

Convective aggregation in idealised models: *Moving towards the real world*



Beth Dingley

Oriel College

University of Oxford

A thesis submitted for the degree of

Doctor of Philosophy

Hilary 2023

Acknowledgements

I feel extremely lucky to have met and worked with such wonderful people throughout my time at Oxford. Firstly, I would like to thank my supervisor Philip Stier for supporting and guiding me through my DPhil, and for allowing me the freedom to research the things which interested me the most. Also, thank you to Guy Dagan for answering any and all questions I sent his way, and in later years for always being on the end of a Zoom call when I needed anything, from science to sometimes just needing some reassurance. Thank you both for helping me craft this project and seeing me all the way through to thesis submission.

I would like to thank the Climate Processes group for the coffees, chats, and generally lovely working environment. I really enjoyed being a part of the group and I have learned a huge amount from all of you. Thanks also go to Cathy Hohenegger for the invaluable discussions on my second two science chapters, and for hosting me at Max Planck Institute for a week.

There are many others who have made this project possible. In particular The NERC Environmental Training Programme, who have provided both funding and training during my DPhil. I would also like to thank the UKRI Policy Internship programme for offering me the chance to spend time working with a select committee in Parliament. I had an incredible three months, and the experience hugely moulded my career aspirations.

I am incredibly lucky to have such an amazing support network around me, who have all helped to keep my head afloat when the DPhil felt impossible. To Nick, Fraser, and Stuart — thank you for the countless coffee breaks. They were, and will remain among my fondest memories of the PhD and I look forward to more adventures in the future. To Nicola, Caroline, Kieran, Rosie, Luke, Becca, and Théa — you've listened to my PhD woes and can always make me laugh. I have nothing to say except thank you for the best friendships.

Finally, to mum, dad, and the whole family who have given endless help and support — thank you for being there for me whenever I needed.

Abstract

Great advances in our understanding of the climate have been made through utilising a hierarchy of models. In idealised models of the tropical climate, deep convection can spontaneously cluster together, a phenomenon termed convective self-aggregation. This clustering impacts the moisture and energy budgets and thus significant work has been undertaken to gain a more complete understanding of self-aggregation and its impacts on the climate. In particular, self-aggregation and convective organisation in the real world present quite differently. Thus, a key open question is how self-aggregation manifests in the real atmosphere. This thesis probes this question by incrementally increasing the complexity of a general circulation model in a radiative-convective equilibrium configuration to investigate the impact of an aerosol plume, a land continent, and a meridional sea surface temperature (SST) gradient on self-aggregation.

The diabatic heating from the aerosol plume generates a large-scale, overturning circulation, which forces convection to aggregate. However, despite the aggregation being forced, self-generated feedbacks between clouds and longwave radiative fluxes are essential for amplifying the aggregation. Thus, I postulate that self-aggregation feedbacks could contribute to real-world convective organisation, even when aggregation is initially driven by external forcing. This hypothesis is reinforced when investigating the impacts of land. A land-sea thermal contrast triggers a circulation which forces convection to aggregate, but as before, self-aggregation feedbacks are necessary for this to be maintained. Finally, I develop a novel budget for the variance in transient integrated frozen moist static energy. This is used to show that self-aggregation feedbacks also drive zonal organisation over a meridional SST gradient. This thesis consistently highlights that self-aggregation feedbacks could be contributing to real-world convective organisation, whilst also showing that the inclusion of more realistic processes can fundamentally alter the geometry, spatial and temporal scales of self-aggregation.

Contents

Acknowledgements	iii
Abstract	v
1 Introduction and motivation	3
1.1 Clouds in the climate system	3
1.1.1 Deep convection	8
1.1.2 Climate models and their representation of clouds	10
1.1.3 The interactions between clouds and circulations	15
1.2 The organisation of deep convection	17
1.2.1 Convective self-aggregation	20
1.2.2 Idealised versus real-world convective organisation	39
1.3 Aerosols and the monsoon	47
1.4 Objectives of thesis	48
2 Forced convective aggregation	53
2.1 Introduction	54
2.2 Methods	58
2.2.1 Model set-up	58
2.2.2 Experimental set-up	59
2.2.3 Aerosol plume model	61
2.2.4 Metric	62
2.2.5 Frozen moist static energy budget	63
2.3 Unforced versus forced aggregation of convection	63
2.3.1 Assessment of hysteresis	68
2.3.2 Sensitivity to aerosol plume strength	69
2.4 Physical mechanisms behind forced aggregation	71
2.4.1 Frozen moist static energy budget	71
2.4.2 Mechanism denial tests	74

2.5	Conclusions and implications	80
3	Aggregation in the presence of an island	85
3.1	Introduction	87
3.2	Methods	91
3.2.1	Model set-up	91
3.2.2	Experimental set-up	92
3.2.3	Analysis methods	94
3.3	Results	94
3.3.1	Land-centred aggregation	94
3.3.2	Mechanism denial tests: Does convection aggregate over land in the absence of horizontal radiative flux anomalies?	107
3.3.3	Sensitivity to island size	112
3.4	Discussion and Conclusions	113
4	Convective self-aggregation over sea-surface temperature gradients	121
4.1	Introduction	123
4.2	Methods	124
4.2.1	Model description	124
4.2.2	Feedback decomposition	125
4.3	Physical mechanisms of zonal clustering	127
4.3.1	Similarities to self-aggregation	127
4.4	Discussion and Conclusions	140
5	Discussion and Conclusions	145
5.1	Summary of thesis	146
5.2	GCMs and parameterised convection	152
5.3	Avenues for future research	154
	List of Figures	160
	List of Tables	162
	Bibliography	165

1 | Introduction and motivation

Science is fun. Science is curiosity. We all have natural curiosity. Science is a process of investigating. It's posing questions and coming up with a method. It's delving in.

SALLY RIDE

1.1 Clouds in the climate system

Throughout history, clouds have inspired artists, writers, musicians, philosophers, and scientists due to their ubiquitous presence in our skies. The omnipresent effects weather has on people's lives has led to centuries of discussion on clouds and why they form, dating as far back as 3000 BC with the Upanishads philosophical writings on the formation of clouds and rain.

A cloud is defined as particles of liquid water or ice, suspended in the atmosphere (Dunlop 2008). They form when moist air parcels rise and cool, allowing the water to condense on an aerosol (Köhler 1936). An atmospheric aerosol is a microscopic solid or liquid particle suspended in the atmosphere (Wallace and Hobbs 1977), with radii ranging between 0.001 to 10 μm (Haywood and Boucher 2000). Direct generation of aerosols (primary aerosols) can be through natural or anthropogenic processes, with natural emissions contributing 89%

of all emissions (Satheesh and Moorthy 2005). Additionally, aerosols can be formed indirectly (secondary aerosols) often through atmospheric oxidation of precursor gases such as sulphur into sulphate aerosols. Aerosols are removed from the atmosphere, either through wet (e.g. precipitation) or dry removal (e.g. interaction with the Earth's surface) (Haywood and Boucher 2000). Within the troposphere, aerosols can live from minutes up to a couple of weeks (Kaufman et al. 2002).

A key mechanism in which aerosols impact the climate is through their direct interactions with radiation. All atmospheric aerosols scatter incoming solar radiation, while some also absorb. Aerosols which primarily scatter radiation have a cooling effect, such as sulphate, while strongly absorbing aerosols have a warming effect, such as black carbon. Forster et al. (2021) estimate the effective radiative forcing¹ from aerosol-radiation interactions be $-0.3 \pm 0.3 \text{ W m}^{-2}$.

Aerosols also interact with clouds, impacting cloud lifetime, albedo, and precipitation although quantifying the magnitude and even the sign of these effects is highly challenging (Forster et al. 2021). This thesis will not investigate aerosol-cloud interactions and so we do not expand further on these effects here.

Clouds are found over a range of altitudes, from sea-level to the bottom of the stratosphere, where different properties are associated with different cloud genera. For simplicity, the International Cloud Atlas splits the troposphere into three levels - high, medium, and low - due to the dependence of cloud properties on their height, and categorises the clouds into ten main genera. A summary of these genera is shown in Figure 1.1.

