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Large-eddy simulation of organized precipitating trade wind cumulus clouds

Axel Seifert[1] and Thijs Heus[2]

[1]Hans-Ertel Centre for Weather Research, Deutscher Wetterdienst, Hamburg, Germany

[2]Max Planck Institute for Meteorology, Hamburg, Germany

Reply to anonymous referee #1 (ACPD 13, C419-C421, 2013)

We thanks the reviewer for the positive review and the comments that helped us to improve the manuscript.

General comments:

Reviewer: *Although I generally agree with the authors that the cold pool plays an important role in organizing precipitating cumuli, to solely attribute the arc shaped cloud mesoscale organizations to the cold pools is something that needs to be further addressed. I dont think that the authors have provided sufficient evidence to approve this conclusion.*

Reply: This is maybe a misunderstanding, and we will re-write some part of the Conclusions to clarify this. We do not claim that cold pool formation and the subsequent effect on the moisture field is the only process that can lead to organization of shallow convection and the formation of the mesoscale structures. What we have tried to show in our study is that in our simulations the cold pool-moisture mechanism is sufficient to explain the formation of structures which look very much like the observed mesoscale arcs. A spatial heterogeneity in the forcing, either SST or the subsidence, is not a necessary condition to develop such mesoscale structures of cloud organisation. This does of course not prove that effects like SST patches or variability in the large-scale forcing do not contribute to the observed cloud structures.

Detailed comments:

Reviewer: *In this paper, the authors showed that the cumuli in the standard RICO case run are not well organized. This is in contrast to the moist RICO run in which arc shaped cloud clusters are observed. The authors attribute this important difference in cloud organization to precipitation, which is only marginal in the standard RICO case run but substantial in the moist RICO run. This seems to be true for the time period from 14 h to 24 h that the authors focused on in this paper. However as indicated by Figure 2, there is a decent precipitation rate in the standard RICO case run after 30 h, which is comparable to that in the moist RICO run in the same time period and is only slightly smaller than that in the time period from 14 h to 24 h. The precipitation in the standard RICO case run after 30 h should also induce the cold pools in* *the sub-cloud layer, then, why clouds are not organized in this case? There are two possibilities here: one is that there must be some other mechanisms to prevent clouds from organizing into the arc shaped cloud clusters, the other is that the mesoscale cloud organizations observed during 14h-24h are not solely caused by precipitation. It would be helpful if the authors could address this issue.*

Reply: Most of our analysis is actually based on the time period from 24 h to 30 h, i.e., after the simulations of the moist case have transitioned to the organized regime. But yes, the domain mean rain rates of the standard and moist case become surprisingly similar after 30 h. This is due to the fact that the moist case is in a quasi-stationary state while the standard case develops larger and larger clouds over time which rain more strongly. We provide here a plot of the timeseries with linear axis for the rain rate (Fig. 1), and will probably use this one in the revised version of the manuscript. We also provide the time averaged profiles over the last 6 hours of the simulations (Fig. 2) as well as over only the last hour (Fig. 3). Please note that the latter is usually not recommended, because the averaging time may be too short for statistically significant results. The domain means of some important quantities are given in Tables 1 and 2, similar to Table 1 of the paper. The Hovmöller diagrams over the full 40 h are shown in Figs. 4 and 5. In summary, those Figures support our conclusion that, although the rain rates are similar, the two simulation are still in different cloud regimes after 40 h. For example, the cloud cover is signficantly lower in the moist case compared to the drier case, a fact which would be hard to explain without mesoscale organization. The vertical profiles of the rainrate, which are shown in Figs. 2 and 3 are conditionally averaged over the rain patches, show that the moist case features much higher local rainrates compared to the drier case (by a factor of 4), although the domain mean is similar. This is another clear sign of different cloud regimes. But in some sense the reviewer is indeed right, the drier case shows some more clumpy cloud structures after 40 h. This can be seen, for instance, from the Hovmöller diagrams. Also the synthetic albedo plots after 35 h shown in Fig. 6 confirm this interpretation. Nevertheless, the spatial structures between standard and moist case remain very different even after 40 h simulation time.
It is also true that, as the reviewer suggests, the standard RICO simulation would transition to the organized regime at some point, but this needs more than 100 hours simulation time (we have performed some simulations on smaller domains to confirm this). At that time the cloud layer has been moistened sufficiently by detrainment to make the vertical profile similar to the moist case. In that sense our hypothesis that the rain rate and the associated cold pools are the cause and the main driver for the organization is consistent with the behavior of the standard case even for longer simulations than discussed in the paper. The standard case would also show organization, if we drastically decrease the CCN or cloud droplet number, which then leads to an increase in rain rate, the formation of significant cold pools etc. This emphasizes our point that additional ingredients other than rain rate, cold pools and their effects on the sub-cloud layer moisture are not necessary to explain the difference between the two cloud regimes.

