

# The impact of a land-sea contrast on convective aggregation in radiative-convective equilibrium

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## Abstract

Convective aggregation is an important atmospheric phenomenon which frequently occurs in idealised models in radiative-convective equilibrium (RCE), where the effects of land, rotation, sea surface temperature gradients, and the diurnal cycle are often removed. This aggregation is triggered and maintained by self-generated radiatively driven circulations, for which longwave feedbacks are essential. Many questions remain over how important the driving processes of aggregation in idealized models are in the real atmosphere. We approach this question by adding a continentally-sized, idealized tropical rainforest island into an RCE model to investigate how land-sea contrasts impact convective aggregation and its mechanisms. We show that convection preferentially forms over the island persistently in our simulation. This is forced by a large-scale thermally driven circulation. First, a sea-breeze circulation is triggered by the land-sea thermal contrast, driven by surface sensible heating. This sea-breeze circulation triggers convection which then generates longwave heating anomalies. We find that these longwave heating anomalies are essential for maintaining the aggregation of convection over the island through mechanism denial tests. We also show, by varying the island size, that the aggregated convective cluster appears to have a maximum spatial extent of 10,000 km. These results highlight that the mechanisms of idealized aggregation remain relevant when land is included in the model, and therefore these mechanisms could help us understand convective organization in the real-world.

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## Key Points:

- Convection preferentially aggregates over land in a global radiative-convective equilibrium simulation
- A global land-centered circulation drives the aggregation and is triggered through surface fluxes, but maintained through longwave fluxes
- The land-based convective cluster appears to have a maximum spatial scale of 10,000 km

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## 13 **Abstract**

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15 in idealised models in radiative-convective equilibrium (RCE), where the effects of land,  
16 rotation, sea surface temperature gradients, and the diurnal cycle are often removed. This  
17 aggregation is triggered and maintained by self-generated radiatively driven circulations,  
18 for which longwave feedbacks are essential. Many questions remain over how important  
19 the driving processes of aggregation in idealized models are in the real atmosphere. We  
20 approach this question by adding a continentally-sized, idealized tropical rainforest island  
21 into an RCE model to investigate how land-sea contrasts impact convective aggregation and  
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30 idealized aggregation remain relevant when land is included in the model, and therefore  
31 these mechanisms could help us understand convective organization in the real-world.

## 32 **Plain Language Summary**

33 Large storm clouds that often form in the tropical atmosphere can cluster together  
34 to form cloud systems, which are associated with large amounts of precipitation within  
35 the cloudy region, and very dry conditions away from the cloudy region. These cloud  
36 systems - known as organized deep convection - are often studied in simplified models of the  
37 atmosphere where the land, Earth's rotation, variations in sea-surface temperature, and the  
38 diurnal cycle are removed. The simplified models allow scientists to understand the processes

39 driving deep convection and why it organizes into these large systems. Using these models  
40 in previous studies has helped us understand that interactions between the atmosphere, the  
41 clouds and longwave radiation have an important role in organizing convection.

42 In this paper we take a step towards reality and look at how including a large, idealized  
43 island in one of these simplified models affects how convection organizes together. We show  
44 that convective clouds will group together over the land throughout our model simulations,  
45 and that the processes driving this are similar to those organizing convection in previous  
46 papers. The results shown in the paper highlight that results from idealized modelling  
47 studies could help us understand how convection organizes in the real-world.

## 48 **1 Introduction**

49 In the tropics, deep convection transports large amounts of water vapour and energy  
50 vertically, as well as playing an important role in setting the Earth’s radiative budget and  
51 large-scale circulations. This deep convection can be organized on a range of scales, from  
52 mesoscale convective systems, up to planetary envelopes of convection like the Madden-  
53 Julian Oscillation (MJO) (Madden & Julian, 1994; Tobin et al., 2012). Organized systems  
54 like these provide a significant contribution to tropical precipitation and cloudiness, with a  
55 large fraction of precipitation extremes occurring during convective organization (Roca &  
56 Fiolleau, 2020). Increased convective clustering has also been shown to affect large-scale  
57 circulations, including the structure and extent of the intertropical convergence zone (Popp  
58 & Bony, 2019).

59 Idealized climate models are a useful tool for studying moist convection in the tropical  
60 climate. In these models rotation, land, the diurnal cycle, and sea surface temperature  
61 (SST) gradients are often removed. This simplified configuration is known as radiative-  
62 convective equilibrium (RCE), where any imbalances in radiative cooling are balanced by  
63 convective heating (Manabe & Wetherald, 1967). Removing these complexities associated

with heterogeneities in the boundary conditions allows for studies to analyse the processes of importance to moist convection, such as its interactions with radiation and circulations (Wing et al., 2020). Due to the negligible Coriolis force in the tropics, previous studies have found that RCE is a reasonable representation of the tropical climate (Jakob et al., 2019), and therefore it has been extensively used in studies on the tropical atmosphere (e.g. Manabe & Wetherald, 1967; Held et al., 1993; Tompkins & Craig, 1998; Robe & Emanuel, 2001; Stephens et al., 2008; Khairoutdinov & Emanuel, 2013; Wing et al., 2020).

In many models using an RCE configuration, deep convection has been found to spontaneously cluster together through radiatively-driven circulations, despite homogeneous boundary conditions; a phenomenon called convective self-aggregation (Held et al., 1993; Tompkins & Craig, 1998; Bretherton et al., 2005; Muller & Held, 2012; Wing & Emanuel, 2014; Coppin & Bony, 2015; Wing et al., 2020). The self-aggregation of convection has been found to require longwave radiative feedbacks for its initiation and maintenance, with shortwave and surface enthalpy feedbacks being shown to contribute to the aggregation’s initiation, but ultimately have been found to not be essential for aggregation to form (Wing & Emanuel, 2014; Coppin & Bony, 2015; D. Yang, 2018a; Muller & Held, 2012).

Despite RCE being regarded as a reasonable simplification of the tropical climate, the real-world relevance of the behaviour of deep convection in these models is debated. In particular, many of the processes which are removed in an RCE model have been shown to influence the organization of convection, such as SST gradients (Tompkins & Semie, 2017; Shamekh et al., 2020a; Müller & Hohenegger, 2020) and land-sea contrasts (Sato et al., 2009; Leutwyler & Hohenegger, 2021; Cronin et al., 2015). There are an increasing number of studies which highlight the possible role of the feedbacks essential to aggregation in real-world convective processes. For example, both the MJO and tropical cyclones have been simulated in RCE models with rotation (Arnold & Randall, 2015; Khairoutdinov & Emanuel, 2018; Davis, 2015; Wing et al., 2016; Muller & Romps, 2018), and the diabatic

90 heating from absorbing aerosol plumes has been shown to force convection to aggregate  
 91 (Dingley et al., 2021). Inhomogeneous surfaces have also been shown to strongly affect  
 92 convective aggregation. Studies have shown that SST gradients force convection to cluster  
 93 over warmer SSTs (Tompkins, 2001; Shamekh et al., 2020a; Müller & Hohenegger, 2020),  
 94 whilst interactive SSTs have been shown to prevent or delay the aggregation of convection  
 95 (Hohenegger & Stevens, 2016; Shamekh et al., 2020b). This is because the SST under a  
 96 convective cluster will cool due to cloud shielding, whilst SSTs away from the convection  
 97 will warm, which will then drive a circulation towards the dry region, disaggregating the  
 98 convection. The organization of convection has also been studied on a land-like planet in  
 99 RCE, with no ocean. Here Hohenegger & Stevens (2018) found that, as with interactive  
 100 SSTs, the ability of land to change temperature causes a homogenization of the precipitation  
 101 field on long time scales. They found that when an area of the domain is not covered by  
 102 a convective cluster, the drying which occurs acts to induce a low-level circulation which  
 103 changes the low-level flow direction towards this dry region, instead of towards the convective  
 104 cluster. This aggregates convection in this originally drier region, until a new dry area  
 105 forms and induces this circulation reversal again. Therefore, these soil moisture-atmosphere  
 106 interactions can act to prevent the long-term aggregation of convection.

107       Aggregation that occurs with inhomogenous boundary conditions (such as SST gradi-  
 108 ents, land, or aerosol plumes) is no longer referred to as 'self-aggregation', due to the external  
 109 processes which now are responsible for forcing the clustering. In these forced aggregation  
 110 cases, it has been shown that convection can sometimes aggregate in the absence of  
 111 the usually essential longwave radiative feedbacks (Shamekh et al., 2020a; Dingley et al.,  
 112 2021), generally due to a temperature gradient being maintained via an external diabatic  
 113 process, such as a hot-spot in the SST (Shamekh et al., 2020a), or the radiative perturba-  
 114 tion from an aerosol plume (Dingley et al., 2021). These inhomogeneities can then drive a  
 115 thermally-driven circulation and aggregate the convection.

