequent new cumulus

786   thermals. Previous trajectory modeling (Heymsfield 1983) also suggested a similar mechanism for

787   enhancing graupel and hail residence time and growth by multiple convective cores. Heymsfield

788   (1983) used the multi-Doppler technique to generate a three-dimensional wind field, but it needed

789   more spatio-temporal resolution to characterize cumulus thermal. However, a stronger updraft core

790   mentioned in his study must be cumulus thermals. This investigation further requires a more

791   complex set of numerical simulations in the future.

792

793   The proposed thermal-driven invigoration process is based solely on thermodynamics and does

794   not consider aerosols' effect on deep convection, as demonstrated by previous studies over the

795   Amazon (William et al. 2002, Lin et al. 2006). Our choice of single-moment microphysics does

796   not consider the variability of background aerosols to initiate cloud droplets. However, this simple

797   microphysics can generate a fundamental dry-wet contrast characterized by the V_{dop} statistics. This

798   suggests that thermodynamics is the primary factor determining convective vigor, while aerosols

799   may have a significant but secondary role in invigorating convection (Matsui et al. 2020). Future

800   studies will require a higher-order moment of microphysics scheme to examine the impact of

801   aerosols on droplet and primary ice nucleation in thermals to confirm our hypothesis that dry-wet

802   aerosol contrast plays a secondary role.

803

804   It is well known that severe hailstorms and large hails are more frequently observed over the central

805   plains of North and South America (Liu and Zipser 2015, Bang and Cecil 2019). The hailstorms

806   in these regions are often associated with supercells, and mesocyclones play a crucial role in the

807   growth of very large hail by enhancing the residence time of the hails within the mixed-phase zone

808   (e.g., Nelson 1983; Ziegler et al. 1983). However, it is not known how a mesocyclone affects

809   thermal-like or plume-like updraft characteristics (Morrison et al., 2020), though satellites have

810   captured thermal chain-like periodic overshooting signals at the top of the supercells (Borque et

811   al. 2020). Thus, further observational and modeling investigations are required for the mid-latitude

812   regions to determine whether our proposed graupel/hail generation mechanisms can be applied.

813

814   The proposed process for graupel-hail generation and convective vigor is a time-dependent,

815   sequential, coupled dynamics-microphysics process. Although the traditional plume-based mass

flux scheme has been successful in representing the moist convection process in climate models (e.g., Arakawa and Schubert 1974), our proposed convective microphysics process is not linear and cannot be adequately represented by the traditional convective mass flux method. To represent this process, thermal chain concepts with detailed microphysics processes must be introduced in the parameterization for large-scale models (Morrison et al., 2020). Fine-resolution simulations produce better continental convective vigor because they can resolve thermal dynamics and microphysics (Robinson et al., 2011; Matsui et al., 2020). The mean radius of the tracked thermal in this study, conducted using a 200 m mesh LES, is around 1 km, with a maximum size of around 2 km, which is comparable to the LES study using a 65-m horizontal grid spacing (Hernandez-Deckers and Sherwood, 2016). However, due to the effective resolution being 5-10 times the actual grid spacing, cumulus thermals, and graupel-hail generation processes are difficult to resolve for storm-resolving models and perhaps any coarser Eulerian-type numerical atmospheric models (Matsui et al., 2016). Conducting LES for regional and global weather and climate models is impractical in the foreseeable future. Therefore, new types of dynamics-microphysics-coupled cumulus thermal parameterization should be developed to better represent deep convection for storm-resolving and coarse-resolution weather and climate models.

New ground-based Doppler phased array radar (PAR) technology (Kollias et al. 2022b) or multi-Doppler agile scans (Kollias et al. 2022a) hold promise in observing and characterizing cumulus thermals. Emerging PAR instruments have started capturing storm motion and microphysical details at spatial and temporal resolutions akin to those seen in LES output (e.g. Takahashi et al. 2019, Kikuchi et al. 2020). These new observational capabilities are necessary for refining the dynamics and microphysics in LESs, particularly in elucidating the process behind thermal-driven convective vigor. Moreover, the advent of vertical motion estimates from high-resolution space-based radars [EarthCARE, Wehr et al. 2023; Investigation of Convective Updrafts (INCUS), https://incus.colostate.edu; the Atmosphere Observing System (AOS), https://aos.gsfc.nasa.gov) will soon enable the global mapping of convective updrafts. These new satellite radar measurements will generate a comprehensive global catalog detailing convective vigor and the speed of intense thermals.

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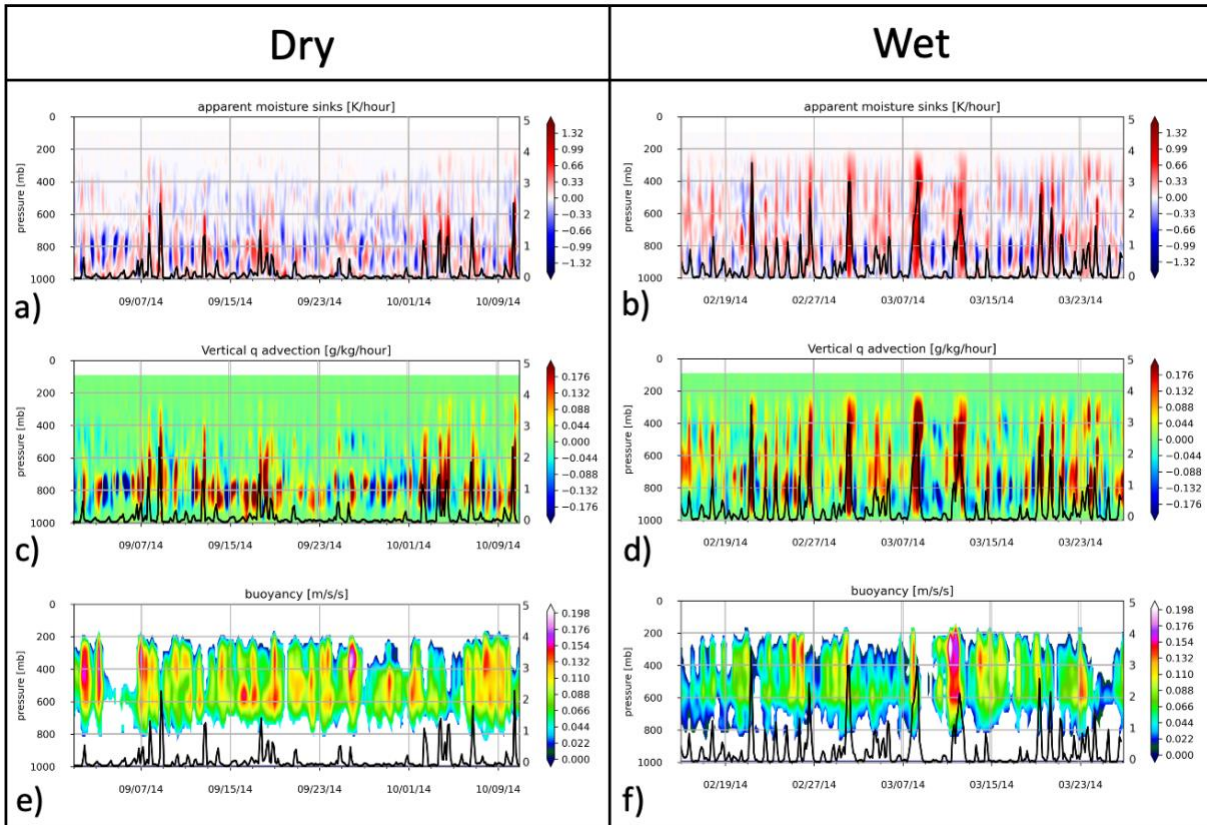
Figures