At any time, clouds cover on average more than two thirds of the Earth's surface (King et al. 2013; Stubenrauch et al. 2013), and can be found almost anywhere within the Earth's troposphere. In addition to defining clouds by their height, we can also define them based

¹Effective radiative forcing is defined as the change in net radiative flux at the top of atmosphere in response to a climate forcing

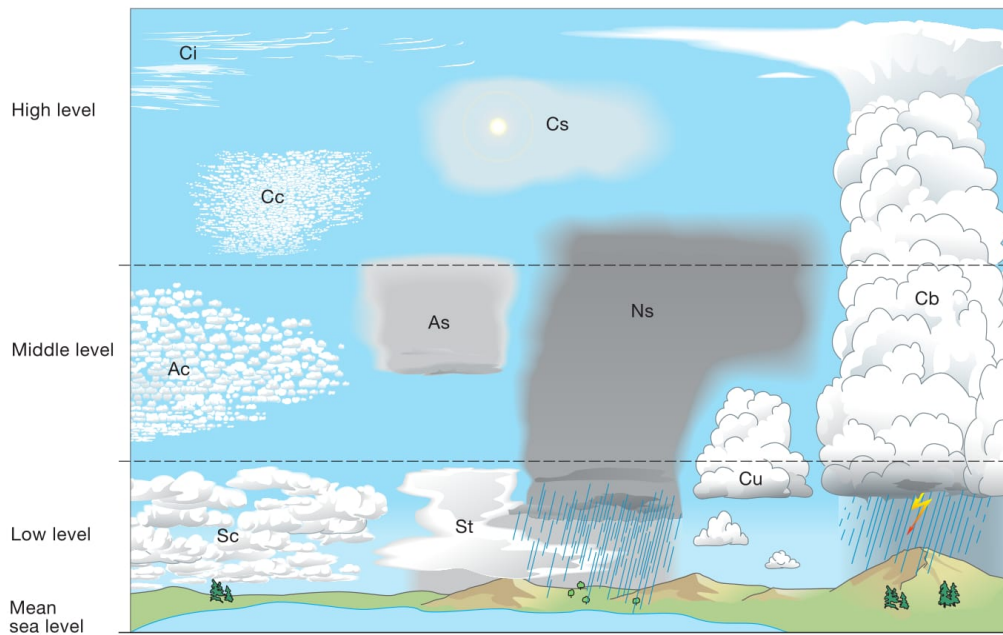


Figure 1.1. Cloud genera. Ci: cirrus, Cc: cirrocumulus, Cs: cirrostratus, Ac: altocumulus, As: altostratus, Ns: nimbostratus, Cb: cumulonimbus, Cu: cumulus, Sc: stratocumulus, St: stratus. Source: World Meteorological Organization

on their macrophysical properties. This was the approach taken by Lamarck (1802) and Howard (1803), who defined the categories *stratiform*, *cumulus*, and *cirrus*.

Stratiform clouds - such as *stratus*, *nimbostratus* and *stratocumulus* - are typically layered with a much greater horizontal extent than vertical, and have a lifetime of several hours (Lohmann et al. 2016). They form when the lower-troposphere is very stable. This often holds true over subtropical oceans, and so large *stratiform* cloud decks form extensively in these regions. In general, they are associated with only light precipitation such as drizzle (Wood 2014), although if thick enough (such as *nimbostratus*), heavier rainfall can occur. Together, *stratus* and *stratocumulus* clouds cover around 30% of Earth's surface.

Cirrus clouds are thin and wispy in appearance, and are purely composed of ice droplets

(Houze 2014). They can be formed through a number of different mechanisms, such as the spreading anvils of deep convective cloud outflows (Mace et al. 2006), or through water vapour deposition due to orographic or frontal lifting (Sassen et al. 2008). *Cirrus* clouds also have a larger horizontal extent than vertical, and this combined with their ice composition means they can appear almost transparent (Lohmann et al. 2016).

The Latin term *cumulus* means heap or pile, and when referring to clouds defines dense, tower-like structured clouds which typically extend higher vertically than they do horizontally (Houze 2014). *Cumulus* clouds are widely categorised as buoyancy-driven convection in unstable environments. Updrafts form when a rising air parcel remains warmer than the ambient air temperature. If the air is sufficiently moist, condensation and cloud droplet activation will occur, releasing latent heat and thus increasing the air parcel's buoyancy, hence allowing convection to develop (Lohmann et al. 2016). Shallow *cumulus* clouds typically have vertical and horizontal extents close to 1 km, have a lifetime on the order of 10 to 60 minutes and consist only of liquid water droplets (Isaac 1986; Cotton et al. 2010; Houze 2014). With greater instability, shallow *cumulus* clouds can develop into taller convective towers known as *cumulus congestus*. These can grow up to 6 km in height and have longer lifetimes of up to an hour, but are still mainly composed of liquid droplets (Lohmann et al. 2016). With sufficiently strong updrafts, ice crystals start to form and the additional latent heat released from the freezing of cloud droplets enhances vertical velocities and allows *cumulus congestus* clouds to develop into deep convective *cumulonimbus*. *Cumulonimbus* clouds typically extend to the top of the troposphere with anvil widths of tens of kilometres and are associated with heavy precipitation and stormy conditions (Houze 2014).

Categorising clouds into their respective categories helps us to understand the different effects they can have on our atmosphere. Clouds are a major part of the hydrological cycle, providing precipitation to the Earth's surface and transporting moisture through the atmosphere (Lohmann et al. 2016). Additionally, clouds also have a large impact on our radiation

budget. Clouds interact with both shortwave and longwave radiation and certain cloud characteristics lead to differences in these interactions. In general, clouds' high albedo means they reflect incoming solar radiation, reducing the amount of radiative reaching the surface which therefore has a cooling effect. Clouds can also absorb longwave radiation emitted from the Earth, and re-emit at a lower temperature to space, which has a warming effect. Typically, this greenhouse warming effect increases with height. High, thin clouds, such as *cirrus* have a minimal shortwave radiative effect, but a large longwave effect, while low *stratocumulus* decks impose a strong cooling, due to their strong shortwave radiative effect. Using both satellite and in-situ observations, Wild et al. (2015, 2019) estimated the warming associated with the global longwave cloud radiative effect at 28 W m^{-2} and the cooling associated with the shortwave effect at 47 W m^{-2} . Globally, this leads to an overall cooling cloud radiative effect on the order of 20 W m^{-2} .

The response of clouds to climate change is one of the largest uncertainties in our understanding of how the atmosphere will behave under anthropogenic forcings. Indeed, current estimates of the net cloud feedback² range from an overall cooling (negative) effect to an overall warming (positive) effect. The latest (6th) assessment report (AR6) from the Intergovernmental Panel on Climate Change (IPCC) estimates that the net cloud feedback is very likely to lie between $-0.10 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ to $0.94 \text{ W m}^{-2} \text{ }^{\circ}\text{C}^{-1}$ (Forster et al. 2021). Figure 1.2 details the current estimates for all climate feedbacks from IPCC AR6, as well as from the Coupled Model Intercomparison Project (CMIP) phases 5 and 6. This clearly shows that the uncertainty associated with cloud feedbacks dominates the total uncertainty in the net climate feedback (Forster et al. 2021). Thus, this highlights why improving our understanding of cloud processes are vital for understanding the impacts of anthropogenically forced climate change.

²Defined as the change in top-of-atmosphere radiative flux resulting from the cloud response to warming

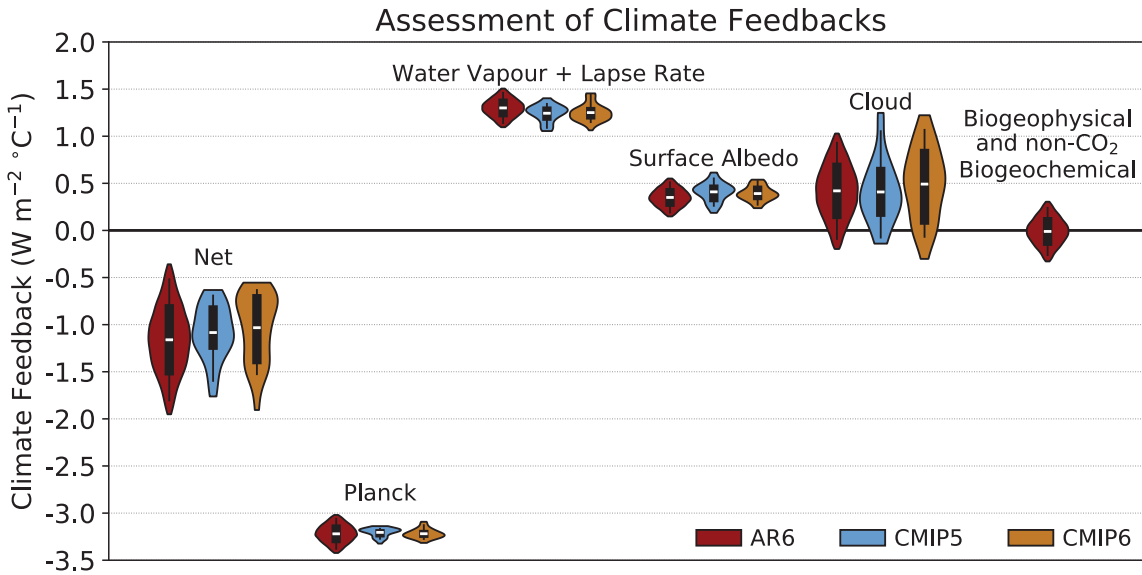


Figure 1.2. Climate feedbacks calculated in IPCC assessment report 6 (AR6), and Coupled Model Intercomparison Project (CMIP) phases 5 and 6. Source: IPCC AR6 (Forster et al. 2021)