116 Thus far, less attention has been given to the impact of land-sea contrasts on aggrega-  
117 tion. Differences in the behaviour of land and ocean could have large impacts on aggregation,  
118 such as the differences in the heat capacities of land and ocean (causing the land-ocean ther-  
119 mal contrast), moisture availability (land has the ability to dry out, whereas the ocean acts  
120 as an infinite water source), orography and the surface roughness length. Each of these fac-  
121 tors can greatly affect the surface fluxes, which have previously been shown to impact the  
122 formation of aggregation (Bretherton et al., 2005; Coppin & Bony, 2015; D. Yang, 2018a),  
123 and so including land in RCE simulations could impact whether aggregation can form, and  
124 its lifetime, whilst also taking a large step towards a more realistic modelling paradigm.

125 Previous investigations of islands in an RCE model have shown that convection and  
126 precipitation tend to favor land (Cronin et al., 2015; Leutwyler & Hohenegger, 2021; Coppin  
127 & Bellon, 2019; Wang & Sobel, 2017). Land has also been found to have an impact on the  
128 domain-mean tropospheric temperature in an RCE simulation. Cronin et al. (2015) found  
129 that the presence of an island increased the tropospheric temperature comparatively to  
130 an all-ocean simulation, and this warming increased monotonically with island size. They  
131 postulate that this is due to the clouds forming at the warmest and moistest areas (which  
132 are over the island), pushing deep convection towards a moister adiabat. Contrastingly,  
133 Leutwyler & Hohenegger (2021) found that the presence of islands has a tendency to cool  
134 the troposphere, with larger islands having a larger cooling effect. They hypothesise that  
135 the reason their result contradicts that of Cronin et al. (2015) is due to a difference in  
136 modelling design: Cronin et al. (2015) model the land simply by changing the ocean’s heat  
137 capacity, and so in their model there is no limit on water availability, whereas Leutwyler &  
138 Hohenegger (2021) use a land surface scheme which allows for soil drying. Therefore, in the  
139 absence of precipitation, the soil is able to dry out, limiting evaporation, and thus drying  
140 the sub-cloud layer. These contradicting results could benefit from additional exploration,  
141 which we will provide in this paper.

Previous studies of islands in an RCE simulation have focused mainly on the effect the land-sea contrast has on the diurnal cycle, precipitation and temperature profile more than the mechanisms behind any organization of convection. They have also exclusively investigated the effect in a cloud-resolving model (CRM), where island size is limited. To our knowledge, no studies thus far have investigated the effect of a larger, continentally-sized island and its impacts on aggregation. In this paper we aim to answer the following questions:

1. How does the inclusion of an idealized island in a global RCE model impact the aggregation of convection? In particular:
  - the spatial structure of aggregation,
  - the domain-mean atmospheric properties.
2. How does the inclusion of an island affect the global circulation?
3. Are the physical mechanisms responsible for aggregation similar to those seen in land-free simulations, or forced aggregation simulations?
4. How sensitive are these results to the island size?

## 2 Methods

### 2.1 Model set-up

We employ the ICOSahedral Nonhydrostatic Atmospheric GCM (ICON; Giorgetta et al. 2018; Zängl et al. 2015), version 1.8, coupled to the JSBACH4 land model (Jungclaus et al., 2022) in all simulations described in this paper. This version of the ICON GCM model uses the ECHAM6 physics packages (for a full description, see Stevens et al., 2013), including a bulk mass-flux convection scheme (Nordeng, 1994; Tiedtke, 1989) and cloud cover calculated using the relative humidity (Sundqvist et al., 1989). Other parameterisation schemes used are the Lohmann and Roeckner microphysics scheme (Lohmann & Roeckner, 1996) and the gravity wave scheme as described in Stevens et al. (2013).



167 The JSBACH4 land model is a dynamic global vegetation model and offers a full repre-  
168 sentation of soil-vegetation-atmosphere interactions. The surface energy budget and soil  
169 thermal layers over land are implicitly coupled to ICON through the vertical diffusion  
170 scheme. There are five soil layers which descend to 10 m depth; heat and water dynamics  
171 are defined on these soil levels.

172 ICON is run on a triangular grid, based on dividing a spherical icosahedron. In this  
173 paper we use the R02B04 grid, which has 20480 cells, with an average cell area of approx-  
174 imately 25000 km<sup>2</sup>, and an approximate equivalent grid-spacing of 160 km. Each grid cell  
175 over land is divided into two sections: a "tiled" fraction, and the fraction of the non-ice cov-  
176 ered grid-cell that is inhospitable to vegetation (for example, rocky terrain or sandy desert).  
177 The tiled fraction of the grid box is then further separated into different surface types to  
178 represent sub-grid scale heterogeneity: a glacier, or one of 11 plant functional types (Reick et  
179 al., 2013). In our simulations, all land grid cells are completely covered by vegetation, with  
180 no glaciers, to mimic warm tropical conditions. The vertical resolution is set by assigning  
181 47 stretched model levels between the surface and model top at 83 km, with grid spacings  
182 ranging from 40 m between the lowest model layers, to around 1350 m at 15 km, and 5900  
183 m near the model top. In these simulations we use a model time step of 15 minutes, with  
184 radiation calculated every 90 minutes.

## 185 **2.2 Experimental set-up**

186 ICON is used in an RCE configuration. The simulations are setup with no rotation, no  
187 diurnal cycle, no large-scale imposed winds, and a fixed SST of 305K, an SST where strong  
188 self-aggregation occurs in the ICON GCM (Dingley et al., 2021). The RCE state is initialized  
189 from homogenised boundary conditions with a solar insolation of 551.58 Wm<sup>-2</sup> and a fixed  
190 zenith angle of 42.05° giving a constant total insolation of 409.6 Wm<sup>-2</sup>, equivalent to  
191 the annual mean insolation in the tropics. The temperature and specific humidity profiles

are initialized from a one month, non-aggregated aquaplanet simulation: we use horizontal means of the temperature and humidity profiles at the end of this non-aggregated simulation, and add some noise in the lowest five layers (see Wing et al., 2018), then set those profiles as our initial conditions in the remaining simulations. The ocean albedo is set to 0.07. Concentrations of tracers CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O and O<sub>2</sub> are set to be constant in space and time and the O<sub>3</sub> profile is the same as used in Popke et al. (2013). This atmospheric configuration follows that of the RCE model intercomparison (RCEMIP) project (Wing et al., 2018). The simulations described in this paper were run for two years.

Land in our simulations is represented by a large, tropical-like, circular island, located at latitude = 0° longitude = 0° with a radius of 40° (giving the land an area of 35.7\*10<sup>6</sup> km<sup>2</sup>). Surface properties have been set to average tropical rainforest-like values, with tropical broadleaf evergreen vegetation covering the island. Rainforest surface properties are taken from the JSBACH4 initialization dataset (Hagemann, 2002; Reick et al., 2021), and averaged over a box in the Amazon with latitudes ranging between -1° to -10° and longitudes ranging between -70° to -60°. Some of the key surface properties are listed in Table 1. Soil temperature is the only property not set using Amazon rainforest equivalent values. Soil temperature is initialized as equal to the SST at all model levels, following Leutwyler & Hohenegger (2021). We ran a test simulation with Amazon rainforest values for the soil temperature and found that our results were invariant to this choice. Results were also tested with island surface temperatures ranging between 300K to 310K at increments of 1K, and again were found to be invariant to our choice of initial temperature. The island has an elevation of 0 m everywhere, to remove effects on convection and its organization from topography.

Here, we describe three simulation setups which differ from the standard simulation described thus far. Firstly, the results from the land simulation we run are compared to an aggregated 'no land' RCE simulation (hereafter referred to as NoLand-Aggregated).

<i>Parameter Name</i>	<i>Value</i>
Soil type	Mixture of loam and clay
Leaf area index	8.928
Root depth	1.351 m
Vegetation albedo	0.122
Roughness length	1.871 m
Soil depth (to bedrock)	2.194 m
Heat capacity	$2.296 \times 10^6 \text{ Jm}^{-3}\text{K}^{-1}$

**Table 1:** Surface properties used to initialize the JSBACH4 land model within the ICON GCM

218 This NoLand-Aggregated RCE simulation is run on an aquaplanet, but is otherwise iden-  
 219 tical to the land simulation described above. Comparing the results from the land and  
 220 NoLand-Aggregated simulations allows us to decipher what effect the land is having on  
 221 the aggregation of convection. Secondly, in order to perform mechanism denial tests, we  
 222 will occasionally refer to homogenized radiation runs. In these simulations, we horizontally  
 223 homogenize radiative heating rates at each model level and timestep, following Muller &  
 224 Held (2012). Finally, results are also often compared to a non-aggregated simulation (here-  
 225 after referred to as NoLand-NotAggregated), in order to isolate the impacts aggregation is  
 226 having on the atmosphere. This NoLand-NotAggregated simulation mirrors the NoLand-  
 227 Aggregated RCE simulation, but with horizontally homogenized longwave radiative heating  
 228 rates, in order to prevent the convection aggregating (e.g. Arnold & Putman, 2018; Muller  
 229 & Held, 2012; Wing & Emanuel, 2014).