1177 Figure 1. Time series of VARNAL large-scale forcing profiles between wet and dry periods: (a-b)
1178 apparent moisture sink (Q2), (c-d) vertical moisture advection, (e-f) potential buoyancy. The black
1179 solid lines on the secondary y-axis represent the surface precipitation rate.
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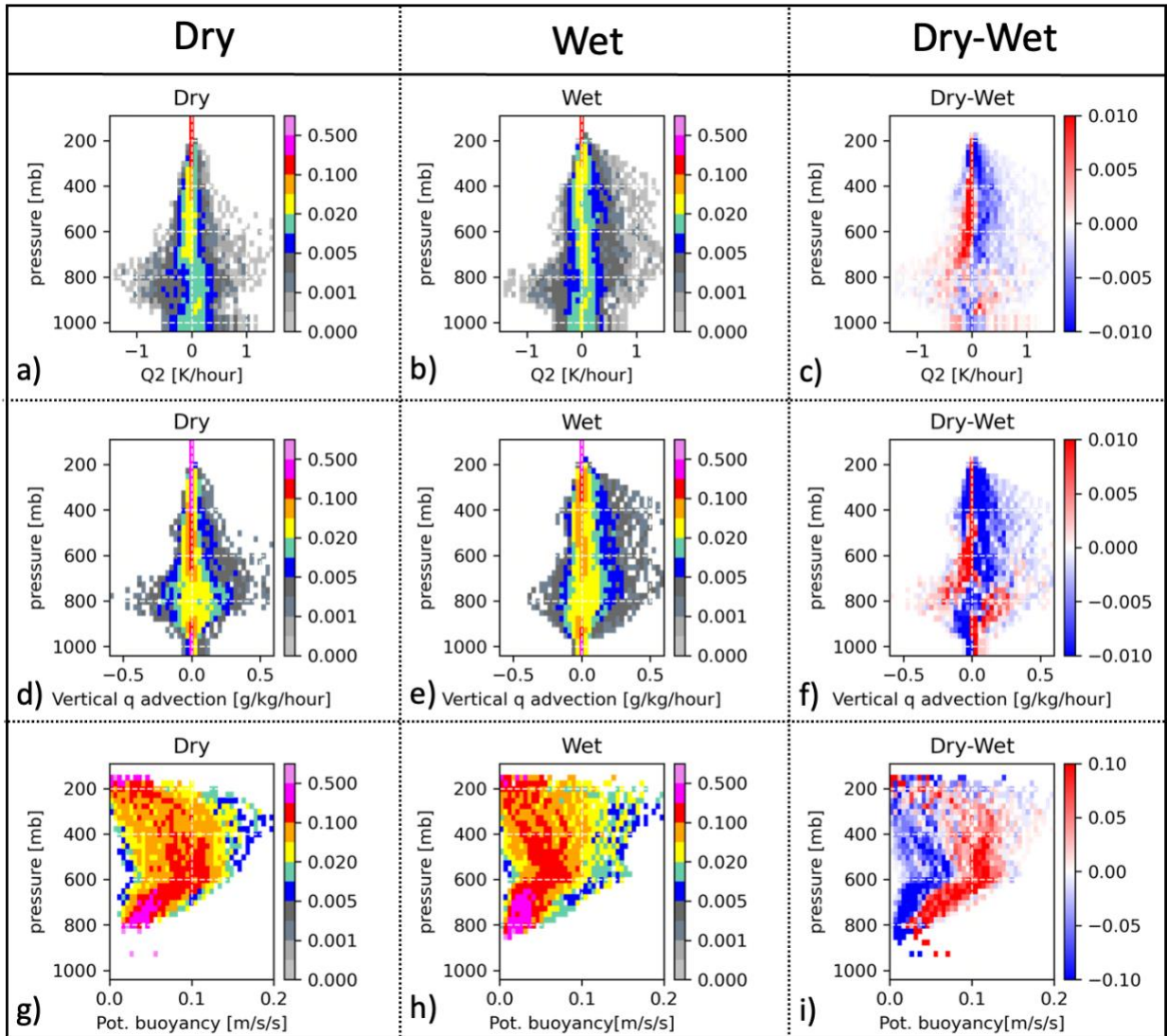
Figure 2. Contoured Frequency of Altitude Diagram (CFADs) of (a-c) apparent moisture sink (Q2), (d-f) vertical moisture (q) advection, (g-i) potential buoyancy integrated over dry and wet periods, as well as dry-wet differences.