Reviewer: *From Figure 2, it seems to me that all three simulations eventually reach a fairly similar mean state, say around or after 40 h, regardless of initial conditions and domain sizes. This may be due to the fact that all three simulations are forced by the same external condi-*

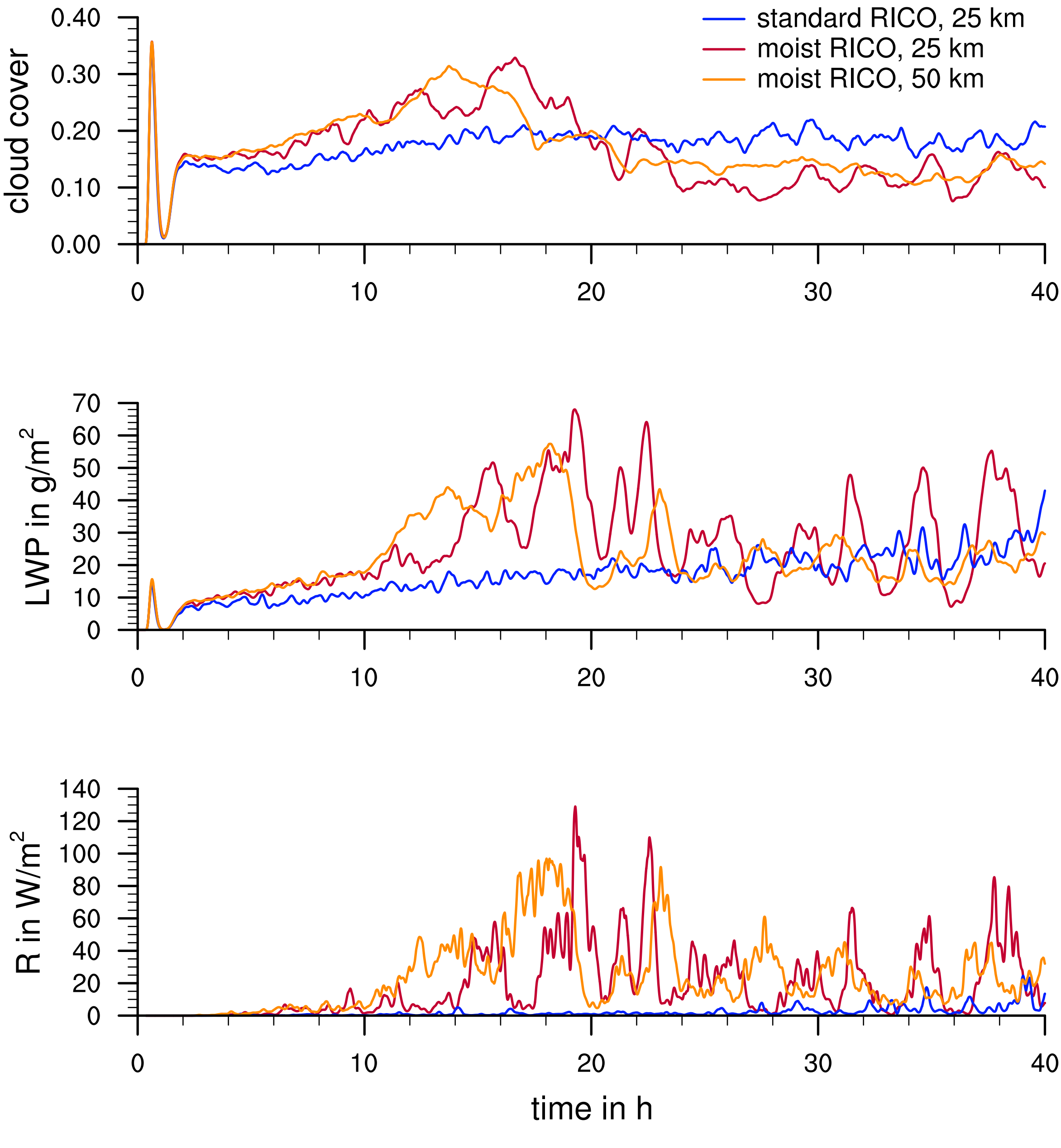