1.1.1 Deep convection

As introduced above, convective clouds occur when atmospheric instability allows buoyant air parcels to rise and condense. The typical life cycle of an individual deep convective cell can be divided into three stages: early (*cumulus*) stage, mature stage, and dissipating stage (Byers and Braham 1948; Emanuel 1994). During the early stage, anomalously buoyant air parcels which form in an unstable atmosphere form vigorous updrafts. The temperature in the updraft is greater than the temperature in the surrounding environmental air due to the latent heat released from condensation and, if sufficiently vigorous, freezing. Towards the end of the *cumulus* stage, precipitation begins to form. The mature phase is characterised by more vigorous convective updrafts, raising the height at which freezing occurs through the upward advection of warm near-surface air, and downdrafts associated with the heavy precipitation. The most vigorous updrafts are in the middle of the cloud, which can slightly overshoot the tropopause. Outside of the most vigorous updrafts, the height to which the cloud can grow is capped by the temperature inversion at the tropopause, and so the new

air lifted by the updrafts drives a horizontal divergence of the existing cloud water. This divergence produces the characteristic anvil that spreads out from the top of the convective updrafts. During the mature phase, precipitation falls from the majority of the cloud and extends to the surface. Downdrafts of cooler, denser air brought down towards the surface, form under the cloud, driven by the re-evaporation of rain and the melting of falling snow/hail/graupel. Upon reaching the surface, this air pocket spreads horizontally, forming a cold pool, sometimes with a sharp leading edge which separates the cold, dense air from the environmental air. The leading edge of a cold pool is frequently referred to as a gust front, which is marked by strong local winds. As the cold pool spreads, it cuts off the supply of warm air to the convective cloud and moves the storm cloud into its third and final stage: the dissipation stage. Here, the now stable sub-cloud air prevents the formation of updrafts and so the dissipation stage is defined by the cloud only having downdrafts and no updrafts. The cloud continues to precipitate, although less intensely than before. The remaining low-level cloud water is either precipitated out, or evaporated due to mixing with the unsaturated environmental air. The icy anvil that formed due to the intense, mature stage updrafts remains as a *cirrus* cloud (Byers and Braham 1948; Emanuel 1994; Lohmann et al. 2016). This typical lifecycle of a deep convective cloud is depicted in Figure 1.3.

The lifetime of an isolated convective cell is typically between 30 minutes to an hour (Emanuel 1994). However, if there is sufficient wind shear, the gust front may initiate new convective cells at the edge of the cold pool as the cold dense air of the cold pool mechanically lifts the warmer ambient air towards the level of free convection, with this happening more readily with increasing wind shear. These new cells extend the lifetime of the storm and transform the original single-cell storm into a multicell or supercell thunderstorm, or eventually a mesoscale convective system (MCS). This happens as the wind shear horizontally displaces the updrafts and downdrafts. This ensures the precipitating region is separated, and therefore can no longer shut off the updraft (e.g. Weisman and Klemp 1982; Rotunno et al. 1988; Emanuel 1994). With more cells forming close to each other, the con-

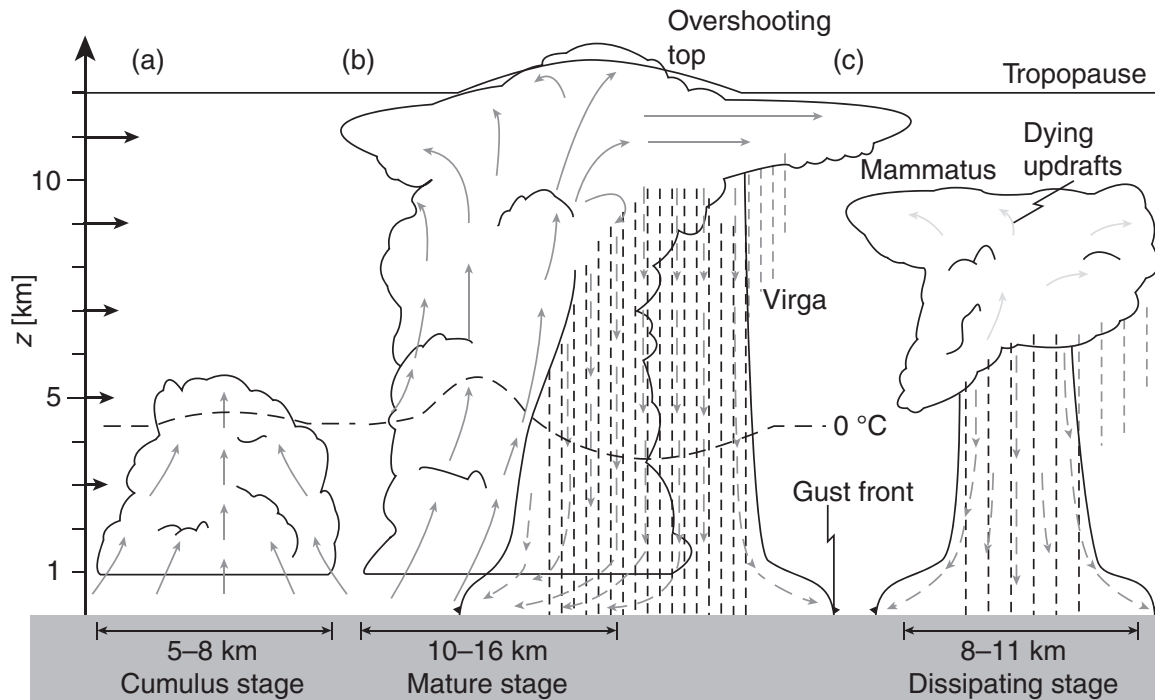


Figure 1.3. Cross section of the three stages in the life cycle of a deep convective cloud. a) early (*cumulus*) stage, b) mature phase, c) dissipating stage. Grey arrows dictate the direction of air flow and black arrows on the vertical axis represent the strength of the horizontal winds. Grey, dashed line show precipitation locations, thin solid lines surrounding these dashed lines represent the boundary of the precipitation-cooled air. Source: Lohmann et al. (2016), adapted from Doswell (1985)

vection can begin to appear organised in space. Organised deep convection is the main topic of this thesis and so will be introduced in more detail in Sections 1.2 and 1.2.1.

1.1.2 Climate models and their representation of clouds

Such is the complexity of the equations used to describe how properties of Earth's atmosphere evolve through time, numerical models are needed to solve them. These equations describe the physical laws which conserve energy and mass and describe how temperature, pressure and winds change over time.

Climate models numerically solve these equations on vertical and horizontal grids. Global climate studies typically make use of General Circulation Models (GCMs), which simulate a

dynamic atmosphere. GCMs will also sometimes model a dynamic ocean and/or cryosphere, however these can also be modelled through prescribed variables based on observations to save computational resources. GCMs are typically run on a grid with horizontal spacings of around 100 km. These scales are too large to resolve many processes, including clouds and convection, and therefore require estimations of how sub-grid scale processes might affect the grid-cell values. Schemes which do these estimations are called parameterisation schemes. GCMs are incredibly useful for understanding how the climate changes over long periods of time and predicting how the atmosphere might respond to different climate forcings, however there remain some issues with their abilities. For example, they can realistically simulate the magnitude of global-mean precipitation, but accurately predicting the different regional distributions of rainfall remains challenging (e.g. Grose et al. 2020; Harvey et al. 2020; Tian and Dong 2020).

Modelling with a higher horizontal resolution is possible, and allows us to resolve individual clouds and cloud processes, whilst sub-grid processes such as turbulence fluctuations are still parameterised. These models are typically referred to as either cloud resolving models (CRM) or large-eddy simulations (LES). CRMs are generally run with a resolution of around 1 km and are able to explicitly represent deep convective updrafts, whilst LES models are run between approximately 10 m and 100 m and can resolve large-scale turbulence. Whilst resolving these processes is an improvement on the estimations made in GCMs, this comes at a computational cost. Therefore, these models are typically unable to run on large domains for a long time (Guichard and Couvreux 2017). Recent strides in computational resource have allowed for increases in domain sizes. CRMs are now able to be run on global domains (Satoh et al. 2008; Skamarock et al. 2012; Stevens et al. 2019) and super-parameterisation techniques, where a CRM is embedded in each atmospheric column (Grabowski 2001; Randall et al. 2003; Khairoutdinov et al. 2005), are becoming more frequent in studies. However, whilst these types of simulations are now possible, their computational cost is still great and so the need for the 'simpler' GCM and CRM simulations remains.

