D5.3 Estimates of convective clouds aggregation indices in different configurations

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1 Method

In the following a description of the Model that has been used, the simultion configuration, and the analysis has been provided. Table 1, 2 and 3 shows all the integration.

1.1 Cloud-resolving model

The CRM used is the model System for Atmospheric Modeling (SAM) version 6.11.1 [1]. This model solves the anelastic equations of conservation of momentum, water (with 6 species present in the model, water vapor, cloud liquid, cloud ice, precipitating rain, precipitating snow, and precipitating graupel), and energy. The relevant energy for moist convection is the moist static energy (MSE), as it is conserved (approximately, i.e. neglecting viscous and subgrid-scale effects) under adiabatic processes including the phase change of water. More precisely in this model, the so-called "frozen" MSE is conserved during moist adiabatic processes, including the freezing of precipitation. The frozen MSE is given by

$$MSE = c_pT + gz + L_vq_v - L_fq_{ice}, \tag{1}$$

with the specific heat capacity of air at constant pressure c_p, temperature T , gravity g, height z, latent heat of evaporation L_v, water vapor mixing ratio q_v, latent heat of fusion L_f, and mixing ratio of all ice phase condensates q_{ice}.

The subgrid-scale turbulence is modeled using a Smagorinsky-type parameterization, and we use the 1-moment microphysics formulation, following [2] and [3]. Surface fluxes are computed using bulk formulae. Further information about the model can be found in [1].

All simulations use interactive radiation, using the radiation code from the National Center for Atmospheric Research (NCAR) Community Atmosphere Model version 3 (CAM3; collins2006formulation). For simplicity, we neglect the diurnal cycle and use the daily mean incoming solar insolation of 413 W m^{-2} (same setting as tompkins1998radiative).

1.2 Experimental setup

The model domain is square, doubly-periodic in both horizontal directions x and y. We run simulations with horizontal domain size (576 km)^2. The horizontal resolution is 3 km and the vertical grid spacing increases gradually with height, with the first level at 25 m and a resolution of 50 m close to the sea surface, reaching a vertical resolution of 500 m in the mid troposphere. There are 64 vertical levels which span 27 km in the vertical. This includes a sponge layer in the upper third of the domain (from $z = 18$ km to 27 km) where the wind is relaxed to zero in order to reduce gravity wave reflection and buildup. No large-scale forcing or wind is imposed in the domain. We neglect the Earth's rotation, a reasonable approximation in the tropics where the Coriolis parameter is small.

The initial conditions for the different mean SSTs are obtained from smaller domain runs with the corresponding SST at radiative-convective equilibrium (RCE) ((96 km)^2 run to 50 days), then using time and domain averaged profiles of the last 5 days. Based on the question we want to answer, three simulation setup has been introduced: 1. Fixed sea surface temperature (SST) simulation, 2. Simulation with a hot-spot, 3. simulations with interactive sea surface temperature. We describe each set-up briefly.

1. Fixed SST: In these simulation the sea surface temperature has kept constant. The initial condition of each SST has been provided using a simulation over smaller domain with the same SST (1).

2. simulations with a warm temperature anomaly referred to as hot-spot experiments. The hot-spot is a circular area with a higher temperature than the surrounding ocean, located at the center of the domain. So the important parameters of a hot-spot are its radius (R) and its temperature anomaly (dT). Table2 shows all the simulations in this category.

3. Simulations with interactive sea surface temperature. To have interactive SST, we use a slab ocean for which the mean SST is relaxed to a target temperature More detail on the methodology has been provided in §1.4. Three different depth of slab (H= 5, 10, and 50 meters) at two domain mean SST= 300 and 305 K have been preformed in order to explore the impact of interactive SST on self-aggregation and compare the impact of interactive SST to the impact of changing domain mean SST. We also perform fix SST simulation for both SST = 300 and 305. A simulation with depth of slab and SST will be referred to by its depth of slab and its SST so that, for example, simulation H5SST305 has slab depth of 5 meters and mean SST = 305 K. Table 3 lists all the inteactive SST simulations

As the time to equilibrium is longer, and thus the computation is more expensive, with interactive SST in particular with shallow slab depth, we stop the simulations when the metric used for the aggregation progress (introduced next §1.3) reaches its maximum and drops back down to its equilibrium value. Worth to mention that after this drop, the metric oscillates around a value between 0.4-0.5 and does not depend on slab depth or mean SST.