Figure 1: Time series of domain averaged cloud cover, liquid water path and precipitation rate for the standard GCSS and the moist RICO case.

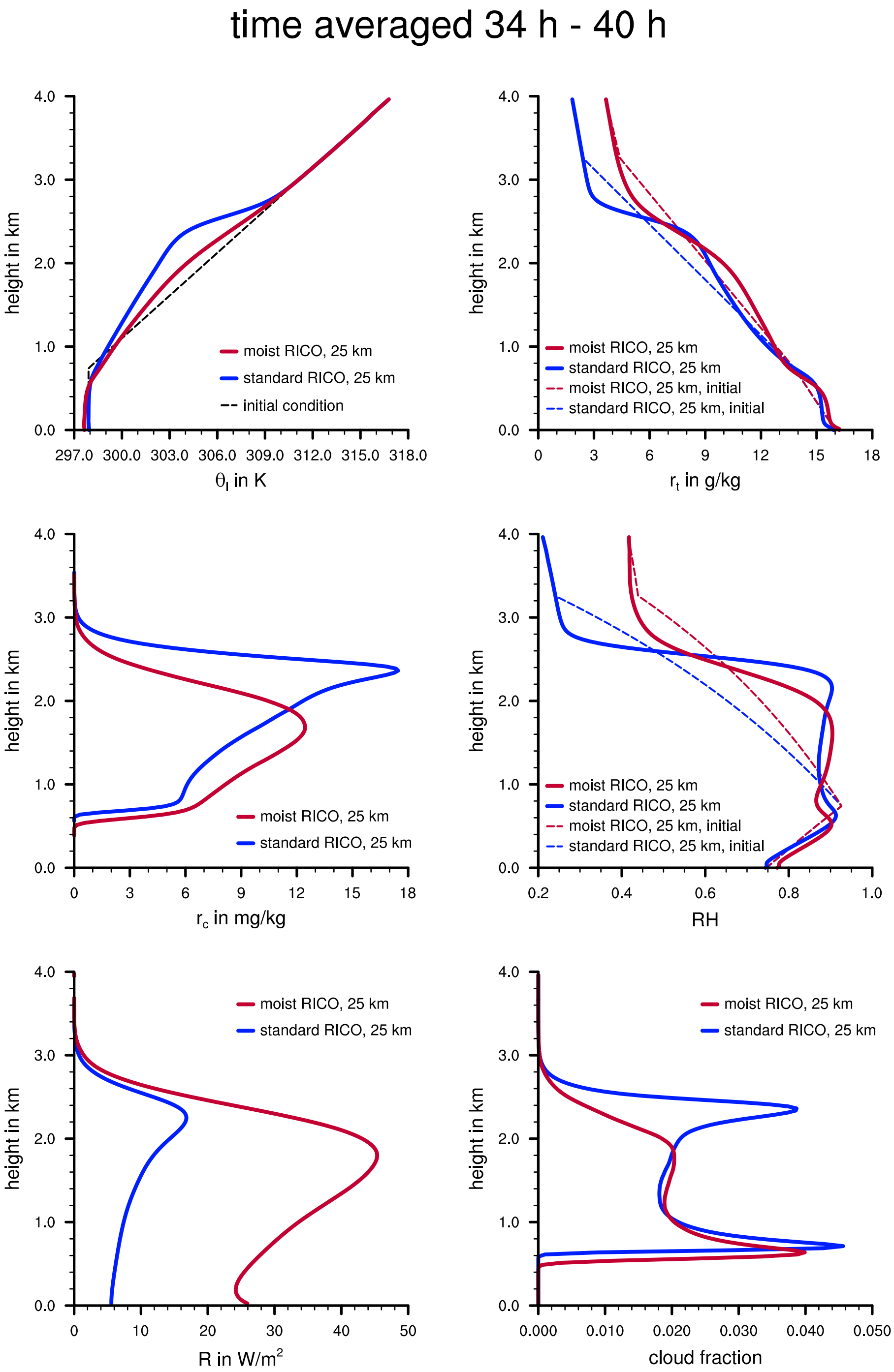

Figure 2: Mean profiles of the standard GCSS RICO case (blue) and the moist RICO case (red) with the corresponding initial conditions (dashed) on the 25 km × 25 km domain. Profiles are averages over the entire domain from 34 h to 40 h of the simulation.