In addition to changing the resolution and domain size of a simulation, it is possible to remove processes from a model to create a more idealised set-up. These idealised models are incredibly useful for enabling scientists to answer fundamental questions about how the atmosphere works. When discussing the need for a range of complexities in models, Held (2005) wrote:

*"On the one hand, we try to **simulate** by capturing as much of the dynamics as we can in comprehensive numerical models. On the other hand, we try to **understand** by simplifying and capturing the essence of a phenomenon in idealized models".*

He went on to identify the need for a climate model hierarchy in order to understand how the dynamics of the climate system change as complexities are added or removed. He concluded that this is especially important so that as a community we do not increase the gap between our understanding of atmospheric circulation and the increasing complexity of atmospheric models. However, Held was certainly not the first to postulate the need for such a hierarchy. Schneider and Dickinson (1974) and Hoskins (1984) were some of the first to advocate for a range of model complexities to provide a balance of model ability and understandability. A recent review of climate model hierarchies highlighted particular atmospheric phenomena which have made great strides in progress due to the use of different models (Maher et al. 2019). The large-scale tropical circulation and convective organisation were among the topics which have effectively made use of model hierarchies.

One of the simplest models used to understand convection in the absence of a prescribed or forced large-scale circulation is radiative-convective equilibrium. The basic principle of the model is very simple - any imbalances caused by radiative cooling are balanced by convective heating. To understand this more fully, we will begin with the concept of radiative equilibrium. For this, the only method of heat transfer in the atmosphere is radiation, and equilibrium is reached when energy is received and lost at the same rate through each layer

of the atmosphere. If such a model is integrated to equilibrium, the resulting temperature profile of the atmosphere is statistically unstable near the surface where the near-surface temperature is too warm, upper tropospheric temperatures are too cold and the lapse rate is also too big. To make the radiative equilibrium model more realistic, we can allow convective heating to redistribute energy vertically, thus leading us to the radiative-convective equilibrium (RCE) model.

RCE was first proposed by Manabe and Strickler (1964) and Manabe and Wetherald (1967) to describe the vertical temperature structure of the atmosphere, yet it has become increasingly used as a simple model of the tropical atmosphere (Held et al. 1993; Tompkins and Craig 1998; Robe and Emanuel 2001; Stephens et al. 2008; Khairoutdinov and Emanuel 2013; Wing et al. 2020). Its success at simulating the tropical atmosphere is due to the negligible Coriolis force in the tropics (Jakob et al. 2019) and enables us to focus on the basic drivers of convection such as humidity, radiation, convective-driven circulation and surface fluxes, without introducing complexities associated with the large-scale atmosphere. Typical RCE simulations are run on an aquaplanet without planetary rotation, interactive sea-surface temperatures (SSTs), or a diurnal cycle, and are simulated in a CRM. More recently, GCMs with parameterised convection have been run in RCE, and Popke et al. (2013) showed that RCE in a GCM provides a good analogue to the structure of the tropical circulation. Becker (2018) showed that large-scale RCE in a GCM could be used to understand how parameterised convection interacts with its environment across different scales.

Due to the plethora of interesting and useful scientific results found in RCE simulations, Wing et al. (2018) designed the RCE model intercomparison project (RCEMIP). In this project, over 30 models were run in both small and large domains over three different SSTs (295K, 300K, 305K). Both CRMs and GCMs were included in the project, and this allowed for a comparison of how the RCE state varies across models, and which of its features are robust to model choice. The main aims of the project were to understand the response of clouds and

the climate sensitivity to warming in RCE and to investigate the phenomenon of convective self-aggregation in RCE (see Section 1.2.1).

How is convection represented in a GCM?

One of the greatest challenges in climate system modelling is parameterising moist convection (e.g. Randall et al. 2003; Arakawa 2004; Bony et al. 2015). The main aim of a convective parameterisation scheme is to determine the tendencies of grid-box variables due to convection which act at a sub-grid scale. There are three main tasks that a convective parameterisation scheme needs to accomplish: determine the occurrence and location of convection onset (trigger condition), calculate the vertical distribution of heat, moisture and momentum changes (the cloud model), and determine the amount of energy conversion through water state changes (closure assumption). There are many different approaches to parameterising convection, but the most common are mass-flux schemes (De Rooy et al. 2013). These are dynamic schemes which calculate the transfer of mass in the updrafts and downdrafts between vertical levels. This requires a plume model to represent each convective plume within the grid-box. The most widely used method for this is a bulk mass-flux scheme, where an approximate 'bulk plume' is used to represent the sub-grid scale ensemble of plumes. A key variable which is responsible for modifying the mass flux is the rate of entrainment of environmental air. However, defining this entrainment rate can be a source of significant uncertainty in the modelling of convection, and has been identified as among the most sensitive model parameters in GCMs (Murphy et al. 2004; Klocke et al. 2011). A commonly used convection scheme, and the scheme used throughout this thesis, is the Tiedke scheme with Nordeng updates, which is a mass flux scheme which predicts either shallow, midlevel or deep convection using a bulk entraining-detraining plume as described above. Closure for shallow and midlevel convection is based on the boundary layer moisture convergence, whilst deep convection closure is based on the convective available

potential energy (CAPE) (Tiedtke 1989; Nordeng 1994).

In addition to parameterising convection, the microphysical processes occurring within clouds also must be approximated. These microphysics schemes describe a number of processes, including cloud water and ice droplet growth, evaporation, freezing, melting, and provide latent heating rates for the model's dynamics. Microphysical properties, such as the shape, distribution and size of droplets can also impact clouds' radiative properties. Modelling is further complicated by the sheer number of hydrometeors - liquid or ice water particles - found in the atmosphere, which has been estimated at 10^8 m^{-3} of cloudy air (Morrison et al. 2020), and the many different interactions between them.

There are two main types of microphysics schemes used in models: bin schemes and bulk schemes (Khain et al. 2000). Bulk schemes use analytic functions to prescribe a particle size distribution for different hydrometeors. Most early bulk schemes used only the mass mixing ratio to describe the distribution (one-moment microphysics), however in the 1970s two-moment microphysics schemes were created which also use the number concentration along with the mixing ratio to define the hydrometeors (Morrison et al. 2020). The small number of parameters in a bulk-scheme makes them more computationally efficient than bin schemes. In bin schemes, each type of hydrometeor is described using size distributions based on several tens of bins of particle mass. In contrast to bulk schemes, the shapes of the size distributions in a bin scheme are not decided in advance, but are instead calculated during model integration (Khain et al. 2000).

1.1.3 The interactions between clouds and circulations

For decades, it has been recognised that the large-scale circulation influences clouds. This is visible on any picture of Earth from space, such as in Figure 1.4, where we can see comma-shaped storm tracks in the mid-latitudes, and the band of deep convection in the tropics,

known as the Intertropical Convergence Zone (ITCZ). However, through time it has become more apparent that convection is not simply a passive tracer of our atmospheric circulations, but indeed the convection is intrinsically influencing and shaping the circulations. In 1958, Rhiel and Malkus used theory and observations to show that there is a net export of energy out of the ITCZ at high levels, and an associated low level moisture import providing an energy source to the ITCZ. Therefore, they inferred that there must be an upwards energy transfer within the ITCZ. They concluded that deep convection is the primary mechanism for this upward energy transport, a conclusion that holds true over 50 years later. The ITCZ is one aspect of a much larger circulation known as the Hadley circulation: the rising air in the ITCZ is forced to diverge poleward once it reaches the tropopause, transporting energy away from the tropics aloft. Due to the conservation of angular momentum, the now cool, dense air begins to subside in the subtropics (Held and Hou 1980) before returning towards the tropics at the surface, advecting moisture along the way.

This highlights just one of the roles convection plays in influencing the large-scale atmospheric circulation. The moisture that convection transports is another key role for deep convection, this time within the atmospheric water cycle. The precipitation associated with convection, particularly in the tropics, brings freshwater - the most essential resource for human life on the planet (Mekonnen and Hoekstra 2016; Djehdian et al. 2019). It provides water for drinking as well as for agriculture and industry. The ITCZ alone provides 32% of global precipitation (Kang et al. 2018). However, too much or too little precipitation can cause disaster through flooding or droughts, and so changes in clouds and their associated precipitation could be catastrophic for much of the world's population. The IPCC AR6 stated with very high confidence that climate change will drive an increase in extreme precipitation events, but also that the severity of droughts will increase (Douville et al. 2021). It is not just the frequency and severity of precipitation extremes that will have a large impact. The position of the ITCZ and how it will change with future warming is not well understood (Douville et al. 2021), and there remain considerable inconsistencies in the regional



Figure 1.4. A series of snapshots stitched together from NASA Worldview (<https://worldview.earth-data.nasa.gov/>) on 26/11/2022 showing Visible Infrared Imaging Radiometer Suite (VIIRS) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery of Earth.

response of precipitation across climate models (Kent et al. 2015; Oueslati et al. 2016). As such, there is a need for improving our understanding of how convection and circulations interact. Indeed, the importance of this was highlighted recently as a grand challenge of climate science (Bony et al. 2015), with the authors stating that

"Fundamental puzzles of climate science remain unsolved because of our limited understanding of how clouds, circulation and climate interact."