1.3 Analysis Framework

To follow the progress of self-aggregation we use column relative humidity CRH (Wing and Cronin 16, Shamekh et al 19).

$$CRH = \frac{\int q_v \rho dz}{\int q_{v,sat} \rho dz}, \tag{2}$$

where $q_{v,sat}$ denotes the saturation water vapor mixing ratio, ρ the air density and the vertical integration is done over the troposphere. We use CRH for our analysis as it is independent of SST so that it allows us to compare self-aggregation progress at different SSTs.

More precisely, to follow quantitatively the progress of self-aggregation, we use as our metric an aggregation index equal to the difference between the 75^{th} and 25^{th} percentiles of column relative humidity, ΔCRH_{75-25}

$$\Delta CRH_{75-25} = CRH_{75} - CRH_{25}. \tag{3}$$

With self-aggregation, ΔCRH_{75-25} increases [**?**], as convective organization yields a drying of the non-convecting dry environment, and to a lesser extent a moisture confinement in the moist convecting region. ΔCRH_{75-25} reaches a maximum and then drops by one or two decimal. The increase in aggregation index is mainly due to a decrease in CRH_{25} as CRH_{75} does not show a significant change at the beginning. The decrease of aggregation index after reaching its maximum is because the moist cluster shrinks to an area smaller than 25 percent of the domain. To compare the timing of self-aggregation among the simulations, we simply use the time at which the aggregation index reaches its maximum.

1.4 Slab ocean

The surface is modeled as a slab ocean of varying depth H. The shallower the H, the stronger the interaction between the ocean and the atmosphere. In other words, the SST evolves locally in response to the net surface energy budget, and we neglect the ocean transport. As mentioned in the introduction, we follow [**?**] and use a fixed target SST (SST_{tr}) to which the domain mean SST at each step is relaxed so that the surplus of energy is removed by this relaxation. This method keeps the domain mean SST constant over time while it allows the SST to vary locally according to the evolution equation:

$$\frac{dSST(i,j)}{dt} = \frac{SWNS(i,j) - LWNS(i,j) - LHF(i,j) - SHF(i,j)}{\rho C_p H} + \frac{SST_{tr} - \overline{SST}}{\tau}, \tag{4}$$

where τ is the relaxation time which is constant and equal to two hours in all of our simulations. H represents the depth of the slab. i and j indices represent the horizontal grid indices (in x and y). LHF and SHF denote surface latent and sensible heat fluxes (positive upward). SWNS (positive downward) and LWNS (positive upward) stand respectively for shortwave and longwave net radiative flux convergence at surface. SWNS has only a downward part while LWNS is defined as:

$$LWNS(i,j) = \sigma SST(i,j)^4 - LW_d(i,j), \tag{5}$$

where σ is the Stephen-Boltzmann constant and LW_d the downward longwave flux at the surface.

References

[1] Marat F. Khairoutdinov and David A. Randall. Cloud resolving modeling of the ARM summer 1997 IOP: Model formulation, results, uncertainties, and sensitivities. *J. Atmos. Sci.*, 60(4):607–625, 2003.

[2] C. S. Bretherton, P. N. Blossey, and M. Khairoutdinov. An energy-balance analysis of deep convective self-aggregation above uniform SST. *J. Atmos. Sci.*, 62(12):4273–4292, 2005.

[3] C. J. Muller and I. M. Held. Detailed investigation of the self-aggregation of convection in cloud-resolving simulations. *J. Atmos. Sci.*, 69:2551–2565, 2012.

Table 1: List of simulations for first configuration: fixed SST. Shown are SST and length of integration .

SST (K)	legth (day)
280	40
290	40
295	40
300	40
305	40

Table 2: List of the simulations for second configuration: hot-spot. Shown are the hot-spot radius, the fractional area covered by it (with one digit for values below 10 %), its temperature anomaly (dT), ocean temperature and domain mean SST.

HS Radius (km)	$A^{hs}/(A^{env}+A^{hs})(\%)$	dT (K)	SST^{env} (K)	$\overline{SST}$ (K)
60	3.4	5	299.83	300
65	4.0	5	299.80	300
70	4.6	5	299.77	300
80	6.1	5	299.69	300
80	6.1	3	299.81	300
180	31	5	298.46	300
220	46	5	297.70	300
285	77	5	296.15	300

Table 3: List of the simulations for third configuration: interactive SST. Shown are the depth of the slab, the mean SST and the length of simulation.