230 In order to compare the aggregated state of different simulations, we use a metric of  
 231 aggregation. In this paper, our metric is the variance of column-integrated relative humidity  
 232 ( $\text{CRH}$ ;  $\sigma_{\text{CRH}}^2$ ) (Wing & Cronin, 2016). Column relative humidity is defined as the density-  
 233 weighted integral of tropospheric precipitable water divided by the density-weighted integral  
 234 of the saturated precipitable water. This metric utilizes the signature of aggregation where  
 235 moist regions moisten and dry regions get drier as convection clusters together, causing

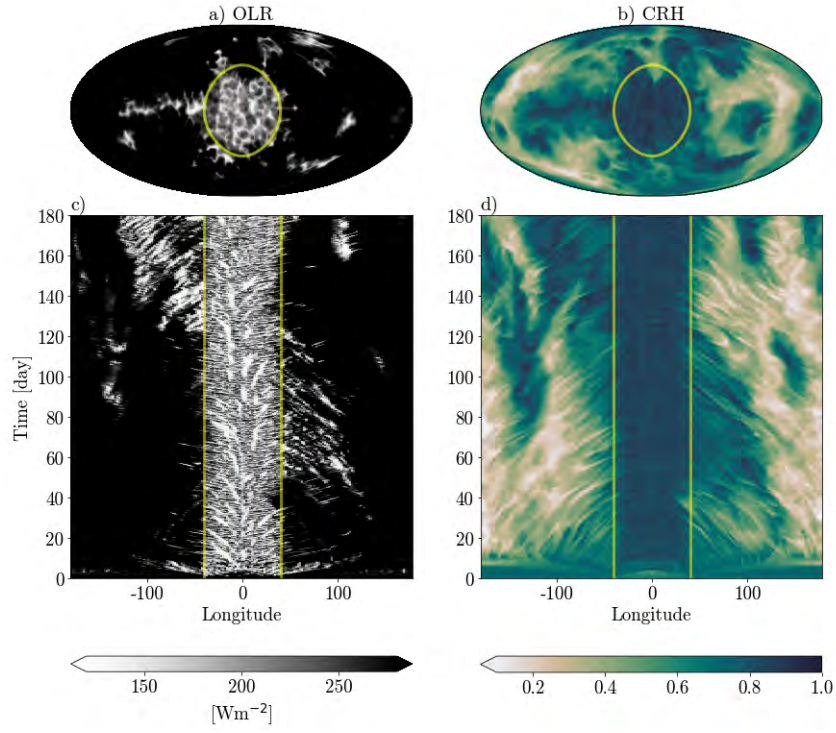
236 a broadening of the moisture distribution. Please note that this metric does not have a  
237 threshold value above which convection is considered as aggregated. Instead, it is used a  
238 comparative metric which allows us to compare the relative degree of aggregation across  
239 different simulations.

## 240 **3 Results**

### 241 **3.1 Land-centered aggregation**

242 Convection primarily forms over the island throughout our simulations (Figure 1a, c),  
243 driving large moisture gradients, with the moistest columns of the domain consistently over  
244 the island, and the driest columns tending to be the ones furthest away from the island  
245 (Figure 1b, d). This aggregated state is visually reached approximately between 5-10 days  
246 after the simulation start, although atmospheric equilibrium and therefore equilibrium in  
247 the moisture variance is reached approximately 70 days after simulation start (Figure 2). We  
248 can also see in Figure 1c that most convection which forms over the ocean subsequently gets  
249 advected towards the island, represented as the diagonal white lines (for example starting  
250 at longitude=100° at approximately day 80) slanted towards the island. Convection which  
251 is triggered over the island itself, typically forms at the centre of the island and is advected  
252 towards the coastline of the island. Videos of the OLR and CRH over the first six months  
253 can be seen in movie S1.

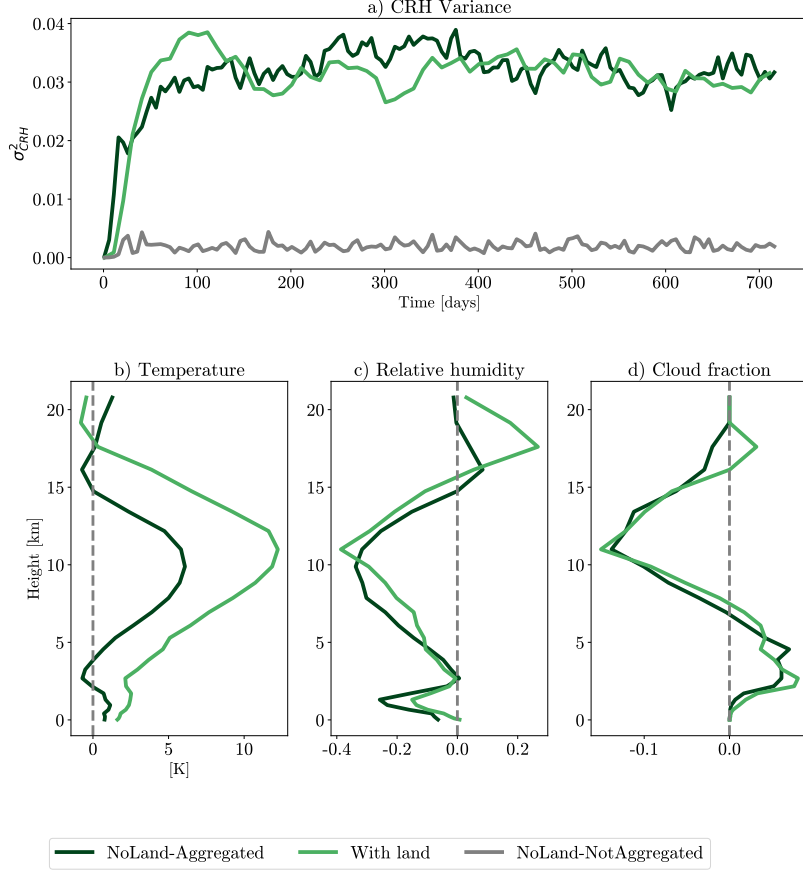
254 Figure 2 shows a comparison of the domain-mean properties of this simulation with  
255 the NoLand-NotAggregated simulation, and the NoLand-Aggregated simulation. We can  
256 see that comparatively to the NoLand-NotAggregated simulation, there is a strong domain-  
257 mean warming, free-tropospheric drying, and a decrease in high level clouds. This is consis-  
258 tent with the results of many previous studies (e.g. Wing et al., 2020; Cronin & Wing, 2017).  
259 The aggregated simulation with land shows similar domain-mean effects of aggregation to  
260 the NoLand-Aggregated simulation, with Figure 2a showing the same degree of aggregation



**Figure 1:** a), b): 4-hour mean snapshots of a) outgoing longwave radiation (OLR) and b) column relative humidity (CRH) 180 days after simulation start. c), d): Hovmöller plots of c) OLR, and d) CRH over the first 180 days of the simulation, taken as a zonal slice through latitude= $0^\circ$ . The yellow lines show the coasts of the island.

261 between these two simulations. There is also little change in the amount of free-tropospheric  
 262 drying and reduction in high cloud fraction between the runs with/without land, but there is  
 263 slightly less drying of the lower troposphere and an increase in tropopause height when land  
 264 is present. Despite these similarities between the simulations with/without land, there is  
 265 a much stronger domain-mean warming throughout the troposphere in the simulation with  
 266 land. This would happen, if the convection in the simulation with land is on a warmer moist  
 267 adiabat than the convection in the simulation without land. This is true in our simulations  
 268 as the experiment with land has convection forming over a warmer lifting condensation level  
 269 than the experiment with no land. Our result here agree with Cronin et al. (2015), but not  
 270 with Leutwyler & Hohenegger (2021). We hypothesise that the difference between our study  
 271 and Leutwyler & Hohenegger (2021) is that their convection doesn't always remain over the  
 272 island. This allows the soil to dry out which limits evaporation and results in their sub-  
 273 cloud layer being drier than over the ocean, meaning that the deep convection ends up on  
 274 a colder adiabat. This difference in spatial pattern of convection is likely due to Leutwyler  
 275 & Hohenegger (2021) including a diurnal cycle in their simulations. The solar diurnal cycle  
 276 has been shown to strongly affect the patterns of precipitation and convection over tropical  
 277 islands (e.g. Wang & Sobel, 2017; Coppin & Bellon, 2019) and tropical continental land  
 278 masses (e.g. G.-Y. Yang & Slingo, 2001), and so it is likely that the inclusion of a diurnal  
 279 cycle would have an impact on the consistency of convection we see over the island in our  
 280 simulations.