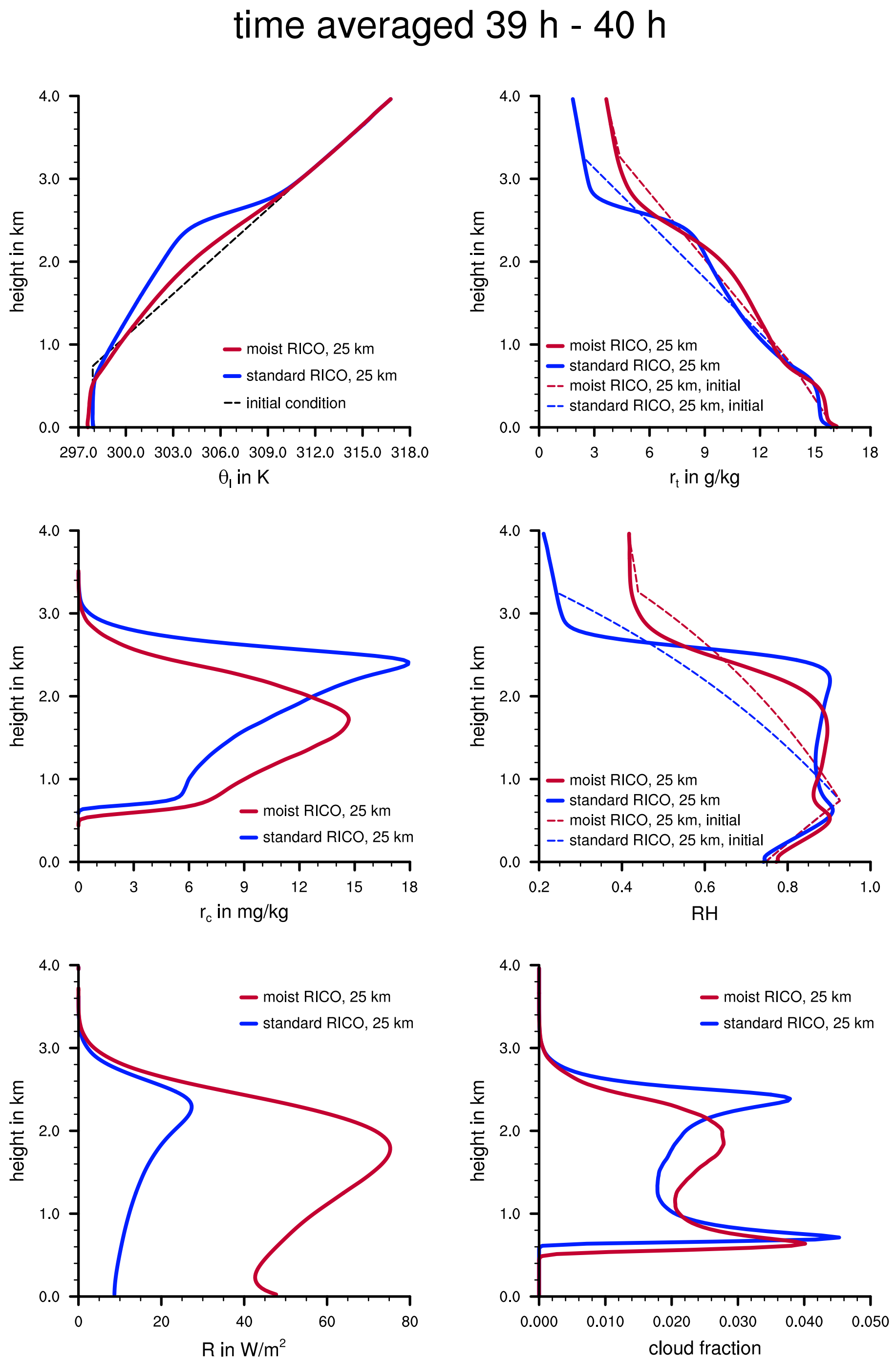

Figure 3: As Fig. 2, but from 39 h to 40 h of the simulation.