Slab depth (m)	SST_{tr} (K)	length (day)
5	305	50
5	300	100
10	305	40
10	300	60
50	305	40
50	300	50

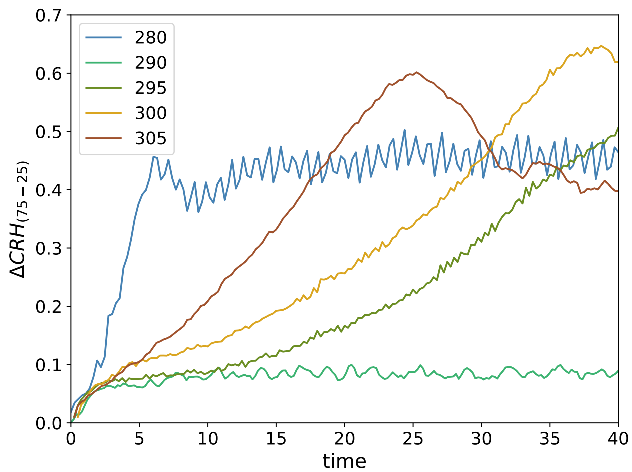

Figure 1: The time series of aggregation index for simulation at different SST (table 1

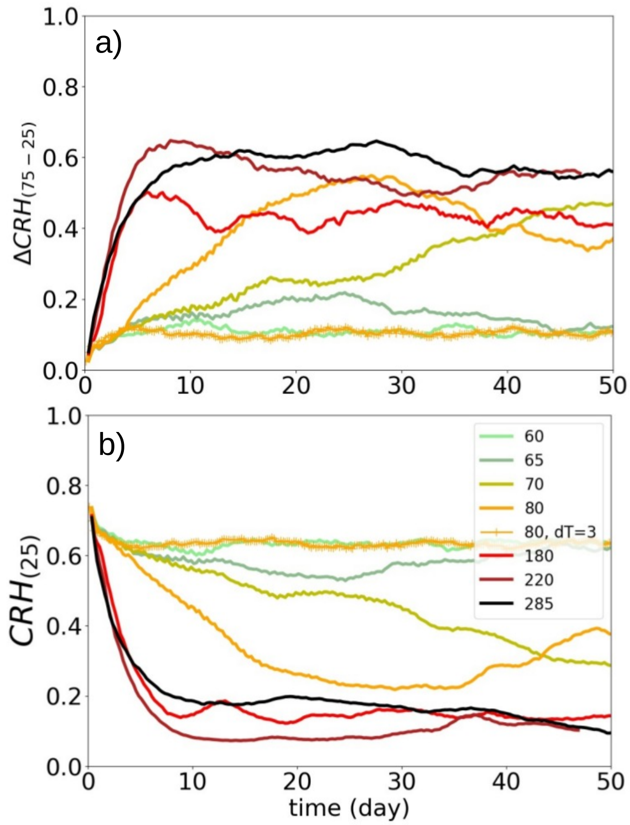

Figure 2: Time evolution of (a) the aggregation index and (b) CRH averaged over driest quartile for different hot-spot radius (table 2). All the simulations have a domain size of 576*576 km^2 and a hot-spot SST anomaly of 5 K except for one simulation with a radius of 80 km and a SST anomaly of 3 K.

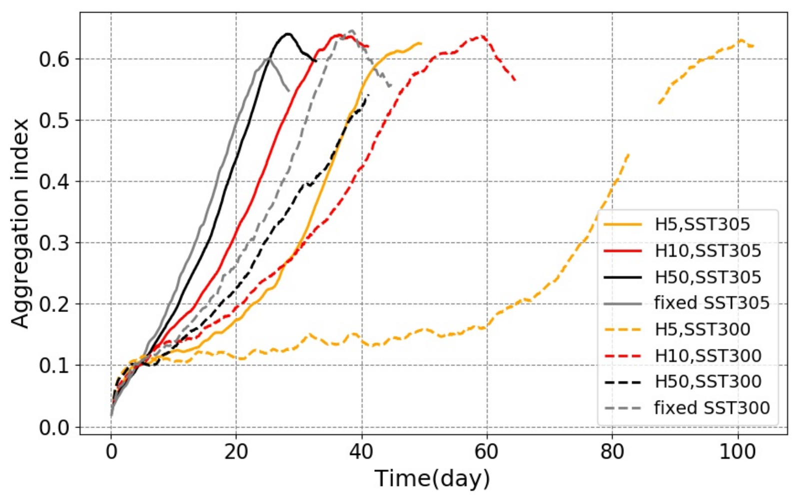

Figure 3: Plot shows the time series of $CRH_{(75-25)}$ for $SST_{tr} = 300K$ (dashed lines) and $SST_{tr} = 305K$ and different slab depths (plain lines). Simulations with fixed SST are also shown for reference (gray lines). (We note in passing that the few days missing in the H5SST300 simulation, around day 85, are due to a technical issue, but do not affect the results discussed here.)