281 It is clear from Figure 1 that there is a large-scale circulation being generated and  
 282 maintained over the island, and that this is likely responsible for the aggregation of con-  
 283 vection throughout our simulation. It has been shown before that the self-aggregation of  
 284 convection is driven by self-generated radiative circulations. These circulations have often  
 285 been shown to start as an anomalous patch of dry sky, which then grows and pushes the  
 286 convection to cluster together (Muller & Held, 2012; Muller & Bony, 2015; Coppin & Bony,  
 287 2015; Holloway & Woolnough, 2016), a mechanism for which longwave radiative feedbacks



**Figure 2:** a) Time evolution of variance of domain-mean column relative humidity (CRH;  $\sigma_{CRH}^2$ ). b)-d): Domain-mean vertical profiles of b) temperature, c) relative humidity, d) cloud fraction, time-averaged over days 100-720 of the simulations. In all plots dark green lines represent a self-aggregated RCE simulation with no land ('NoLand-Aggregated'), light green lines represent an aggregated RCE simulation with land, and grey lines represent a non-aggregated simulation with no land ('NoLand-NotAggregated'). For figures b)-d), the vertical profiles from the non-aggregated simulation are subtracted from the 'no land' and 'land' aggregated simulations' profiles.

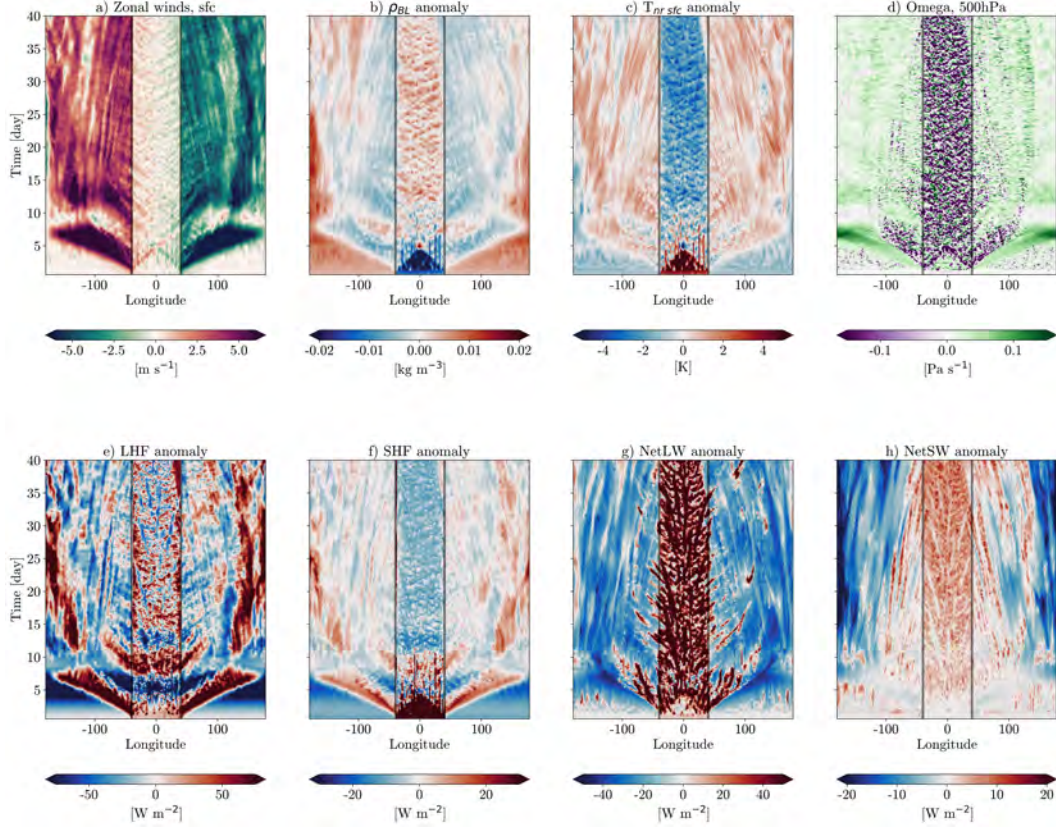
288 are generally essential both for triggering and maintenance. We investigate here whether the  
289 convection is aggregated through the same mechanisms as self-aggregation. We will study  
290 this first by discussing the thermodynamics responsible for triggering the circulation, and  
291 then for maintaining the circulation.

292 Figure 3 shows some of the key physical quantities driving the circulation over the first  
293 40 days of our simulation. Figure 3a illustrates the aforementioned circulation, and its ex-  
294 tent. We can see that the surface winds are converging towards the island at every oceanic  
295 point, with approximate speeds of  $3 \text{ ms}^{-1}$  once aggregation has been reached (roughly 10  
296 days after simulation start). This circulation is being triggered initially by very strong sensi-  
297 ble heat flux anomalies at the start of the simulation, driving high near-surface temperature  
298 anomalies. These anomalies cause strongly negative boundary layer (here boundary layer  
299 is defined as the lowest 1 km) density anomalies (Figure 3b), and hence strongly positive  
300 buoyancy anomalies over the island. The land-sea thermal contrast begins to cause surface  
301 winds to converge bringing cool, dense oceanic air over the island. The circulation described  
302 here is analogous to the well documented sea-breeze circulation (Miller et al., 2003). The  
303 advected dense oceanic air elevates the warmer, more buoyant air hence triggering convec-  
304 tion. This convection starts at the edge of the island, and as the surface circulation grows  
305 in strength, moves inwards until the whole island is covered by convecting air (Figure 3d).  
306 For a more zoomed in version of Figure 3, please see Figure S1. It is becoming increasingly  
307 clear in the field that boundary layer feedbacks are essential for triggering aggregation (e.g.  
308 Muller & Bony, 2015; Naumann et al., 2017; D. Yang, 2018b,a; Dingley et al., 2021), and  
309 our results support this hypothesis. The convection over the island triggers a gravity wave  
310 propagating at  $30 \text{ ms}^{-1}$  at 500 hPa, which acts to eliminate horizontal density gradients in  
311 the free-troposphere. This gravity wave is responsible for propagating the temperature of  
312 the warmer moist adiabat that the convection is on to the rest of the domain, consistent with  
313 the weak temperature gradient approximation (Sobel et al., 2001; Leutwyler & Hohenegger,  
314 2021), and can be seen in Figure 3, especially in Figure 3d as a wave of subsiding air moving



315 outwards away from the island. The subsidence associated with this wave causes a strong  
 316 drying of the columns far away from the island (Figure 1d), which completes the process  
 317 of aggregation. Figures 3g and h show that in the initial two day period during which  
 318 this circulation is being spun-up, the horizontal anomalies in both column longwave and  
 319 shortwave radiative fluxes are minimal. Thus, it seems from Figure 3 that the circulation  
 320 which aggregates the convection is triggered in this simulation with land primarily through  
 321 surface fluxes, mostly the sensible heat flux, not radiative feedbacks as in previous aggrega-  
 322 tion studies. Once the convection starts to form, the longwave radiative anomalies start to  
 323 grow, implying that longwave feedbacks play an important role in our circulation, but are  
 324 not important for the circulation to be triggered initially. Similarly, once the dry patches  
 325 away from the island form, shortwave convergence anomalies grow quite strong (Figure 3h),  
 326 again implying that shortwave feedbacks play a role in amplifying the circulation.

327 We now turn to investigating the mechanisms responsible for maintaining this circula-  
 328 tion. In particular, we are interested in why the convection does not disaggregate, despite  
 329 the cold, dense surface air underneath the formed convective cluster. Figure 4 shows some  
 330 time averaged, zonal cross-sections of various physical quantities. Figure 4a again shows  
 331 the global circulation that is keeping the convection aggregated together, i.e. surface con-  
 332 vergence towards the island center with strong upper tropospheric divergence away from  
 333 the island. Figure 4b shows the vertical motions associated with convection. Inspecting  
 334 the 3d temperature anomalies (Figure 4c) reveals that the near-surface negative tempera-  
 335 ture anomalies in Figure 3c are confined to less than 1 km above the surface. Above this,  
 336 there is still a temperature gradient with warmer anomalies over the island than ocean, and  
 337 therefore the circulation aggregating the convection is still being thermally driven. However,  
 338 initially this circulation was being driven by the land-sea thermal contrast caused by the  
 339 land surface heating up. This poses the question, what is now driving the thermal anomalies  
 340 over the island? Figure 4d illustrates the strong gradients in longwave heating anomalies in  
 341 the lower troposphere, which are positive over the island and negative away from the island.