a) standard RICO case, 25^2 km^2 domain b) moist RICO case, 25^2 km^2 domain

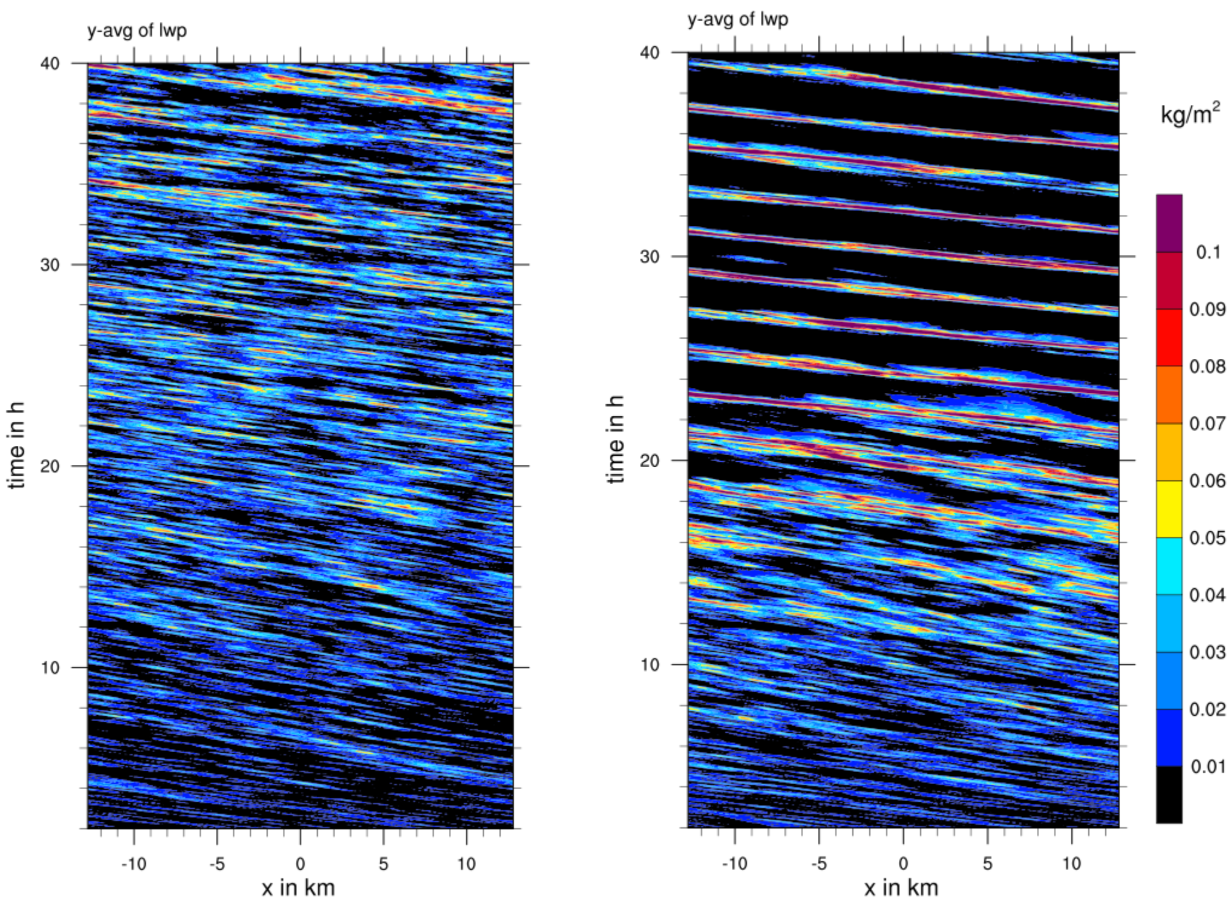

Figure 4: Hovmöller diagrams of y-averaged liquid water path for three different simulations of the RICO trade wind cumulus case. The standard GCSS RICO case on a 25 km $\times$ 25 km domain (a) and the moist case on the same domain (b) and the moist case on a 50 km $\times$ 50 km domain.