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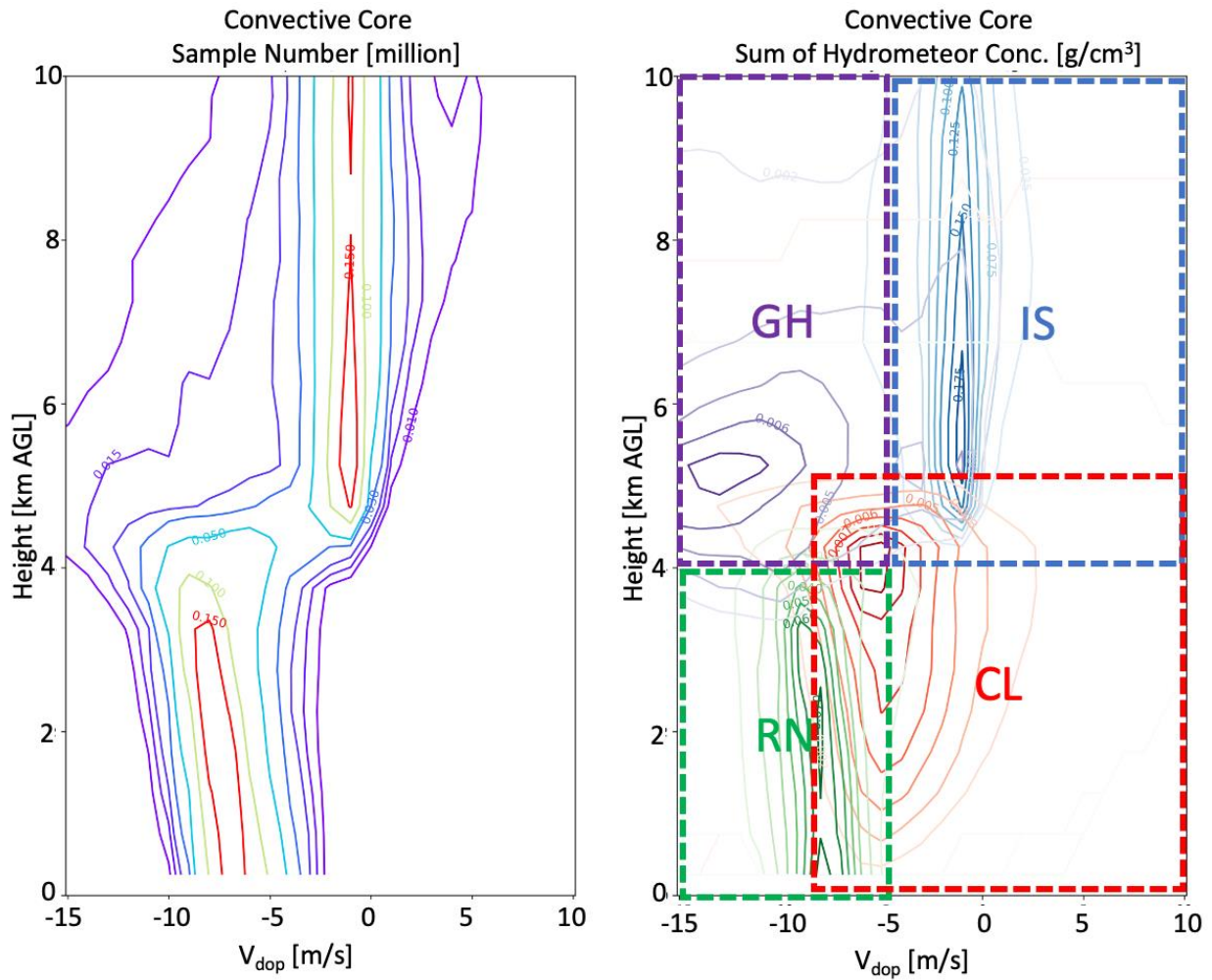
Figure 3. (a) Cumulative V_{dop} sample numbers from LESs during dry and wet periods, presented as CFADs for each V_{dop} bin and altitude. (b) the cumulative hydrometeor mass concentrations from each V_{dop}-altitude bin. Red contours represent "cloud (CL)", green contours represent "rain (RN)" blue contours represent "ice and snow (IS)", and purple contours represent "graupel and hail (GH)".
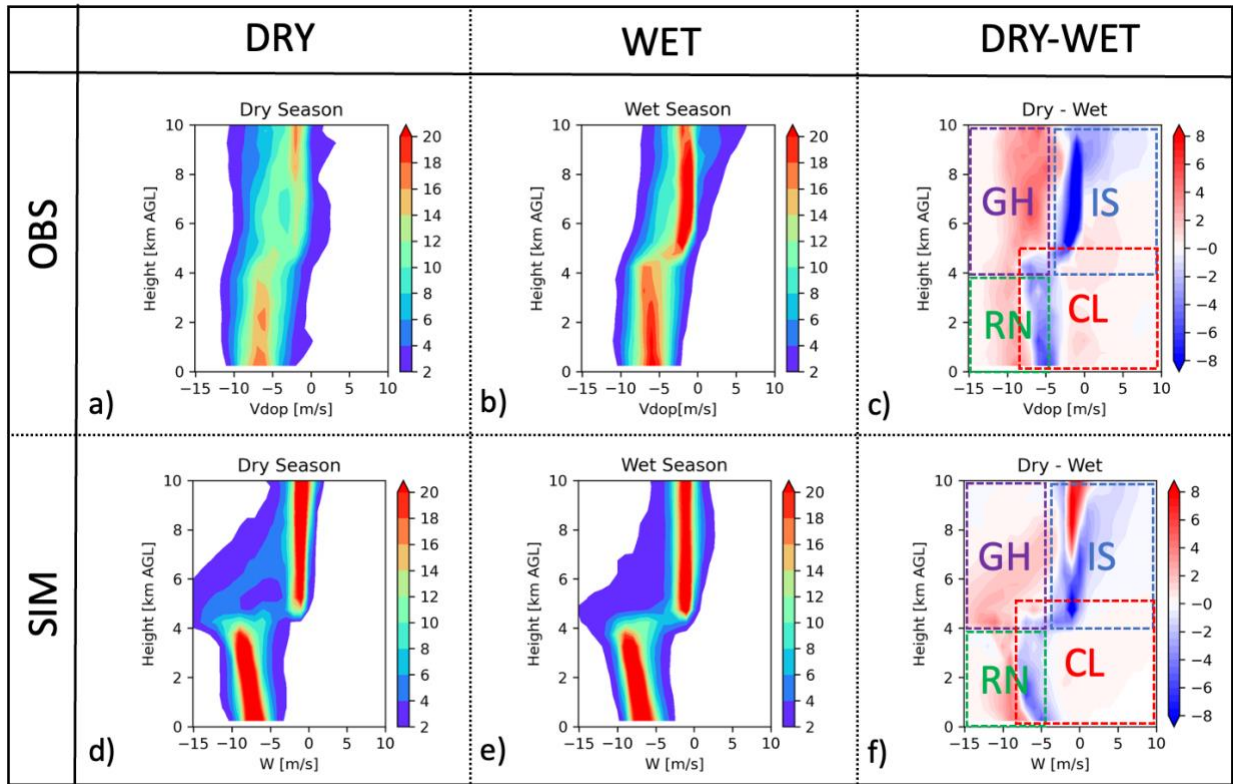
Figure 4. Contoured Frequency of Altitude Diagram (CFADs) of V_{dop} integrated over dry and wet periods, as well as dry-wet differences. The upper raw (a-c) represents observed composites, while the lower raw represents simulated composites. CL, RN, IS, and GH represent the hydrometeor regimes defined in Fig. 3.