1.2 The organisation of deep convection

In Section 1.1 we discussed the ways a deep convective cloud develops. Sometimes these clouds will grow, precipitate, then evaporate away, spending the clouds' lifetime as a single convective tower. However, the most severe storms happen when these clouds develop

into multicell, organised systems. Organised storms like this are referred to as mesoscale-convective systems (MCS) and are on the order of at least 100 km in horizontal scale (Houze 2014). They are incredibly important for the climate system, as they provide a significant proportion of the global mean precipitation amount and tropical cloudiness (Houze 2014; Tan et al. 2015). MCSs can occur year-round in the tropics, or in the mid-latitudes during the warmer months.

There are a variety of forms that MCSs can take with different shapes and spatial scales, depending on the environmental conditions in which they form. Squall lines, tropical cyclones, and mesoscale convective complexes (MCCs) are all examples of MCSs. Even on the planetary scale, the Madden-Julian Oscillation, an eastward propagating planetary envelope of convection, is organised with intense convection and precipitation in its *active* phase, and a suppression of convection to both the east and west (*inactive* or *suppressed* phase) (Madden and Julian 1971, 1972). All of these systems have a large, contiguous precipitation area of at least 100 km, although the shape of this will vary between systems. Squall lines typically form a long, narrow band of precipitation, whilst the MCCs tend to be more circular. MCSs persist for much longer than an isolated deep convective cloud and can precipitate for a number of days (Houze 2014). The precipitating region distinctly splits into an intensely convecting region with stronger precipitation, and a stratiform region with lighter, more uniform precipitation (Houze 1977; McAnelly and Cotton 1989; Houze et al. 1990).

MCCs are typically defined by their large ($>10^5$ km²), long-lasting (>6 hours), cold contiguous cloud shield (Maddox 1980; Laing and Fritsch 1997) and are associated with severe weather and significant rainfall (Maddox 1980; Fritsch et al. 1986; McAnelly and Cotton 1989). Laing and Fritsch (1997) compiled a global database of MCCs in order to identify common characteristics of the large-scale cloud clusters. They found that the majority of the MCCs occur over land and at night, however oceanic systems tend to be larger and longer lived. Typically, the most active areas for MCCs are those with warm oceanic tem-

peratures, orographic lifting, and low-level convergence (Velasco and Fritsch 1987). Whilst these studies focused on globally distributed MCCs, Machado and Rossow (1993) studied more specifically tropical cloud clusters to examine their features and cloud properties. Machado and Rossow also found a preference for tropical cloud clusters to form over land and used a radiative transfer model to determine that clusters cause a local decrease in radiative cooling due to their associated large, cold anvil. There is now also observational evidence that the climate state depends on the degree of clustering (Tobin et al. 2013). Tobin et al. (2012) used different metrics of organisation to conclude that a more organised scene leads to reduced area-averaged humidity, higher surface fluxes, less outgoing long-wave radiation, and more reflected shortwave radiation. Tropical cloud clusters are also recognised as precursors to tropical cyclones in the right conditions with 6.4% of clusters developing into tropical cyclones per year (Hennon et al. 2013).

Over the past three decades it has been observed that the frequency of organised convection is increasing (Tselioudis et al. 2010; Tan et al. 2015; Wodzicki and Rapp 2022). With climate change driving changes in precipitation, studies have generally found that this follows a 'wetter gets wetter' and 'drier gets drier' pattern (e.g. Held and Soden 2006; Chou et al. 2009; Allan et al. 2010; Chou et al. 2013; Huang et al. 2013; Liu and Allan 2013). Tan et al. (2015) investigated these precipitation changes with respect to organisation and found that increases in organised convection frequency is driving the increase in tropical precipitation. However, understanding the effect of climate change on different types and features of organised convection is difficult. Under climate change it is thought that tropical cyclones are likely to increase in intensity and precipitation rate, but there is currently no agreement on whether their frequency will decrease as many models predict (e.g. Sugi et al. 2002; Oouchi et al. 2006; Sugi et al. 2009; Knutson et al. 2010; Murakami et al. 2012; Emanuel 2013; Murakami 2014; Yoshida et al. 2017; Knutson et al. 2020). The MJO is also expected to change with climate change. Models have predicted that MJO activity should increase in a warming climate (e.g. Caballero and Huber 2010; Arnold and Randall 2015),

which seems to be consistent with observations that the number of MJO events has linearly increased over the past 50 years (Jones and Carvalho 2006). Ultimately, more work is required to increase our understanding of how different forms of organised convection interact with climate change.

1.2.1 Convective self-aggregation

An interesting phenomenon, first discovered when running two-dimensional CRMs in RCE, is the tendency for convection to spontaneously cluster together: this is known as convective self-aggregation (Held et al. 1993). This clustering occurs in these numerical simulations in the absence of any inhomogeneities in the boundary conditions and forcings, and therefore has sparked much interest within the convective organisation field in the last two decades. Self-aggregation has since been simulated in a wide range of models in an RCE configuration, from limited-area two- and three-dimensional CRMs (e.g. Grabowski and Moncrieff 2001; Tompkins 2001a,b; Bretherton et al. 2005; Khairoutdinov and Emanuel 2010; Muller and Held 2012; Wing and Emanuel 2012; Abbot 2014; Emanuel et al. 2014; Wing and Emanuel 2014; Muller and Bony 2015; Hohenegger and Stevens 2016; Holloway and Woolnough 2016; Wing and Cronin 2016; Becker et al. 2017; Tompkins and Semie 2017; Hohenegger and Stevens 2018; Yang 2018a; Wing et al. 2020), to GCMs with parameterised convection (e.g. Su et al. 2000; Held et al. 2007; Popke et al. 2013; Becker and Stevens 2014; Coppin and Bony 2015; Reed et al. 2015; Bony et al. 2016; Pendergrass et al. 2016; Coppin and Bony 2017; Arnold and Putman 2018; Becker 2018; Wing et al. 2020), and global CRMs with either super-parameterised or explicit convection (e.g. Satoh and Matsuda 2009; Arnold and Randall 2015; Wing et al. 2020). Examples of self-aggregation in CRMs and GCMs are shown in Figures 1.5 and 1.6. Unlike many of the types of convective organisation introduced thus far, self-aggregation is not forced by any external mechanism such as wind shear or SST gradients and recently, Bony et al. (2015) identified that under-

standing the role aggregation plays in climate is one of the four key themes within the cloud-circulation grand challenge.

In addition to its geometrical features, self-aggregation also has impacts on the large-scale climate state of the model's domain. With increasing aggregation, the domain partitions into intensely convecting moist patches, surrounded by extremely dry areas (Bretherton et al. 2005). Typically, the dry areas expand to cover over 50% of the domain (e.g. Coppin and Bony 2015; Bony et al. 2016; Becker et al. 2017), leading to an overall drying of the domain-mean humidity and a broadening of the moisture distribution, increasing the horizontal variance of column-integrated humidity. The drying occurs throughout the atmospheric column, but peaks in the mid-troposphere (Bretherton et al. 2005; Wing et al. 2016). The increase in spatial coverage of dry regions, and these dry regions' enhanced dryness also makes the domain more efficient at radiating longwave radiation (Muller and Held 2012; Tobin et al. 2012, 2013; Wing and Emanuel 2014; Wing and Cronin 2016; Stein et al. 2017; Wing et al. 2020), and drives an increase in surface enthalpy fluxes. Additionally, when convection is self-aggregated, a smaller fraction of the domain is convecting, leading to a reduction in high cloud fraction (e.g. Wing and Cronin 2016; Cronin and Wing 2017; Bony et al. 2020; Wing et al. 2020; Zhang et al. 2021).

Self-aggregation is also associated with a domain-mean warming of several degrees, estimated to be between 1-7 K by the RCEMIP ensemble (Wing et al. 2020). This is due to the locally moister environment in which air parcels are convecting in. The locally warmer, moister boundary layer pushes the air parcels' ascent onto a warmer moist adiabat (Wing 2019). Additionally, the locally moister free troposphere reduces the influence of entrainment, again driving the convection towards the moist adiabat (Tompkins 2001c; Singh and O'Gorman 2013; Wing and Cronin 2016; Tompkins and Semie 2017). In tropical atmospheres, gravity waves rapidly propagate due to the low Coriolis force and thus large Rossby deformation radii. Therefore, we can assume that horizontal anomalies in temper-