tions. It is interesting to see what the differences of cloud organization structures are at this stage since all three simulations produce comparable precipitation. Id suggest the authors to do some analyses on clouds at this stage, which may help us to understand what processes, in addition to precipitation, may have an impact on cloud organizations. It also seems to me that different setting of simulations (including initial conditions and domain size) requires different time periods to spin up to reach the quasi-steady state. The strong precipitation episode during 14h-24h in the moist runs may be considered as a specific event during the spin-up period. Its quite possible that the precipitation-moistening feedback mechanism only works for certain conditions.

Reply: Most of this has been discussed in the answer to the previous question. We might add, that we agree that the transient behavior of the RICO case is maybe a minor weakness of our study and it would therefore be valuable and desirable to repeat our study with a model

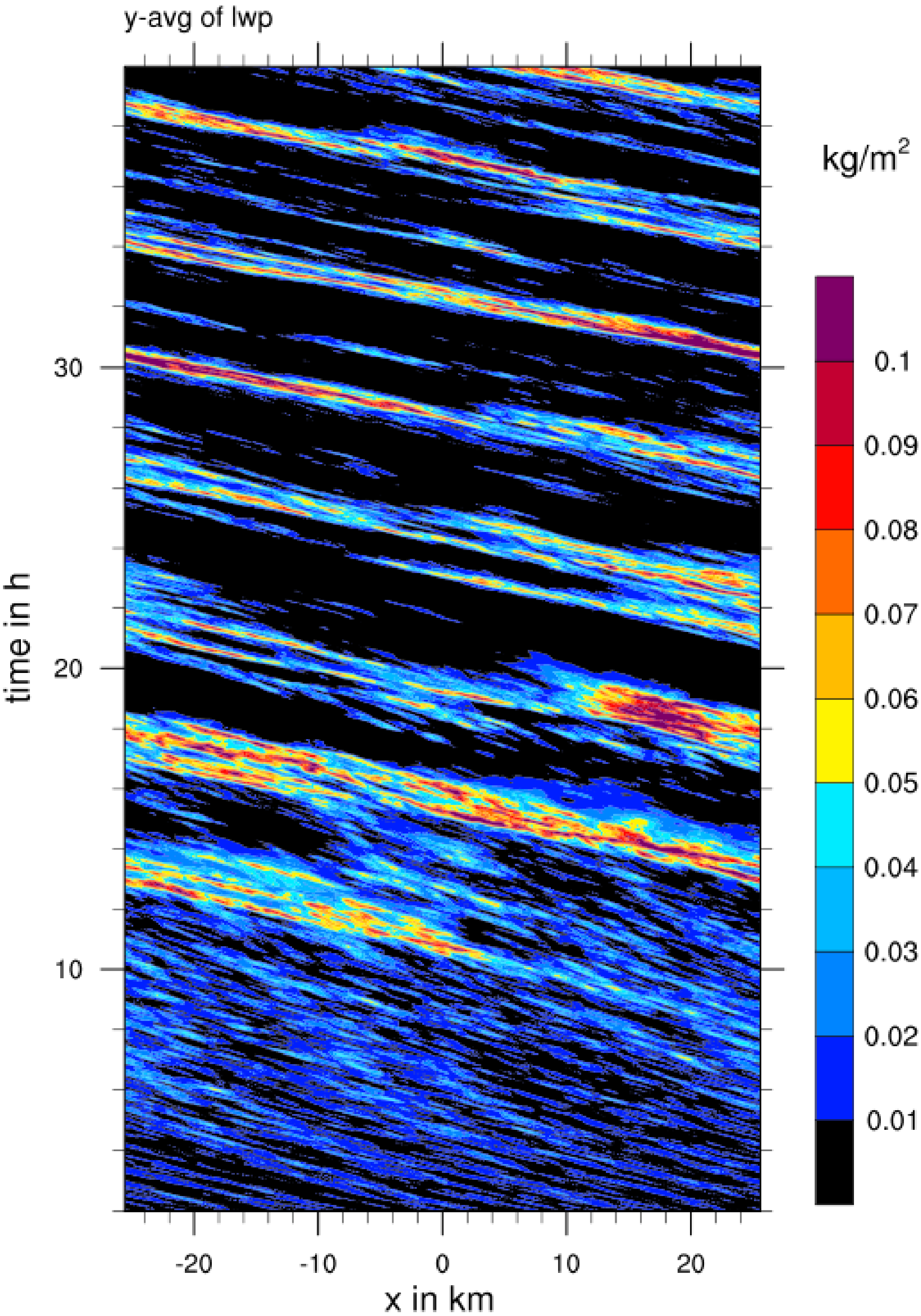

Figure 5: As Figure 5, but for the moist case on a 50 km × 50 km domain.

Table 1: Statistics average over 34-40 h. Variables are cloud liquid water path CWP, rain water path RWP, fraction of cloudy columns C and surface rain rate R_{sfc}.

Run	Description	**CWP** [gm^{-2}]	**RWP** [gm^{-2}]	C [-]	$R_{\textbf{sfc}}$[Wm^{-2}]
R01	standard RICO	18.5	6.4	0.18	7.5
M01	moist RICO, control	13.9	16.6	0.12	32.0
M01^{big}	moist RICO, 50 km domain	10.8	10.3	0.13	25.6

setup that can be run into a true equilibrium (for the random and the organized cloud regime). Only then it would be possible to answer the question which boundary condition or forcing does support the random vs organized cloud regime and whether the degree of organization shows a unique relation to the large-scale area-averaged rain rate or whether multiple equilibria exist. Nevertheless, our main finding is that trade wind cumulus cloud fields with significant precipitation develop self-organization due to cold pool dynamics and the resulting mesoscale structures in the moisture field. This result is not affected by the slightly transient behavior of the RICO setup.