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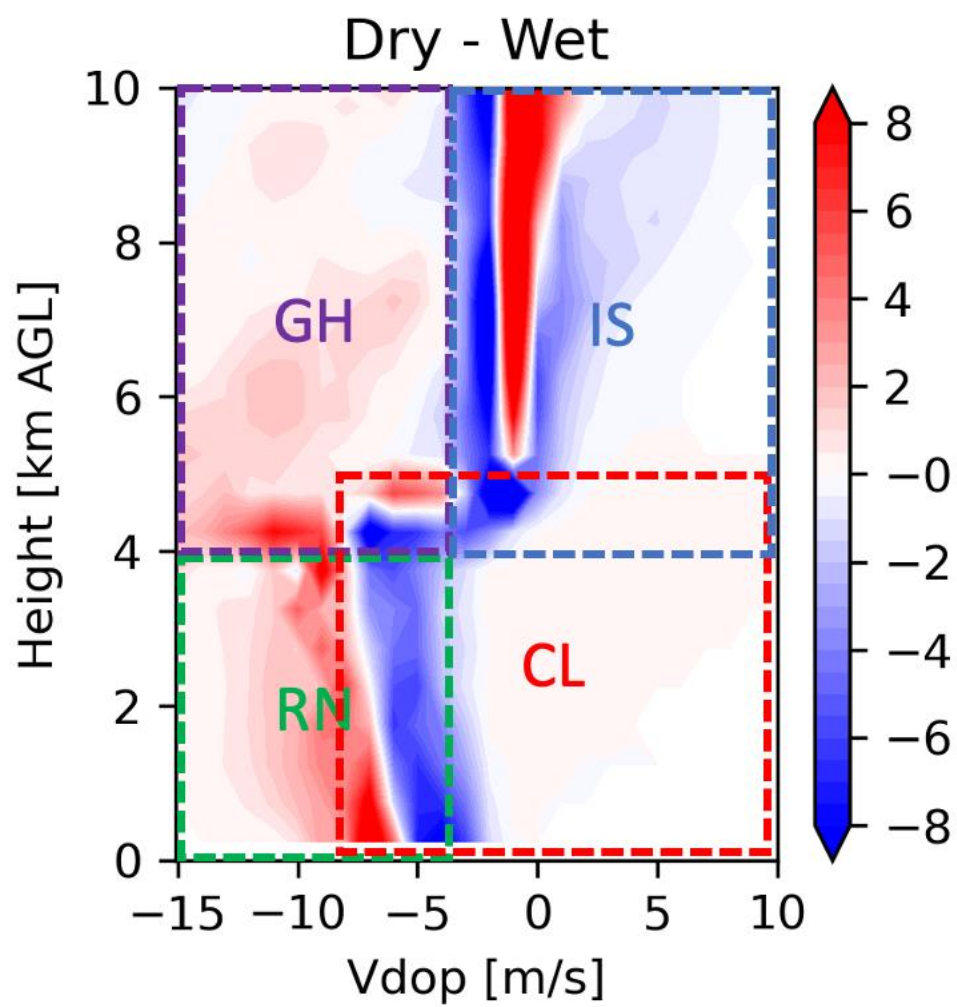
Figure 5. Contoured Frequency of Altitude Diagram (CFADs) of simulated V_{dop}, differentiated for
dry- and wet-season golden cases.