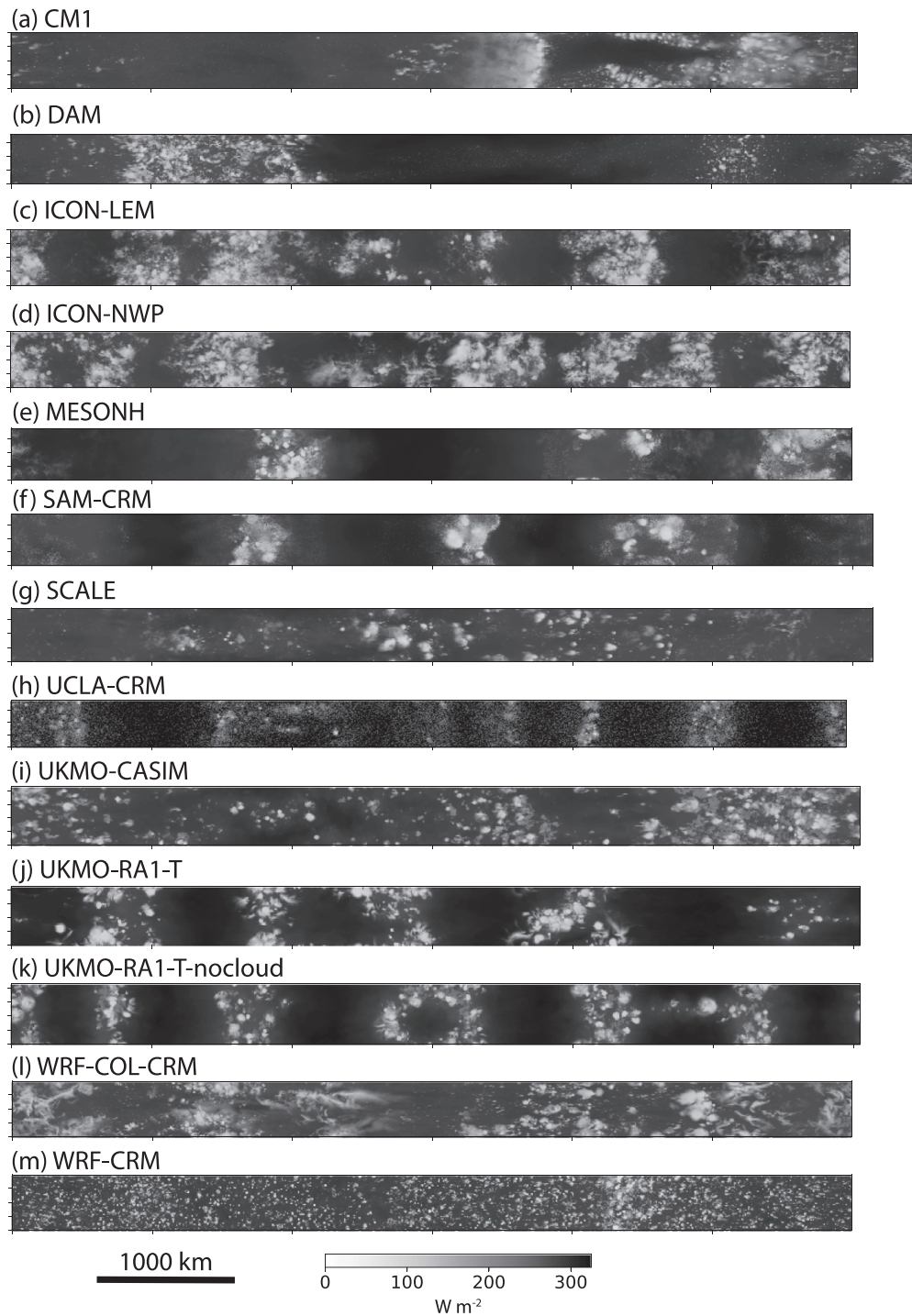


Figure 1.5. Self-aggregation in different cloud-resolving models (CRMs): hourly averaged outgoing longwave radiation (W m^{-2}) at Day 80 of the long-channel CRM simulations participating in RCEMIP. Each panel displays a different model and the size of each panel represents the domain size, which varies slightly across models. Simulations were performed for a 300K sea-surface temperature. From Wing et al. (2020), Figure 4.

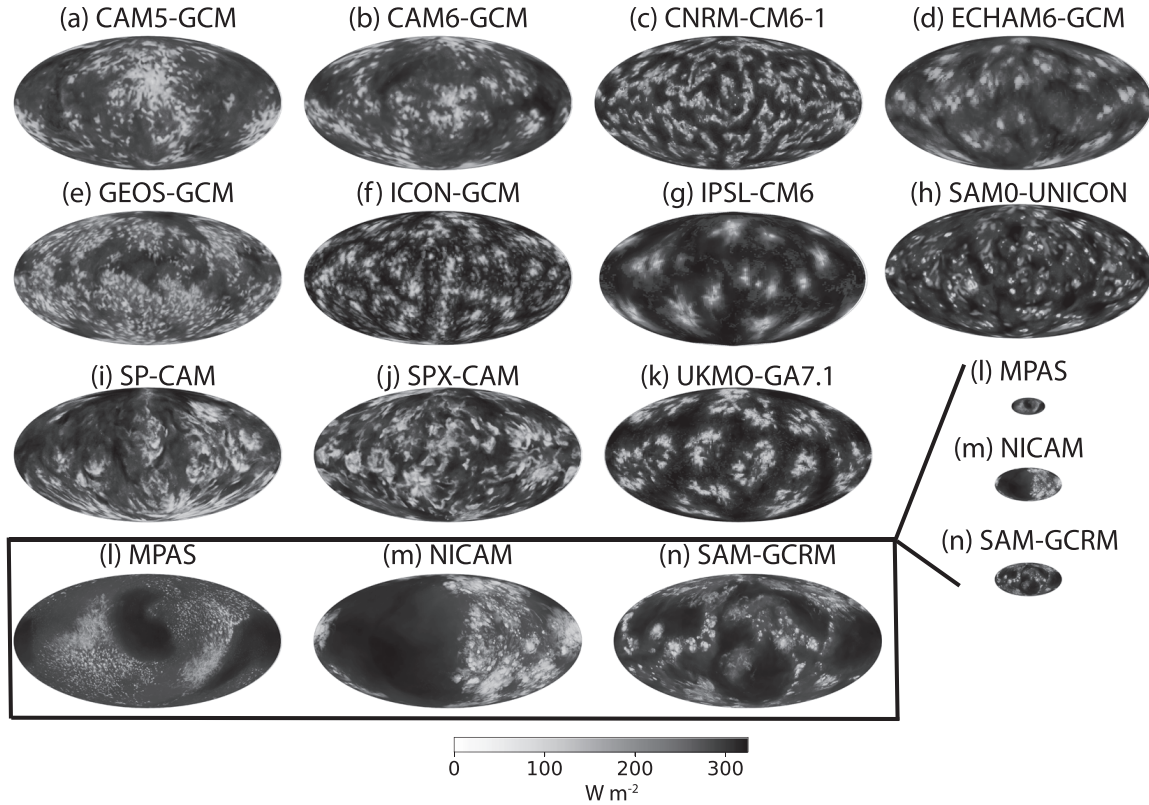


Figure 1.6. Self-aggregation in different general circulation models (GCMs): hourly averaged outgoing longwave radiation (W m^{-2}) at Day 80 of the GCM simulations participating in RCEMIP. Each panel displays a different model. Panels a)-k) show GCMs with parameterised convection, panels l)-n) are global cloud-resolving models that employ reduced Earth radius (r_E) of $r_E/8$, $r_E/4$, and $r_E/4$, respectively, and are shown to scale and, in the box, zoomed in. Simulations were performed for a 300K sea-surface temperature. From Wing et al. (2020), Figure 6

ature and density are approximately zero (Sobel and Bretherton 2000; Sobel et al. 2001). This is known as weak temperature gradient (WTG) approximation. Thus the locally warmer temperature profile in the convecting region is propagated across the domain, raising the domain-mean temperature. The combination of these large-scale effects show that self-aggregation can have large impacts on the energy budget, especially due to the changes in cloud and moisture distributions (e.g. Khairoutdinov and Emanuel 2010; Cronin and Wing 2017; Becker and Wing 2020; Muller et al. 2022).

Additionally, self-aggregation drives changes in the hydrological cycle. Precipitation is on average approximately 0.75 mm day^{-1} greater in aggregated simulations, which is energet-

ically consistent with increased atmospheric radiative cooling and increased surface fluxes (Wing et al. 2020). Perhaps more interestingly, aggregation has also been shown to impact the intensity of extreme precipitation events (Pendergrass 2020). Studies in RCE have shown that when organisation increases with warming, so do extreme rain rates (Pendergrass et al. 2016; Bao et al. 2017), although this can depend on the model used and the simulation design (Fildier et al. 2017; Pendergrass 2020). This increase in precipitation extremes occurs due to the persistence of convection, both temporally and spatially, when aggregated (Colin et al. 2019; Masunaga and Mapes 2020), which allows for large amounts of rain accumulation even if instantaneous rain rates remain the same (Bao and Sherwood 2019).