Reviewer: *In Figure 1, the authors showed the very nice arc shaped cloud organizations from the run with a domain size of 50 km × 50 km. But as indicated by Figs. 2 and 4, there must be significant differences in the cloud mesoscale structures between the two moist simulations with domain sizes of 50 km × 50 km and 25 km × 25 km. Apparently, the cloud mesoscale structures depend on the model domain size. It would be helpful if the authors could address how the cloud organizations change as the model domain increases, and if there is a critical domain size from which the simulated cloud organizations start to converge. Also since most of the analyses in this study are done based on the runs with a domain size of 25 km × 25 km, it is not clear to what extent the small model domain affects the analysis results.*

Reply: From our simulations we found that a domain size of 25 km × 25 km is sufficient to distinguish the random cloud field from the organized regime. For a more quantitative evaluation a domain size of 50 km × 50 km should be used. This is why we decided to use the smaller domain size (which is actually not small, but has 1024 × 1024 grid points) for the sensitivity studies, but have based the analysis shown, e.g., in Figs. 8 and 9 on the larger domain simulation.
Very recently we have been able to run the moist RICO case on a 100 km × 100 km domain

Table 2: As Table 1, but averaged over the last hour only, i.e, from 39-40 h.

Run	Description	**CWP** [gm^{-2}]	**RWP** [gm^{-2}]	C [-]	$R_{\textbf{sfc}}$[Wm^{-2}]
R01	standard RICO	22.0	10.3	0.20	13.2
M01	moist RICO, control	11.3	9.1	0.11	15.9
M01^{big}	moist RICO, 50 km domain	12.9	12.5	0.14	29.1

at 25 m grid spacing, i.e., a domain of 4096 $\times$ 4096 grid points. The analysis of this dataset is cumbersome and therefore still ongoing (and we would rather not include it in the current paper), but Figure 6 shows a comparison of the cloud fields using synthetic cloud albedo after 35 h simulation time. The new simulation is visually very similar to the 50 km $\times$ 50 km domain which supports our choice of this simulation for quantitative analysis. The moist case on the smaller domain does, in some sense, overestimate the effect of organization. This is probably because, due to the periodic boundary conditions, the cold pool of a single cluster or squall line fills the entire domain and the clouds are restricted to a narrow intense line. Nevertheless, the 25 km $\times$ 25 km seems to provide a reasonable representation of one of the shallow convective squall lines (aka mescoscale arcs) of the bigger domains.