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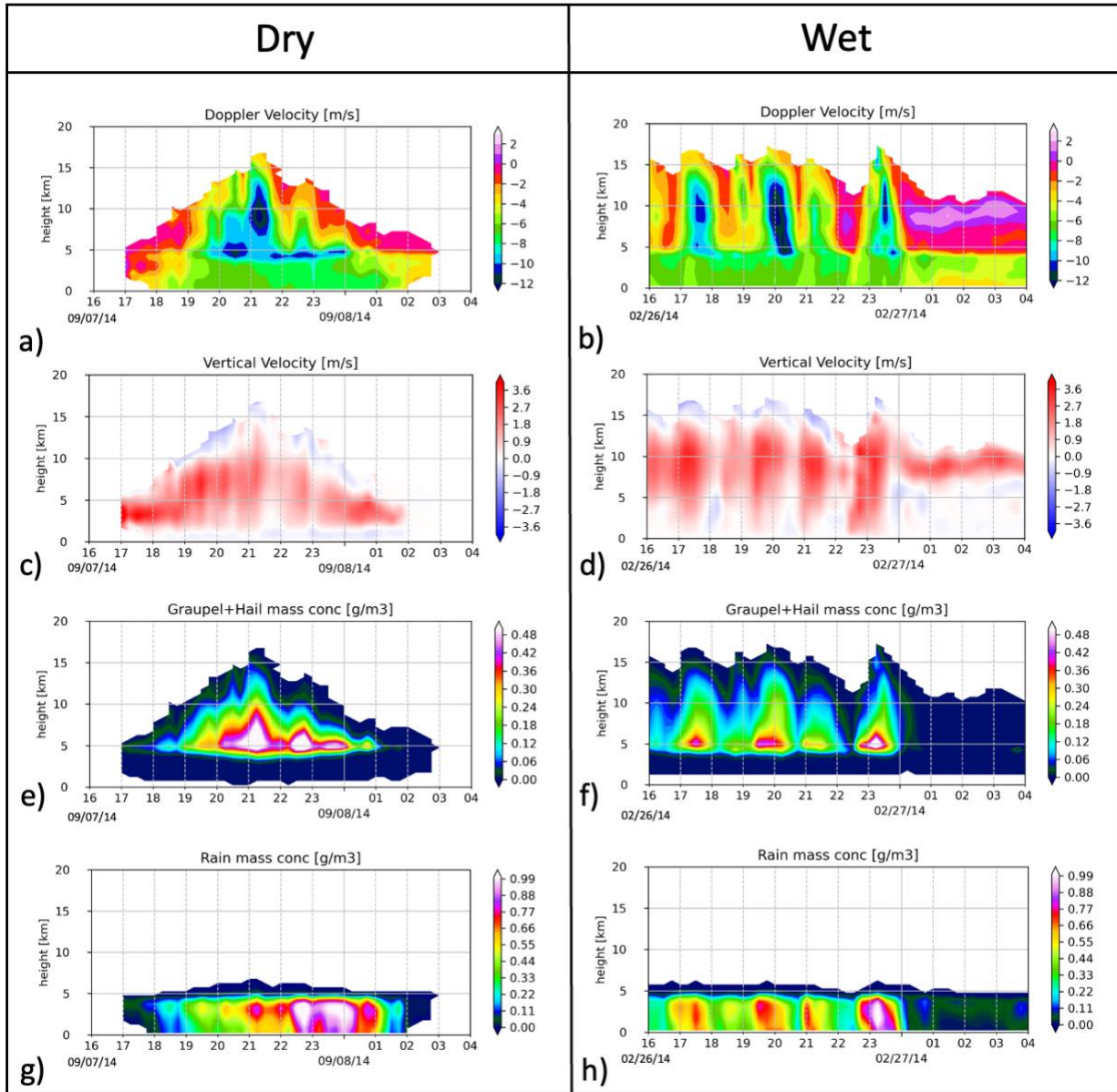
Figure 6. Time series of convective core-mean (a-b) Doppler velocity, (c-d) vertical velocity, (e-f) graupel and hail concentrations, and (g-h) rain concentrations profiles of convective grids from the dry- and wet-season golden cases.
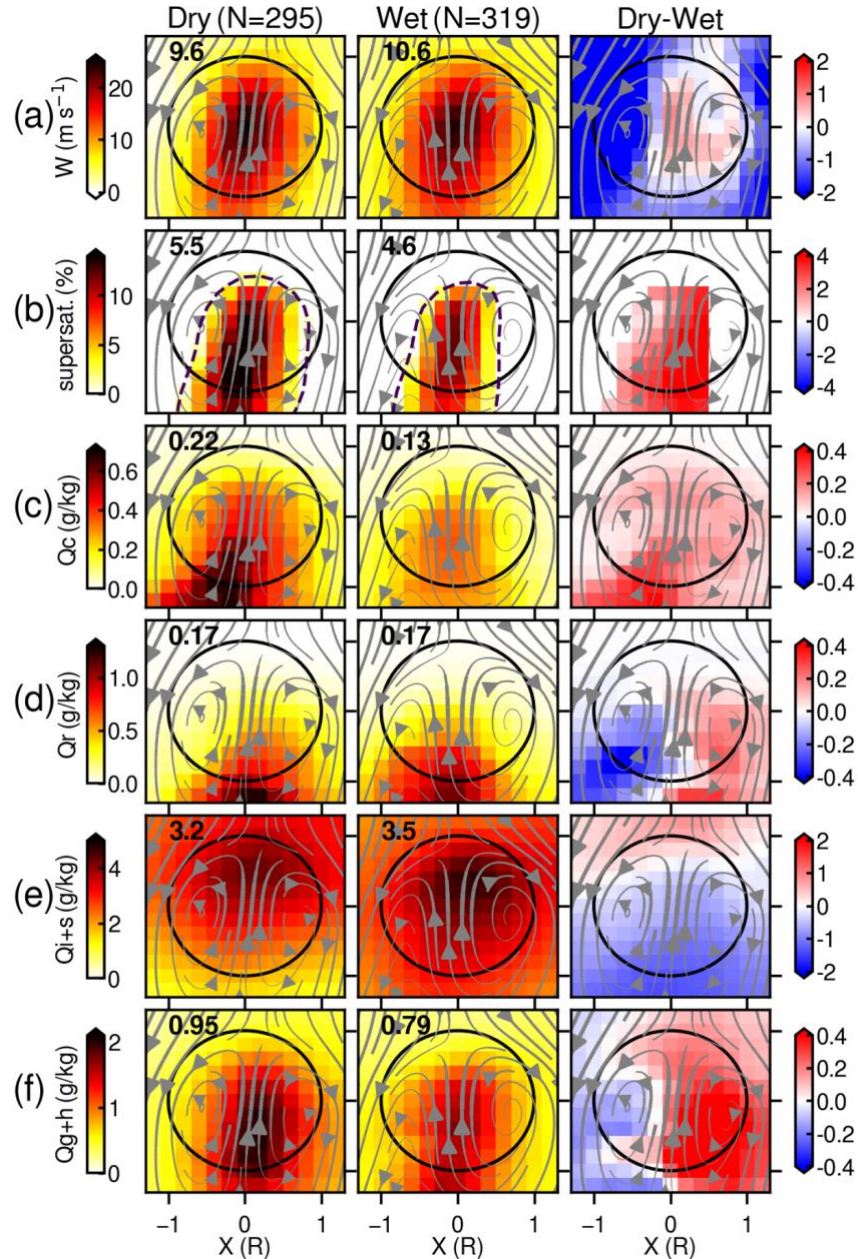
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Figure 7. Cross sections along the x-z plane of flux-weighted thermal values of (a) vertical velocity
(W), (b) supersaturation (S), (c) cloud droplet mass concentration (Qc), (d) rain mass concentration
(Qr), (e) ice and snow mass concentration (Qi+s), and (f) graupel and hail mass concentration
(Qg+h), for composites of all tracked thermals at the point of their maximum vertical velocity,
scaled by their radius (horizontal and vertical coordinates are in units of mean thermal radii). Left,
middle, and right column corresponds to the dry-season golden case, the wet-season golden case,
and dry-wet case difference, respectively. Upper left values in each panel are the flux- and radius-
weighted mean over all samples. Arrows indicate the average flow streamlines in the rising thermal
reference frame. The dashed contour in supersaturation values corresponds to 100% relative
humidity. These are reference-time (t=0) mean values.