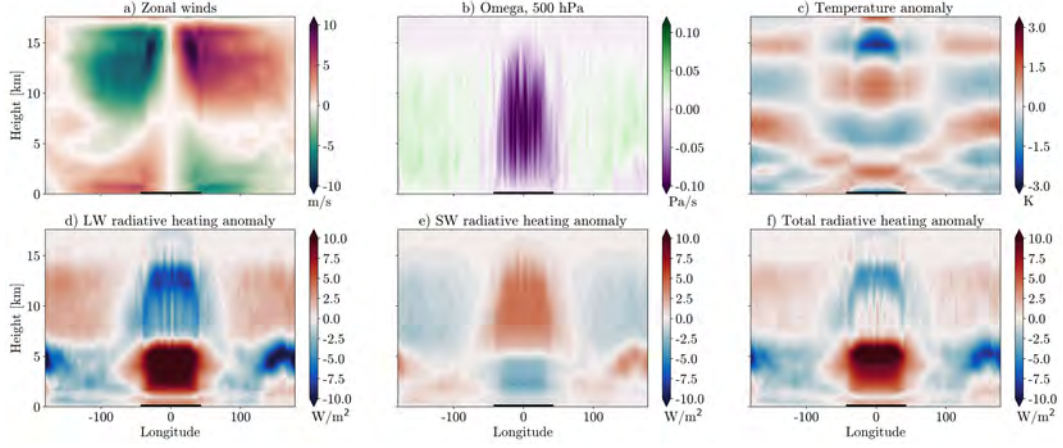


**Figure 3:** Hovmöller plots of a) Surface zonal winds, b) Density anomaly averaged over the boundary layer (lowest 1km) c) Near-surface temperature anomaly d) Omega at 500 hPa, e) Latent heat flux anomaly, f) Sensible heat flux anomaly, g) NetLW anomaly, h) NetSW anomaly, over the first 40 days of an RCE simulation with land, taken as a zonal slice through latitude=0°. The black lines show the coasts of the island.  $\text{NetLW} = LW_{sfc} - LW_{toa}$ ,  $\text{NetSW} = SW_{toa} - SW_{sfc}$ , where  $LW_{sfc}/SW_{sfc}$  are the net longwave/shortwave fluxes at the surface and  $LW_{toa}/SW_{toa}$  are the net longwave/shortwave fluxes at the top of atmosphere. Positive fluxes are defined upwards. Anomalies are calculated from the horizontal mean.

342 These gradients drive the temperature gradient in Figure 4c and are responsible for driving  
 343 the maintenance of the global circulation. This mechanism is the same as is discussed in  
 344 previous studies (e.g. Wing et al., 2017). The shortwave heating anomalies show a pattern  
 345 one would expect - negative anomalies in the lower troposphere representing the effects of  
 346 cloud shielding and positive anomalies in the upper troposphere due to absorption by water  
 347 vapour. However, the overall radiative heating anomaly pattern is driven by the longwave  
 348 radiative feedbacks (Figure 4f). We hypothesise that these radiative heating anomalies are  
 349 responsible for maintaining the island-centered circulation and therefore maintaining the  
 350 aggregation of convection over the island.

### 351 **3.2 Mechanism denial tests: Can land aggregation occur in the absence of** 352 **radiative flux anomalies?**

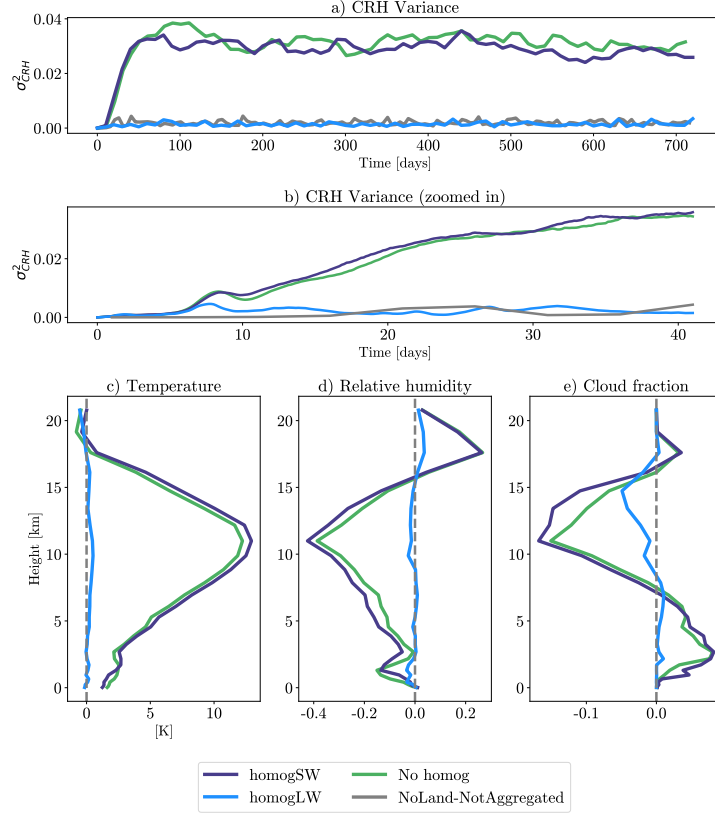
353 In order to test our radiative heating hypothesis, we perform some mechanism denial  
 354 tests. These tests involve horizontally homogenizing the radiative heating rates at each  
 355 model level, and each time step. This allows the radiative heating rates to change through  
 356 time, but removes the horizontal gradients, thought to be responsible for maintaining the  
 357 aggregation of convection (Muller & Held, 2012). Figure 5a shows that that homogenizing  
 358 the shortwave fluxes has had little impact on the overall degree of aggregation, whereas  
 359 homogenizing the longwave fluxes has decreased the degree of aggregation to the same as  
 360 the NoLand-NotAggregated experiment. If we inspect the first 40 days of the simulations  
 361 more closely (Figure 5b) then we can see that the CRH variance increases similarly in the  
 362 first 7 days of each simulation with land, then it is after this that the degree of aggregation  
 363 drops in the simulation with homogenized longwave feedbacks. This supports the findings  
 364 in the previous section that the surface fluxes are driving the spin up of the circulation, with  
 365 longwave feedbacks taking over as the dominant feedback after this.



**Figure 4:** a) Zonal winds, b) Omega, c) Temperature anomaly, d) Longwave radiative heating anomaly, e) Shortwave radiative heating anomaly, and f) Total radiative heating anomaly zonal slices taken at latitude= $0^\circ$ , averaged over days 100-720 of the RCE simulation with land. Island is located between longitudes  $\pm 40^\circ$ . Anomalies are calculated from the horizontal mean. Thick black line on the x-axis shows the horizontal island extent.

Figures 5c, d, and e present the same domain-mean properties as in Figure 2. Here, as in Figure 5a, the simulation with homogenized shortwave feedbacks mirrors the simulation with no homogenization, and the simulation with homogenized longwave feedbacks mostly mirrors the NoLand-NotAggregated simulation with no land. This also implies that the large domain-mean effects we see in Figure 2 are due to the aggregation process, not due to the inclusion of land itself.

The results from Figure 5b suggest that the circulation that is triggered in Figure 3 would also be triggered in the absence of longwave feedbacks, but that it is not being maintained, as we are no longer seeing any implied convective aggregation. Indeed, if we study how the same physical quantities act in the simulation without longwave feedbacks (Figure 6) we can see that this is true. The same circulation spin up can be seen by the land-sea thermal contrast in Figure 6c, and the subsequent gravity wave of subsidence in Figure 6d, however, without the convection triggering longwave feedbacks over the island, this circulation cannot be maintained, and instead the horizontal motion is now being dominated by wave-like motions across the globe (Figure 6a). This wave also travels at roughly  $30 \text{ ms}^{-1}$ ,