Many of the early self-aggregation studies used non-rotating, square domains with size lengths on the order of 100s of kilometers. In such studies, convection tends to aggregate together into one large cluster, covering ~20-25% of the domain (e.g. Bretherton et al. 2005; Muller and Held 2012; Wing and Emanuel 2014; Muller et al. 2022). Grabowski and Moncrieff (2001) also found that convection could aggregate into multiple clusters of different scales when a much larger (20,000 km side length) domain was used. Since these studies, aggregation has been simulated in a range of domain sizes, leading to many different numbers and scales of clusters being found. This is best exemplified in the results from RCEMIP. Figures 1.5 and 1.6 show how convection spatially organises itself in 34 different models and configurations. There is currently no agreed theory for what sets the spatial scale of aggregation (λ), although there is an increasing body of work investigating this. Wing and Cronin (2016) theorised that λ is determined by boundary layer height, surface moisture exchange and surface warming. However, Yang (2018b) found that λ varies non-monotonically with surface temperature and instead suggested that λ is determined by boundary layer height and boundary layer buoyancy variations and found that the horizontal buoyancy differences were driven by the virtual temperature effect³. Whilst these two theories differ, they do agree on the importance of density and moisture variations in the

³The effect of humid air being lighter than dry air under the same temperature and pressure conditions, which allows cold, humid air to rise

boundary layer in determining convective aggregation's spatial scale. Additionally, Beucler and Cronin (2019) recently developed a budget for the size of self-aggregation, relating the evolution of λ to the physical mechanisms driving the aggregation process. Similarly to the spatial scale, what sets the time scale of aggregation also remains an open question. In studies with constant SSTs and incoming solar radiation, it typically takes $\mathcal{O}(10 \text{ days})$ for self-aggregation to emerge (Muller et al. 2022), but the factors driving this time scale are less well known, as is how this time scale varies under different modelling scenarios.

As previously alluded to, the properties of self-aggregation are highly dependant on the model and simulation design used. Some of the largest contributors to self-aggregation variability are model resolution, domain-size, sub-grid scale process schemes, and SST. Bretherton et al. (2005) identified that self-aggregation seemed to display a domain size dependency; in their study a 384 km domain was necessary for aggregation to occur. Following this, Khairoutdinov and Emanuel (2010) also found that a sufficiently large domain was required for convection to aggregate. Muller and Held (2012) undertook a detailed investigation of this domain size dependency. They found that aggregation only occurs on large domains, with a side length of at least 200 km. Other studies have also found that the spatial scale of aggregation can be dependent on domain size (Su et al. 2000; Arnold and Randall 2015; Arnold and Putman 2018; Patrizio and Randall 2019). This dependency has been attributed to models' representation of low clouds and cold pools (Jeevanjee and Romps 2013; Muller and Bony 2015; Silvers et al. 2016). In addition to this domain size dependency, self-aggregation also displays a model resolution dependency. Muller and Held (2012) found that aggregation only occurs with horizontal model resolutions of 2 km or more, hence aggregation seems to favour coarser resolutions. However, they also found that if a simulation was started from aggregated initial conditions, aggregation could be maintained regardless of resolution, provided the domain was large enough. In their study, Muller and Held (2012) attribute the sensitivity of aggregation to resolution and domain size to the sensitivity of the distribution of low clouds to these two parameters. Tomp-

kins and Semie (2017) found that the model resolution dependency is likely due to how the resolution impacts the sub-grid scale representation of water vapour horizontal mixing. Additionally, Arnold and Randall (2015) showed that aggregation is sensitive to the entrainment rate, typically set within the convective parameterisation scheme. The authors found that aggregation increased with increased entrainment, a result which was also found by Becker et al. (2017), with the latter study highlighting that this could help to explain the temperature dependencies some self-aggregation feedbacks have.

Early studies of self-aggregation postulated that the degree of aggregation appeared to show a surface temperature dependence (Held et al. 1993; Khairoutdinov and Emanuel 2010; Emanuel et al. 2014; Wing and Emanuel 2014). In particular, Khairoutdinov and Emanuel (2010) showed that aggregation only occurred above a threshold SST. However, subsequent studies have disproved this, with models showing aggregated convection at a range of surface temperatures (Coppin and Bony 2015; Bony et al. 2016; Holloway and Woolnough 2016; Wing and Cronin 2016; Coppin and Bony 2017; Cronin and Wing 2017; Wing et al. 2020), with Abbot (2014) even finding aggregation in a snowball Earth⁴ simulation. Understanding the temperature dependence of self-aggregation is one of the key themes in RCEMIP. In the initial summary paper from the project, Wing et al. (2020) found that self-aggregation displayed no consistent response to an increase in surface temperature, with approximately half of the included models showing a net increase in aggregation with warming and the other half showing a net decrease. Although, Becker and Wing (2020) did note that GCMs almost always shown an increase in aggregation with warming in the RCEMIP ensemble.

⁴a hypothesis where the Earth was historically covered in kilometre thick ice

1.2.1.1 Metrics of aggregation

A key difficulty in aggregation studies is using a metric to quantify the degree of aggregation. There are three key types of metrics: humidity indices, spatial metrics and the subsidence fraction. They each represent different features of self-aggregation (Wing 2019).

Humidity based indices use the property that self-aggregation broadens the moisture distribution within the domain. A commonly used example of this metric group is the variance of column relative humidity (CRH; σ_{CRH}^2): as convection aggregates, the moist regions get wetter, and the dry regions dry leading to an increase in σ_{CRH}^2 (Wing and Cronin 2016). The advantage of this metric is that it is defined on one of the key properties under which aggregation can impact the climate. The broadening of the moisture distribution is what drives changes in the atmospheric radiative cooling, and so comparing σ_{CRH}^2 for different simulations is a good way to distinguish potential energy budget changes. However, a drawback of using this humidity based index and similar others, is the lack of a defined threshold above which convection can be defined as aggregated. Instead, it is better used to compare between different simulations and make conclusions based on their relative degree of aggregation. Other examples of humidity-based indices are the variance of column integrated frozen moist static energy and the interquartile range of column relative humidity.

The second type of index are geometrical indices, of which the most prominent is the organisation index (I_{org}) (Tompkins and Semie 2017). This metric compares the spatial organisation of convection to a random distribution. Therefore, this metric has the advantage of providing a theoretical definition and threshold above which convection can be defined as aggregated. In RCEMIP, different metrics were calculated for all the model simulations. In doing this, Wing et al. (2020) noted that I_{org} could be sensitive to nuances in calculation parameters, particularly in GCM simulations. They suggest that I_{org} may not be the best metric to use when investigating GCM output, and that the typically used aggrega-

tion threshold of $I_{\text{org}} = 0.5$ may be unsuitable in these models. Other geometrical indices have also been proposed. The Simple Convective Aggregation Index (SCAI) was proposed by Tobin et al. (2012) which measures clustering using a combination of cluster number and inter-cluster distance. However, SCAI does not take into account cluster size. Therefore, White et al. (2018) developed the Convective Organisation Potential (COP) which takes into account the distance between clusters and cluster radii to calculate the interaction potential of convective systems.

The final type of metric is the subsidence fraction (f_{sub} ; Coppin and Bony 2015). As introduced above, when convection aggregates, the convecting area covers approximately 20-25% of the domain, with the remaining area of the domain covered by large-scale subsidence. The subsidence fraction metric uses this result to define that if $f_{\text{sub}} > 0.5$, the simulation can be considered aggregated.

In their comprehensive RCEMIP summary, Wing et al. (2020) compared σ_{CRH}^2 , I_{org} , and f_{sub} for each participating model. They showed that the metrics were often inconsistent with one another, both in determining which models had the highest degree of aggregation, and especially in determining a model's self-aggregation response to surface warming: 53% of models had disagreement in the sign of the change in degree of aggregation as the SST was increased. The need for improved metrics has been repeatedly suggested (Wing 2019; Jin et al. 2022; Muller et al. 2022).

1.2.1.2 The mechanisms of aggregation

In addition to understanding the ways in which self-aggregation impacts the large-scale climate state of a simulation, a significant amount of research has gone towards understanding the physical mechanisms behind self-aggregation. Studies have identified multiple processes involving interactions and feedbacks between radiation, surface fluxes, mois-

ture and convection which are able to encourage convection to form in the close vicinity of existing convection.

One popular diagnostic framework for diagnosing these feedbacks is the frozen moist static energy (FMSE) variance budget, first employed for self-aggregation by Wing and Emanuel (2014). This framework exploits the fact that FMSE is conserved under moist adiabatic processes, including during phase changes in water. We start by defining the FMSE:

$$h = gz + C_p T + L_v q_v - L_f q_{ice} \quad (1.1)$$

where gz is the geopotential, C_p is the specific heat capacity of dry air, T is the temperature, L_v is the latent heat of vaporisation, q_v is the water vapour mixing ratio, L_f is the latent heat of fusion, and q_{ice} is the ice mixing ratio. The density-weighted integral of h is also defined as:

$$\hat{h} = \int_0^{z_{trop}} h \rho dz \quad (1.2)$$

where ρ is the air density and z_{trop} is the height of the troposphere. FMSE is useful in convective aggregation studies as it remains constant under mass-weighted integrals, but can be redistributed by convection. Due to WTG in tropical atmospheres (Sobel et al. 2001), it is assumed that increases in $\hat{h}$ are dominated by changes in humidity. Therefore, as aggregation increases and broadens the domain's moisture distribution, there is also an increase in the variance of FMSE ($\sigma_{\hat{h}}^2$) making this a useful diagnostic of aggregation. Additionally, the mass-weighted integral of FMSE can only be changed by radiation, surface fluxes, and advection. Therefore, following Wing and Emanuel (2014), it is useful to begin by examining the budget equation for $\hat{h}$:

$$\frac{\partial \hat{h}}{\partial t} = \text{NetSW} + \text{NetLW} + \text{SEF} - \text{Adv.} \quad (1.3)$$