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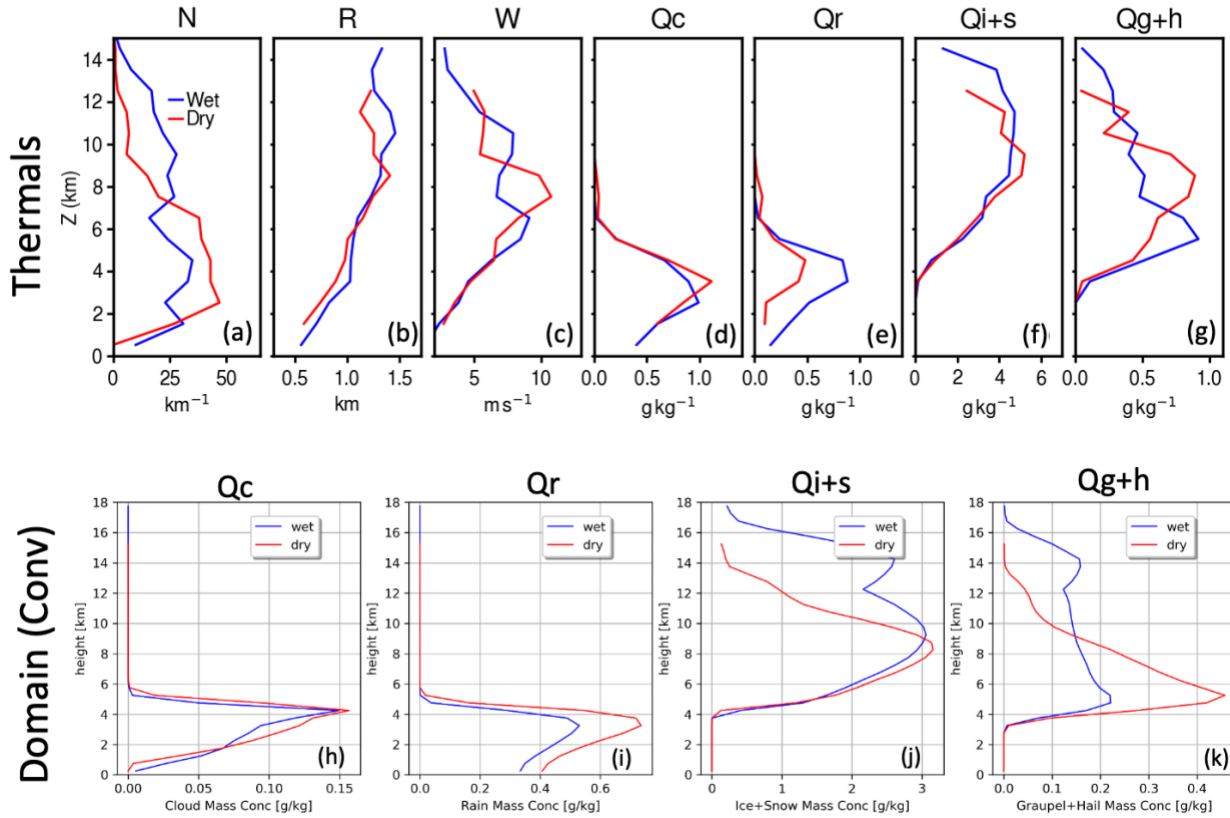
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Figure 8. (a-f) Vertical profiles of thermal-mean (a) number concentrations (N), (b) radius (R), (c) vertical velocity (W), (d) cloud droplet mass concentration (Qc), (e) rain mass concentration (Qr), (f) ice and snow mass concentration (Qi+s), and (g) graupel and hail mass concentration (Qg+h). These are all-thermal mean values.

(g-j) Vertical profile of domain-mean (h) cloud droplet mass concentration (Qc), (i) rain mass concentration (Qr), (j) ice and snow mass concentration (Qi+s), and (k) graupel and hail mass concentration (Qg+h)   of convective grids from the dry- and wet-season golden cases.