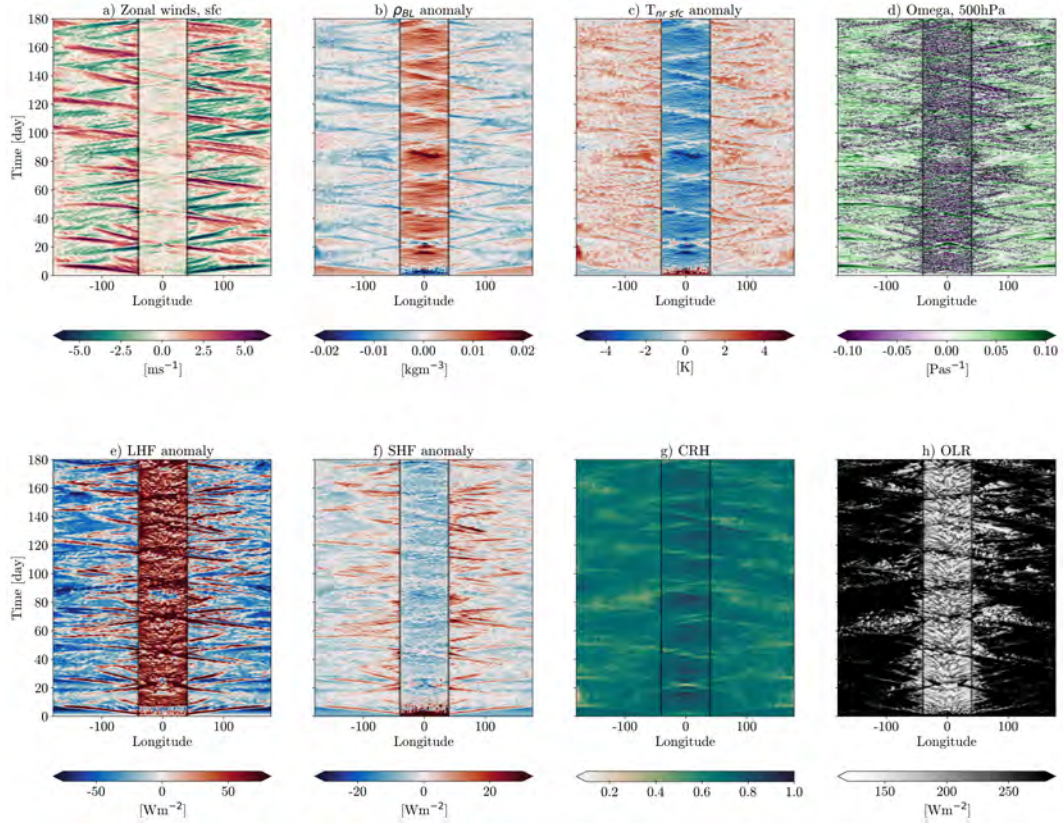


**Figure 5:** a), b) Time evolution of variance of domain-mean column relative humidity (CRH;  $\sigma_{CRH}^2$ ). c)-e): Domain-mean vertical profiles of c) temperature, d) relative humidity, e) cloud fraction, time-averaged over days 100-720 of the simulations. In all plots, green lines represent a aggregated RCE simulation with land and fully interactive radiative fluxes ('no homog'), purple lines represent an RCE simulation with land where shortwave fluxes are horizontally homogenized at each time step ('homogSW'), blue lines represent an RCE simulation with land where longwave fluxes are horizontally homogenized at each time step ('homogLW'), and grey lines represent a non-aggregated simulation with no land ('NoLand-NotAggregated'). For figures c)-e), the vertical profiles from the non-aggregated simulation are subtracted from the 'No homog', 'homogLW', and 'homogSW' aggregated simulations' profiles.

381 as in our original simulation. These waves travel away from the island, passing through  
 382 each other at the island’s antipode, creating a circulation which alternates between land-  
 383 centered and ocean-centered and repeats periodically approximately every 15-25 days. At  
 384 the points of strongest surface-level divergence away from the island (for example, around  
 385 day 20 in Figure 6a), the surface windspeeds over land increase, creating a warm, dry  
 386 anomaly over the center of the island, above which there is clear-sky (Figure 6h). This point  
 387 dries due to the increased windspeeds and the subsidence associated with the diverging  
 388 circulation, and warms because of the increased surface shortwave absorption due to the  
 389 clear-sky above as well as the increased windspeeds again. This warm anomaly then triggers  
 390 new convection, resulting in the same thermally-driven circulation and subsequent gravity  
 391 wave mechanism discussed. Over the island, convection tends to persist, except during the  
 392 brief suppression period at the peak of the ocean-centered circulation. Whilst this still  
 393 appears to provide a relatively visually aggregated scene in Figure 6h, the lack of persistent  
 394 land-centered circulation means that the moisture field doesn’t separate into extremely  
 395 moist and extremely dry patches, as is synonymous with convective aggregation (Figure  
 396 5a; Bretherton et al. 2005; Muller & Held 2012), and that convection is not therefore fully  
 397 suppressed away from the island, as in our original simulation (Figure 1). This wave-like  
 398 motion across the atmosphere is nicely illustrated in the supplementary movie S2 of OLR and  
 399 CRH. These results were also tested for simulations which were started from the equilibrium  
 400 aggregated state shown in Figure 1, and then had the longwave heating rates homogenized.  
 401 The results for this were the same as in Figure 5 and 6, and can be seen in Figure S2.

### 402 **3.3 Sensitivity to island size**

403 In order to test our results’ sensitivity to the island size, we ran an ensemble of simula-  
 404 tions where the island radius was increased from  $10^\circ$  to  $80^\circ$  in  $10^\circ$  increments. The winds,  
 405 near-surface temperature, OLR and CRH Hovmöller plots for these experiments are shown  
 406 in Figure 7. The standard result we’ve seen in this study, that convection will preferentially



**Figure 6:** Hovmöller plots of a) Surface zonal winds, b) Density anomaly averaged over the boundary layer (lowest 1km) c) Near-surface temperature anomaly d) Omega at 500 hPa, e) Latent heat flux anomaly, f) Sensible heat flux anomaly, g) Column relative humidity, h) Outgoing long-wave radiation, over the first 180 days of an RCE simulation with land where longwave fluxes are horizontally homogenized at each timestep, taken as a zonal slice through latitude=0°. The black lines show the coasts of the island. Anomalies are calculated from the horizontal mean.

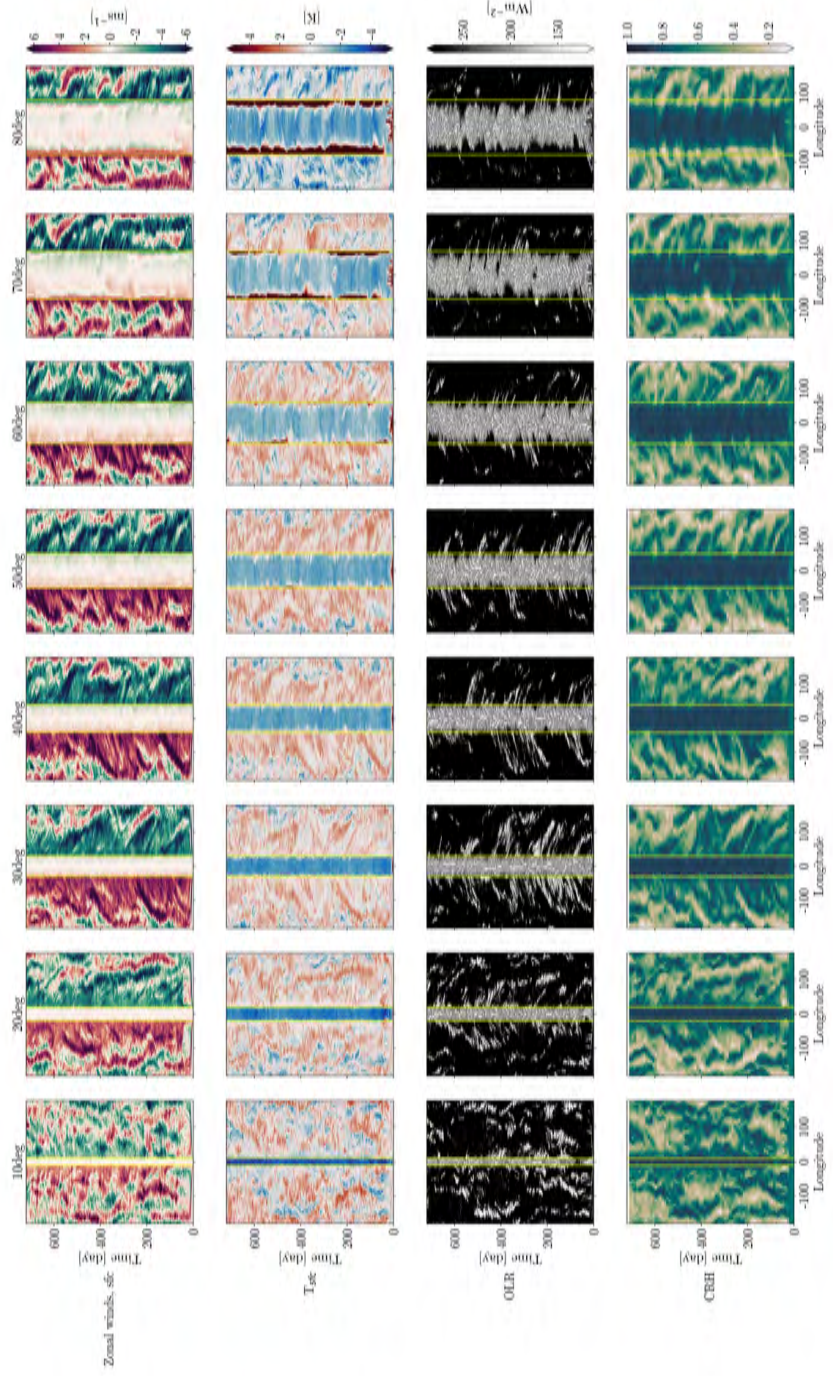


407 form over the island, forced by a large thermally-driven circulation mostly holds at all island  
 408 sizes. The extent of the circulation is much smaller in the  $10^\circ$  island simulation, as are the  
 409 maximum horizontal windspeeds. This circulation extent grows, reaching across almost the  
 410 whole globe in the simulations with island sizes between  $20^\circ$  and  $50^\circ$ . Along with this the  
 411 convective cluster also grows to cover the whole island, leading to cool near-surface tem-  
 412 perature anomalies over the island, due to the cloud shielding effect. Interestingly, above  
 413  $50^\circ$  the circulation stops growing in extent, and the convective cluster stops growing in size.  
 414 At  $60^\circ$ ,  $70^\circ$ , and  $80^\circ$  the convective cluster stays mostly the same size as the cluster in  
 415 the  $50^\circ$  simulation, and so is no longer covering the whole island. This results in clear sky  
 416 patches around the convective cluster, leading to large near-surface temperature anomalies.  
 417 There is also a reduction in the horizontal extent of the zonal winds. We speculate that  
 418 these results could point to a maximum size of aggregation cluster which would cover ap-  
 419 proximately 20% of the globe. Theories have previously been developed to try and explain  
 420 the spatial scale of aggregation (Beucler & Cronin, 2019; D. Yang, 2018b; Arnold & Put-  
 421 man, 2018). These have typically pointed to the importance of boundary layer processes  
 422 on controlling this spatial scale, and D. Yang (2018b) found that a typical length-scale of  
 423 self-aggregation is  $\mathcal{O}(2000km)$ . The maximum length-scale of aggregation in our simulations  
 424 is larger than this ( $\mathcal{O}(10000km)$ ), however we speculate that this is likely due to the large  
 425 forcing which the island is providing in these simulations. Interestingly, the typical scale of  
 426 the MJO, a phenomenon that has previously been linked to convective aggregation (Arnold  
 427 & Randall, 2015; Khairoutdinov & Emanuel, 2018), is also  $\mathcal{O}(10000km)$ . Nevertheless, these  
 428 results could provide a new environment in which to further investigate the spatial scale of  
 429 aggregation, especially looking towards how aggregation might manifest in the real world.