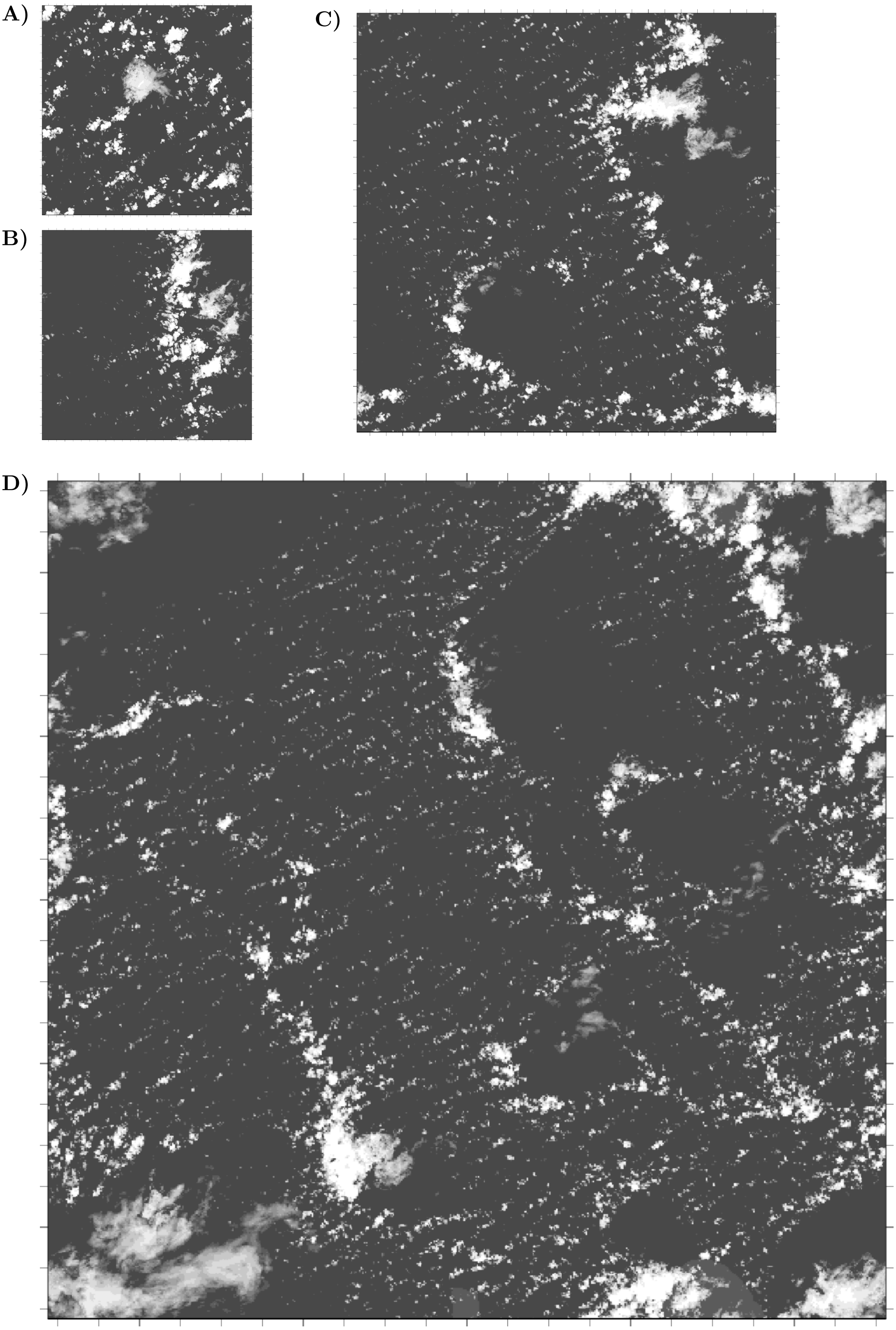

Figure 6: Synthetic cloud albedo as calculated from simulated cloud liquid water path after 35 h. Shown are (A) standard-RICO, 25 km $\times$ 25 km and moist RICO on (B) 25 km $\times$ 25 km, (C) 50 km $\times$ 50 km and (D) 100 km $\times$ 100 km. All simulations with a isotropic grid of 25 m grid spacing.