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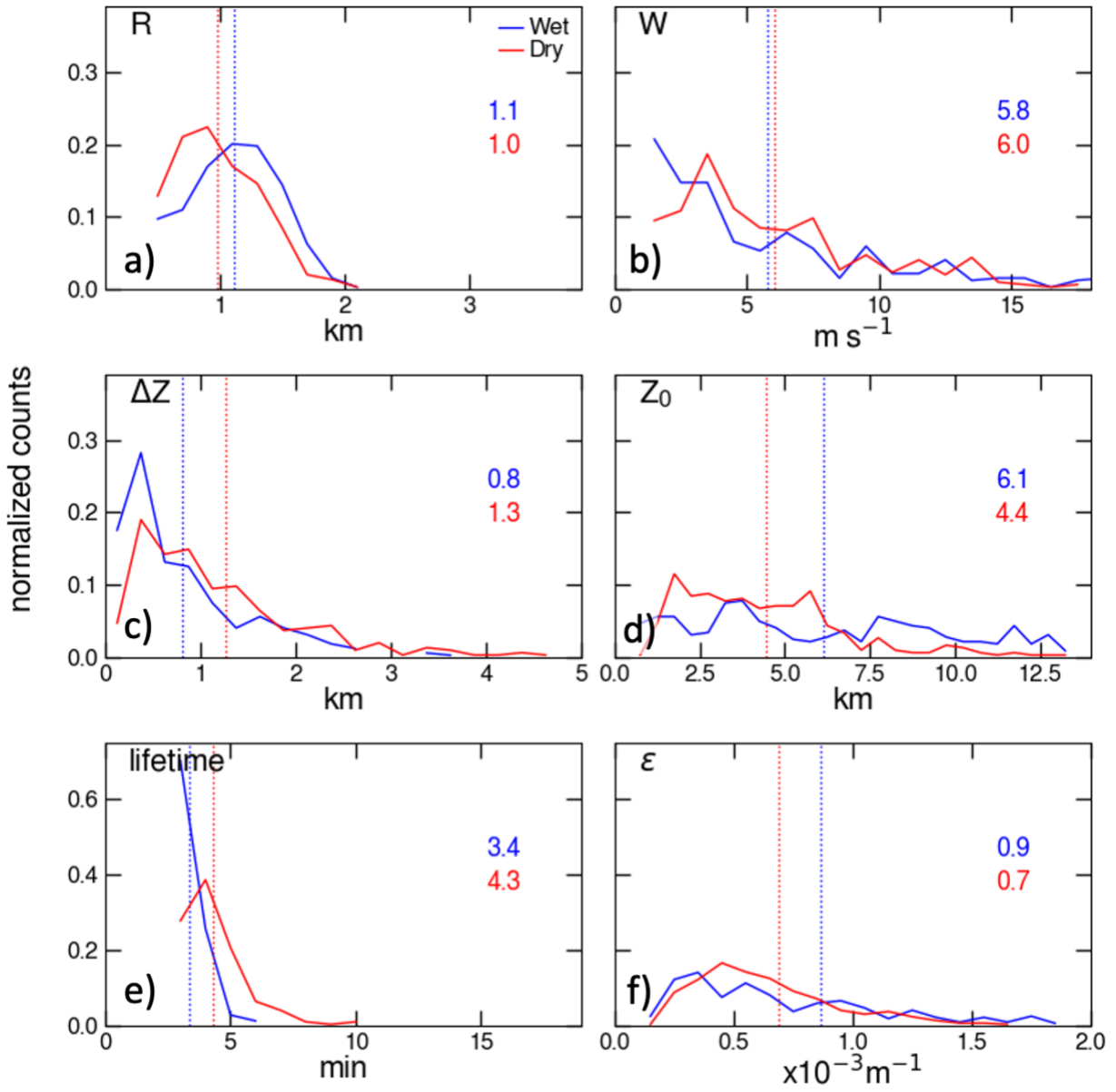
Figure 9. Normalized histogram of thermal (a) radii (R), (b) vertical velocity (W), (c) travel distance (ΔZ), (d) initiated level (Z_0), (e) lifetime, and (f) entrainment rate (ε) from the dry- and wet-season golden cases.
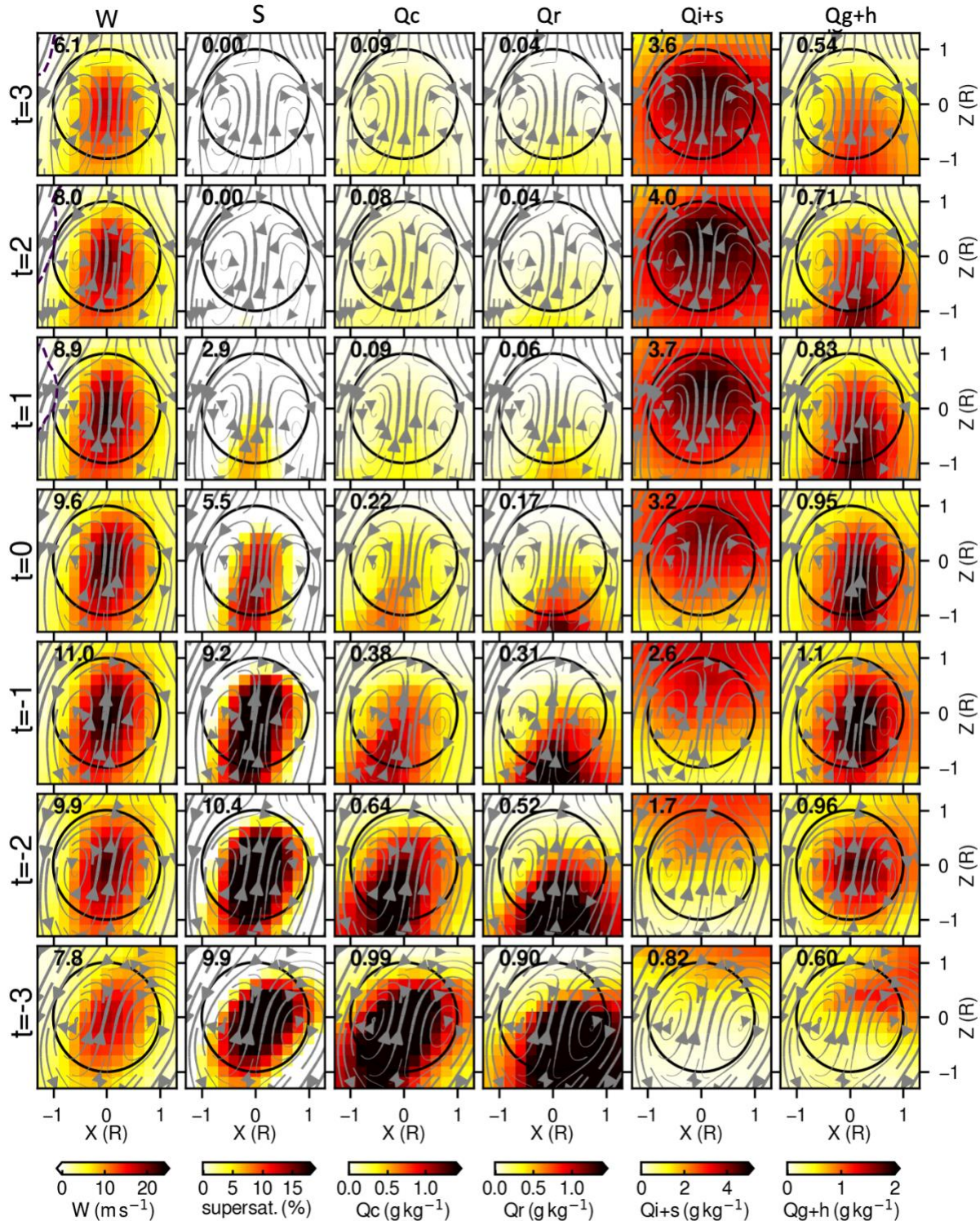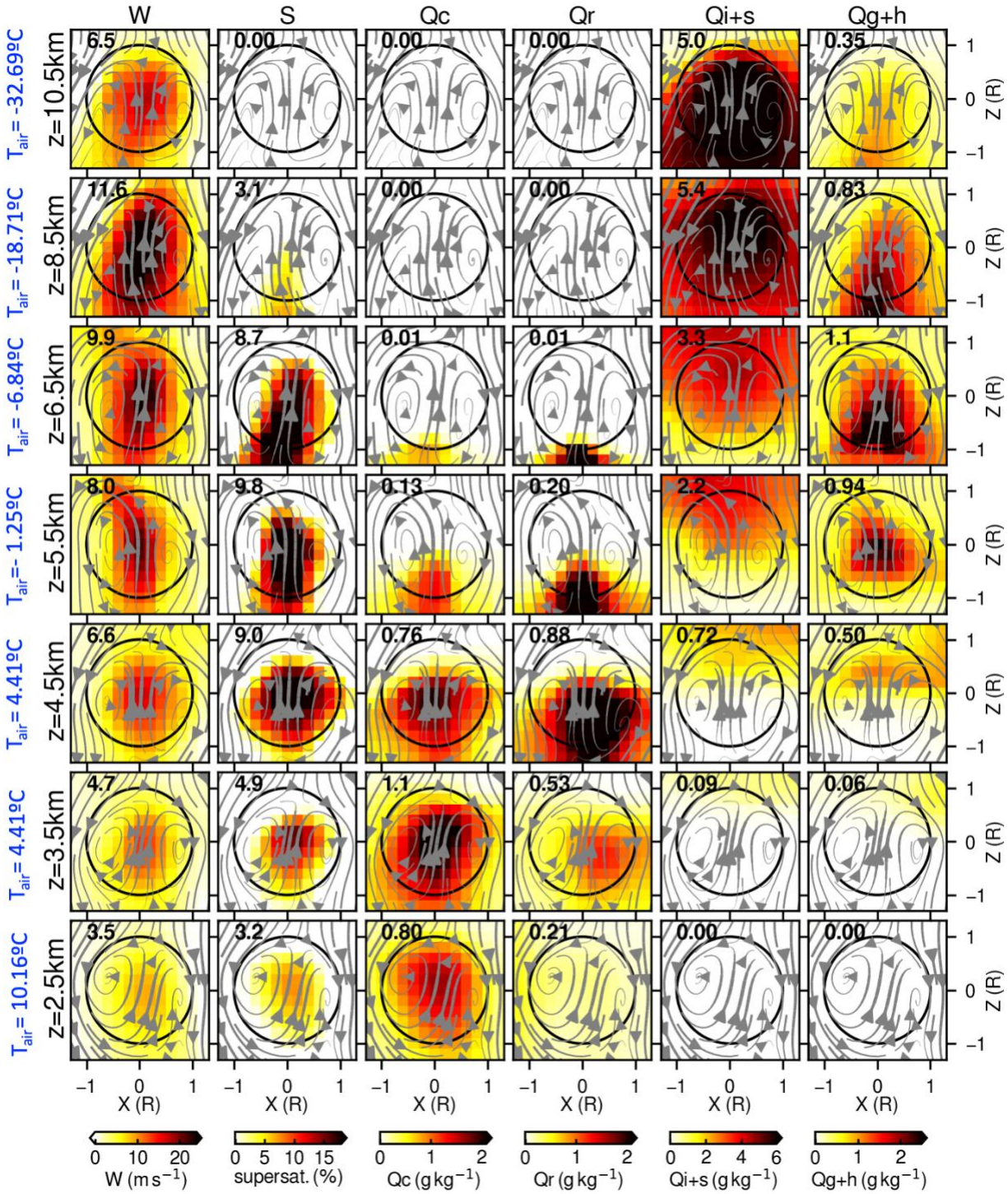
Figure 10. Time series of cross sections along the x-z plane of thermal mean values of vertical velocity, supersaturation values, cloud droplet mass concentration (Qc), rain mass concentration (Qr), (e) ice and snow mass concentration (Qi+s), and graupel and