## 430 **4 Discussion and Conclusions**

431 Using the ICON GCM, we ran RCE experiments which included a large, continentally  
 432 sized island to investigate how the inclusion of land affects the phenomenon of convective





**Figure 7:** Hovmöller plots of a)-h) Surface zonal winds, i)-p) Near-surface temperature anomaly, q)-x) Outgoing longwave radiation, y)-ff) Column relative humidity for 720 days RCE simulations with different land sizes. Land sizes increase from 10° (column 1) to 80° (column 8) in 10° increments. Anomalies are calculated from the horizontal mean.

433 aggregation. The island here represents a tropical rainforest-like land mass, with no elevation  
434 and no large-scale imposed winds, surrounded by a constant SST of 305K.

435 We showed that the inclusion of an idealized island in these global RCE simulations  
436 causes the convection to aggregate persistently over the island. This aggregation takes ap-  
437 proximately 5-10 days to form spatially, however, it takes closer to 70 days for the model  
438 to reach statistical equilibrium, and therefore for the maximum degree of aggregation to be  
439 reached. The forced aggregation in these simulations causes similar domain-mean effects  
440 as self-aggregation has been shown to have before. This includes a domain-mean warm-  
441 ing, free-tropospheric drying and a reduction in the high cloud amount comparatively to  
442 a non-aggregated simulation (e.g. Bretherton et al., 2005; Coppin & Bony, 2015; Wing &  
443 Cronin, 2016; Cronin & Wing, 2017). One key difference between self-aggregation, and this  
444 land-forced aggregation is the domain-mean temperature profile. As in Cronin et al. (2015),  
445 we find that aggregation over the island causes a large increase in the domain-mean tem-  
446 perature, much greater than the temperature increase seen in a self-aggregated simulation  
447 (Figure 2). This is due to a warmer cloud-base temperature in the land simulation, which  
448 drives the convection onto a warmer moist adiabat. This warmer moist adiabat is then  
449 propagated to the rest of the domain through convectively-triggered gravity waves.

450 The aggregation seen in these simulations is forced by a large-scale thermally-driven  
451 circulation. We showed that the circulation is initially triggered by a strong land-sea thermal  
452 contrast at the surface, causing surface wind convergence. This circulation mirrors the  
453 manifestation of a sea-breeze circulation, which has been shown to have important impacts  
454 on convection and precipitation over tropical islands, particularly in the Maritime Continent  
455 (Miller et al., 2003; Leutwyler & Hohenegger, 2021). In our simulations, we found that the  
456 sea-breeze circulation triggers convection, first at the edge of the island before being triggered  
457 increasingly inland. This convection then incites a gravity wave, moving at approximately  
458  $30 \text{ ms}^{-1}$  outwards from the island. Gravity wave induced subsidence dries the columns

459 furthest away from the island, which forms large gradients in the CRH. Once these moisture  
460 gradients form, radiative feedbacks start to dominate the maintenance of the circulation with  
461 the strong longwave heating within the cloud layer combined with longwave cooling from  
462 the low emission temperature at the top of the cloud layer driving this maintenance. We  
463 have shown that this radiatively-driven circulation then persists throughout the simulation,  
464 despite negative near-surface temperature anomalies over the island.

465 We tested these results through mechanism denial experiments, which confirms the  
466 importance of longwave feedbacks for both the formation and maintenance of aggregation.  
467 When longwave heating rates are horizontally homogenized, aggregation no longer forms and  
468 the large-scale circulation is no longer be maintained. Instead, horizontal motion becomes  
469 dominated by gravity waves moving radially away from the island, causing a reversal of  
470 the land-sea circulation after the waves pass through each other at the island's antipode.  
471 This happens periodically throughout the simulation, with the waves converging on the  
472 island approximately every 15-25 days. With the lack of a constantly subsiding region away  
473 from the island, moisture gradients synonymous with aggregation do not form. Longwave  
474 feedbacks being essential for self-aggregation is a result that has been shown previously (e.g.  
475 Wing & Emanuel, 2014; Coppin & Bony, 2015; D. Yang, 2018a; Muller & Held, 2012). This  
476 study extends current understanding by demonstrating that even when land is included in an  
477 RCE model and could therefore change the mechanisms of aggregation through an increased  
478 importance of surface fluxes, longwave feedbacks are still the most important mechanism  
479 for driving and maintaining the aggregation of convection.

480 The results we have presented in this paper mostly scale with island size, until islands  
481 have a radius greater than  $50^\circ$  with the large-scale circulation roughly increasing in extent  
482 with island size, and the resulting convective cluster always covering the entire island. For  
483 experiments with an island radius greater than  $50^\circ$  the convective cluster never grows any  
484 greater than roughly 20% of coverage of the globe. This could point to a maximum size of

485 aggregation, something that has been a recent topic of interest (Beucler & Cronin, 2019;  
486 D. Yang, 2018b; Arnold & Putman, 2018). We highlight that the framework used in this  
487 study could provide some interesting insights to this work concerning the spatial-scale of  
488 aggregation.

489 We present this paper as an investigation of the impacts land-sea contrasts have on  
490 convective aggregation in a global configuration, and provide it as a useful addition to  
491 the growing literature on connecting idealized aggregation studies to the manifestation of  
492 real-world convective organization (e.g. Tompkins, 2001; Shamekh et al., 2020a; Müller &  
493 Hohenegger, 2020; Hohenegger & Stevens, 2016, 2018; Becker & Wing, 2020; Bony et al.,  
494 2020; Arnold & Randall, 2015; Muller & Romps, 2018; Beucler et al., 2020). We have shown  
495 that, whilst the shape and scale of aggregation change when a continentally-sized island is  
496 included in an idealised RCE world, many of the features of aggregation remain the same,  
497 including its effects on the large-scale environment and the feedbacks driving the formation  
498 and maintenance of aggregation. We have highlighted the key role that gravity waves  
499 play in shaping atmospheric circulations in RCE experiments in the absence of essential  
500 aggregation feedbacks. It can be difficult to draw conclusions on how results shown in this  
501 and other similar papers might be manifested in the real-world, due to the experiment’s  
502 highly idealized configuration. To that end, there are many extensions to this paper that  
503 we feel will help to further elucidate the relationship between idealized aggregation and  
504 it’s real-world manifestations, including investigating the effects of the diurnal cycle, SST  
505 gradients and rotation on the results presented here.

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**The impact of a land-sea contrast on convective aggregation in radiative-convective equilibrium**

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**Contents of this file**

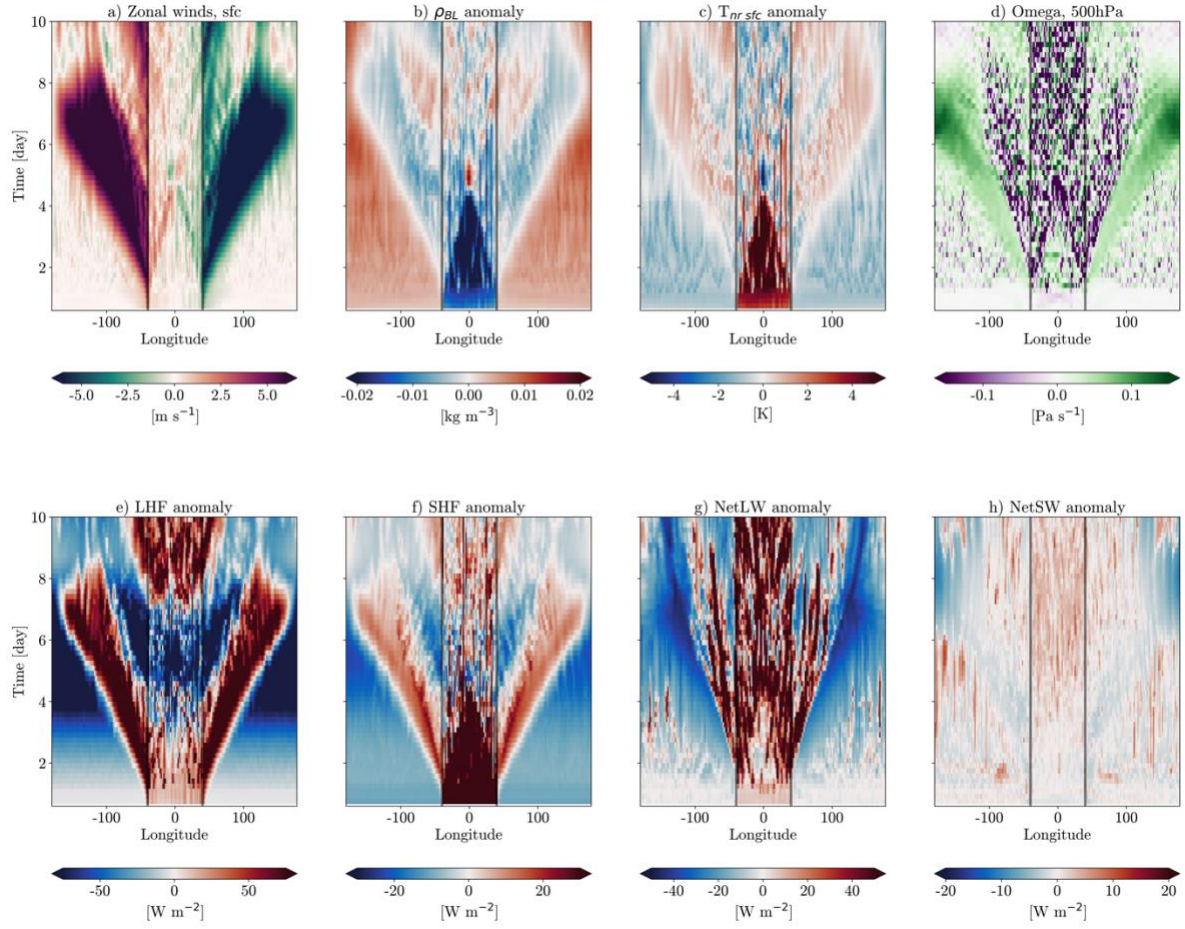
1. Captions for Movies S1 to S2
2. Figures S1 to S2

**Introduction**

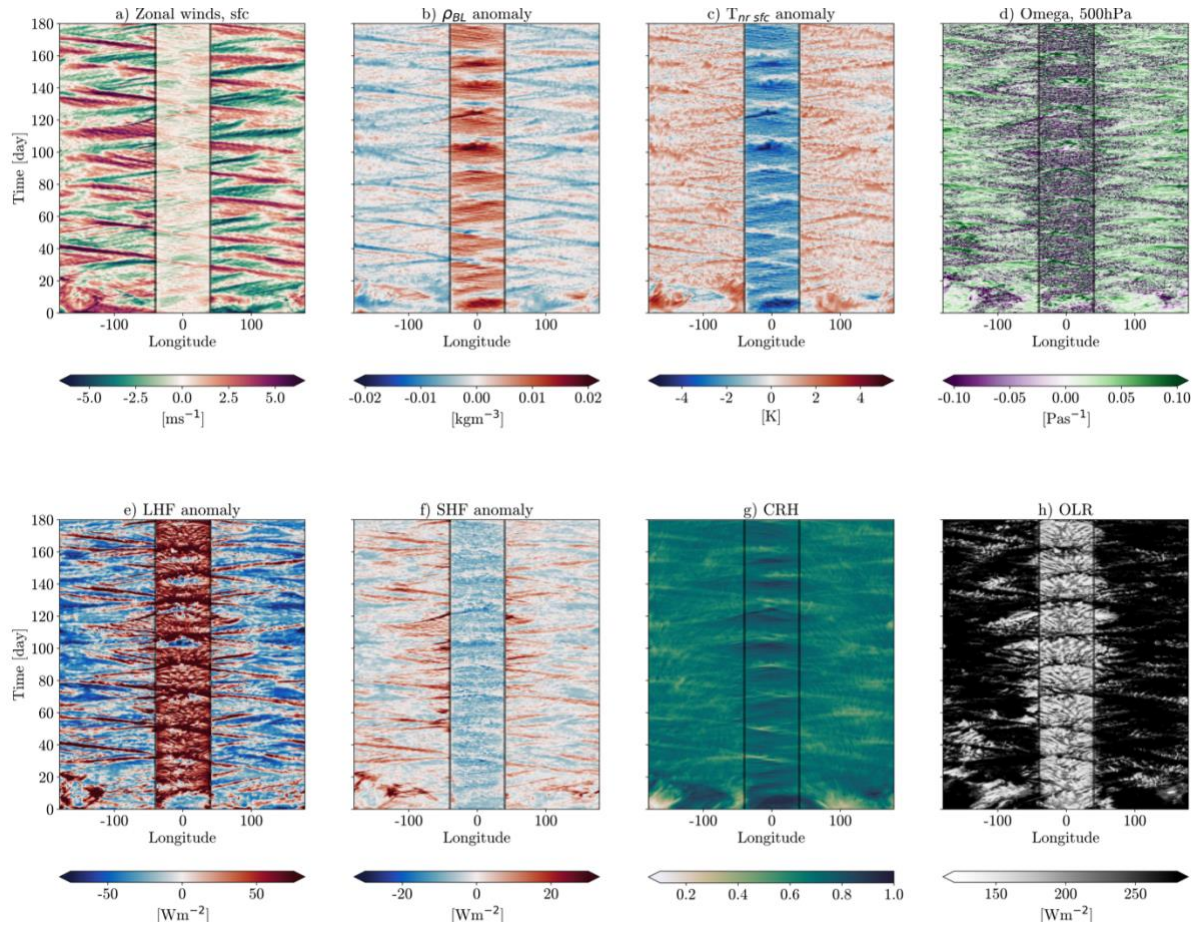
- This supporting information contains animations to show the aggregation of convection through the outgoing longwave radiation (OLR) and column relative humidity (CRH) for radiative convective equilibrium global simulations with an idealized, flat, circular island. These simulations have the same setup as described in Section 2.2 of the main manuscript, where S1 has interactive radiation and movie S2 has homogenized radiative heating rates. Also included are a 'zoomed in' version of Figure 3 for closer inspection of the initial 10 days of the simulation, and an alternative version of Figure 6 where the simulation was initialized from a previously aggregated simulation.

**Movie S1.** 180-day animation of the column relative humidity (CRH; top) and outgoing longwave radiation (OLR; bottom) in a global RCE simulation with an idealized, circular (40° radius), flat tropical rainforest island. Sea surface temperatures are fixed at 305K and there is no rotation or diurnal cycle. (File attached separately: nohomog\_olr\_crh.mp4)

**Movie S2.** 180-day animation of the column relative humidity (CRH; top) and outgoing longwave radiation (OLR; bottom) in a global RCE simulation with an idealized, circular (40° radius), flat tropical rainforest island. Sea surface temperatures are fixed at 305K and there is no rotation or diurnal cycle. Longwave heating rates have been horizontally homogenized at every model timestep. (File attached separately: homogLW\_olr\_crh.mp4)



**Figure S1: Hovmöller plots of a) Surface zonal winds, b) Density anomaly averaged over the boundary layer (lowest 1km) c) Near-surface temperature anomaly d) Omega at 500 hPa, e) Latent heat flux anomaly, f) Sensible heat flux anomaly, g) NetLW anomaly, h) NetSW anomaly, over the first 10 days of an RCE simulation with land, taken as a zonal slice through latitude=0°. The black lines show the coasts of the island.  $\text{NetLW} = \text{LW}_{\text{sfc}} - \text{LW}_{\text{toa}}$ ,  $\text{NetSW} = \text{SW}_{\text{toa}} - \text{SW}_{\text{sfc}}$ , where  $\text{LW}_{\text{sfc}}/\text{SW}_{\text{sfc}}$  are the net longwave/shortwave fluxes at the surface and  $\text{LW}_{\text{toa}}/\text{SW}_{\text{toa}}$  are the net longwave/shortwave fluxes at the top of atmosphere. Positive fluxes are defined upwards.**



**Figure S2: Hovmöller plots of a) Surface zonal winds, b) Density anomaly averaged over the boundary layer (lowest 1km) c) Near-surface temperature anomaly d) Omega at 500 hPa, e) Latent heat flux anomaly, f) Sensible heat flux anomaly, g) Column relative humidity, h) Outgoing longwave radiation, over the first 180 days of an RCE simulation with land where longwave fluxes are horizontally homogenized at each timestep, taken as a zonal slice through latitude=0\degree. The black lines show the coasts of the island. Simulation shown here was initialized with the equilibrium state of an aggregated RCE simulation with land.**