hail mass concentration (Qg+h), for composites of all tracked thermals scaled by their radius. The time unit is minute.
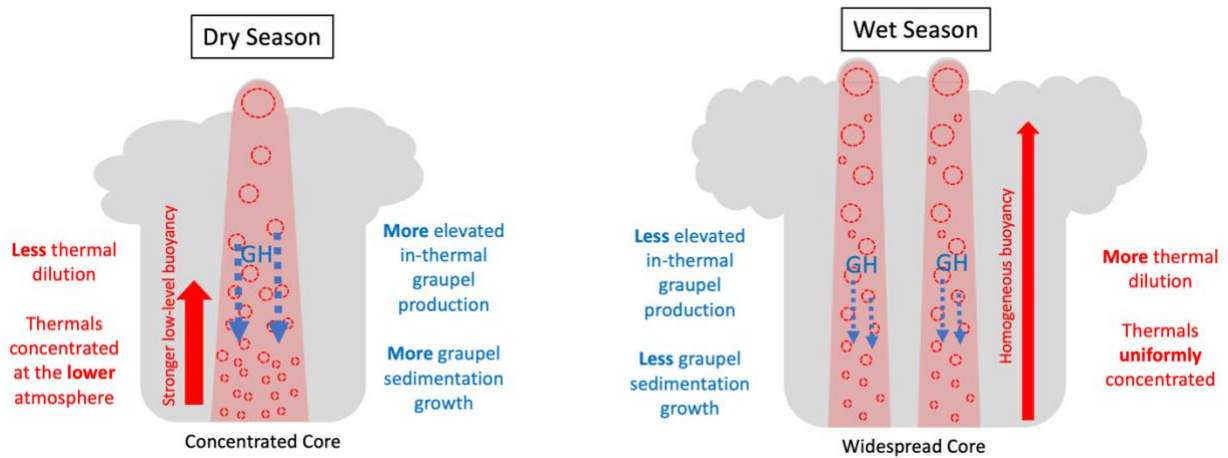
Figure 11. Similar to Fig. 10, but composited at different altitude levels. Note that the shade scales are different from Fig. 10 for clarity.
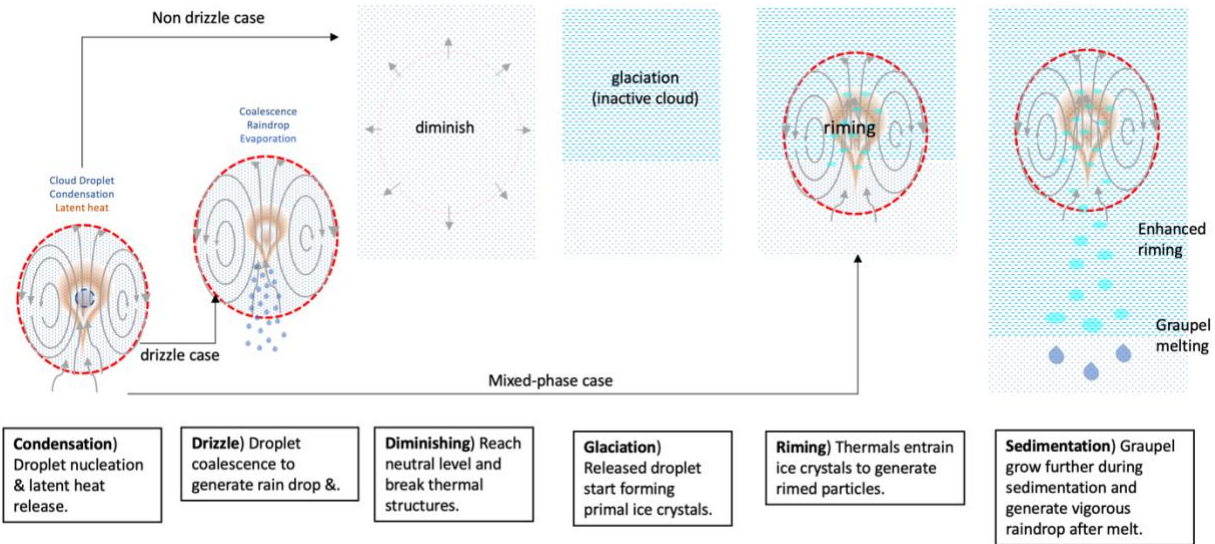
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1262 Figure 12. (a) Diagram of the suggested mechanisms for generating graupel and hail through
1263 thermal processes. (b) Diagram of thermal characteristics in deep convection in the dry and wet
1264 seasons.
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