Here, a variable $\hat{[]}$ indicates a density-weighted vertical integral. NetLW and NetSW are the column convergences of longwave and shortwave radiative fluxes respectively. They are defined as:

$$\text{NetLW} = \text{LW}_{\text{sfc}} - \text{LW}_{\text{toa}} \quad (1.4)$$

$$\text{NetSW} = \text{SW}_{\text{toa}} - \text{SW}_{\text{sfc}}, \quad (1.5)$$

where $[\cdot]_{\text{sfc}}$ and $[\cdot]_{\text{toa}}$ are the net fluxes at the surface and top-of-atmosphere respectively. Longwave fluxes are defined to be positive upwards and shortwave fluxes are positive downwards. The surface enthalpy flux (SEF) is defined as the sum of the latent heat flux (LHF) and sensible heat flux (SHF), which are both defined by the standard bulk formulae:

$$\text{LHF} = \rho c_E L_v U (q_{T_s}^* - q_v) = \rho c_E L_v U \Delta q \quad (1.6)$$

$$\text{SHF} = \rho c_H c_p U (T_s - T_a) = \rho c_H c_p U \Delta T \quad (1.7)$$

$$\text{SEF} = \text{LHF} + \text{SHF} \quad (1.8)$$

Adv is the horizontal convergence of the density-weighted vertical integral of the flux of FMSE (equivalent to $-\nabla_h \cdot \hat{\mathbf{u}}\hat{h}$). For equations 1.6 and 1.7 ρ is the air density at lowest model level, c_E is the latent heat exchange coefficient, U is the surface wind speed, $q_{T_s}^*$ is the saturation water vapour mixing ratio at the surface temperature, q_v is the water vapour mixing ratio at lowest model level, c_H is the sensible heat mixing coefficient, T_s is the surface temperature, and T_a is the air temperature at lowest model level. To derive the budget for the spatial variance in vertically integrated FMSE, we simply subtract the horizontal mean of equation 1.3 from its full form. This gives us

$$\frac{1}{2} \frac{\partial \hat{h}'^2}{\partial t} = \hat{h}' \text{SEF}' + \hat{h}' \text{NetLW}' + \hat{h}' \text{NetSW}' - \hat{h}' \nabla_h \cdot \hat{\mathbf{u}}\hat{h} \quad (1.9)$$

In Eq 1.9, primes denote the anomaly from the horizontal mean. The first three terms on the right-hand side of equation 1.9 are the correlations of anomalies in the integrated FMSE, $\hat{h}'$ with the anomalies of the diabatic sources and sinks of FMSE. We refer to $\hat{h}' \nabla_h \cdot \mathbf{u} \hat{h}$ as the advective term. As magnitudes of $\hat{h}'^2$ vary considerably through time, equation 1.9 is often normalised by the domain-mean of σ_h^2 to give growth rate units of day^{-1} (Wing and Cronin 2016).

As aforementioned, increases in self-aggregation are associated with increases in σ_h^2 , thus processes which act to increase σ_h^2 favour aggregation. Therefore, from equation 1.9 if a feedback term is positive, that means there is either an anomalously high FMSE source in an anomalously high FMSE region, or anomalously low FMSE source in an anomalously low FMSE region. Therefore, the relevant feedback will be increasing FMSE in already moist regions (and vice versa), and so driving an increase in σ_h^2 , thus favouring aggregation. However, whilst this method can effectively diagnose the direct effect of radiative and surface flux processes, it cannot explicitly diagnose the effects of radiatively-driven circulations, or other dynamical contributions. These effects are combined into the advective feedback term. Additionally, as the budget is vertically integrated, it is also unable to vertically-resolve shallow circulations, or the sensitivity to radiative flux profiles. Again, these are indirectly included in the advective term, as they determine the circulation response (Wing et al. 2017). Other methods to diagnose feedbacks have been proposed in recent years, such as the available potential energy (APE) budget (Yang 2018b).

Another popular method by which mechanisms can be identified is through mechanism denial tests. For this, a feedback in the model is prevented and thus we can test the sensitivity of aggregation to removing that feedback. Muller and Held (2012) use this method to test aggregation against feedbacks diagnosed from the vertically integrated FMSE budget (equation 1.3). They achieved this by horizontally homogenising various fields to remove horizontal gradients which could be influencing the aggregation. Findings from Muller and

Held (2012), Wing and Emanuel (2014), Yang (2018b) and other mechanism studies will be summarised by feedback below.

Longwave radiation

One consistent result from studies which have investigated the mechanisms behind self-aggregation, is the importance of the interactions between radiative heating and atmospheric humidity. In particular, the longwave radiative feedback is regularly identified as the most important for self-aggregation to occur (e.g. Tompkins and Craig 1998; Bretherton et al. 2005; Muller and Held 2012; Abbot 2014; Wing and Emanuel 2014; Arnold and Randall 2015; Coppin and Bony 2015; Muller and Bony 2015; Holloway and Woolnough 2016; Arnold and Putman 2018; Beucler et al. 2018; Yang 2018b; Pope et al. 2021).

This feedback was initially identified as essential to self-aggregation by Muller and Held (2012). Through horizontally homogenising longwave radiative heating rates, the authors found that in the absence of interactive longwave cooling convection did not aggregate in any of their simulations. Further, they found that it was the longwave cooling near the top of low clouds in the dry regions which was responsible for the onset of self-aggregation. They attribute this feedback to the upgradient transfer of FMSE which this low-level cooling drives (this will be discussed in more detail in the **Advective processes** section below).

There is broad agreement that it is the interactive longwave cooling in the dry regions of the domain which drives the aggregation of convection (Coppin and Bony 2015). This triggers aggregation in two ways: the first is due to the longwave cooling decreasing FMSE in the driest regions of the domain, and the second, indirect effect is that the enhanced longwave cooling drives a circulation from the dry to moist regions, transporting FMSE upgradient. Both effects work to suppress convection in the dry regions and enhance convection in the moist regions, therefore aggregating the convection (Wing et al. 2017). It is not always the case that the dry regions will have enhanced longwave cooling - this is dependent on

the temperature, clouds, and vertical humidity structure (Emanuel et al. 2014; Beucler and Cronin 2016). Also, the upgradient transport of FMSE is also dependent on the vertical structure of the radiative cooling anomalies (Muller and Held 2012). The FMSE variance budget has shown that both the clear- and cloudy-sky components of the direct longwave feedback are often large and positive at the beginning of simulations which aggregate, and therefore important in driving the initial aggregation of convection (Wing and Emanuel 2014; Holloway and Woolnough 2016; Wing and Cronin 2016; Pope et al. 2021).

An increasing body of work is elucidating the role of the vertical distribution of longwave cooling. Muller and Held (2012) argued that the combination of strong longwave cooling from the top of shallow clouds in dry regions and reduced longwave cooling by high clouds in moist regions creates differential cooling between moist and dry regions. The strong cooling in dry regions caused subsidence, while there is convection in the moist regions. This generates a low-level circulation in the boundary layer regions which transports FMSE from dry to moist regions (i.e. upgradient). Other work has also highlighted the importance of the boundary layer in aggregation (Jeevanjee and Romps 2013; Muller and Bony 2015; Naumann et al. 2017; Yang 2018b). Yang (2018b) performed mechanism denial experiments where the radiative cooling rates were horizontally homogenised in the boundary layer and free troposphere separately. The authors found that when the homogenisation happened in the boundary layer alone self-aggregation was suppressed, whilst with homogenisation in the free troposphere only, self-aggregation still occurred.

Importantly, in both Muller and Held (2012) and Wing and Emanuel (2014) it was shown that the relative importance of different feedbacks changes as the simulations progress. Muller and Held (2012) investigated the role of feedbacks through mechanism denial experiments which were started from both disaggregated and aggregated initial conditions. They found that aggregation exhibited a hysteresis property: once convection aggregates, it remains aggregated, even in the absence of feedbacks which are essential for driving the

aggregation. When simulations were initialised from disaggregated initial conditions, the longwave feedbacks were necessary for convection to aggregate. However, when simulations were initialised from already aggregated conditions, convection remained aggregated, even when the longwave fluxes were homogenised. Studies using the FMSE variance budget have also confirmed that the importance of the longwave feedback appears to change through time, typically reducing in magnitude or sometimes even changing in sign from a positive to a negative feedback (Wing and Emanuel 2014; Beucler and Cronin 2019)

Shortwave Radiation

In FMSE variance budget analysis, the direct shortwave feedback is found to be positive. This is driven by shortwave absorption by water vapour, which is anomalously high (low) in moist (dry) regions. The cloudy-sky feedback can be positive or negative, but is generally negative after convection has aggregated due to the reflection of shortwave from high clouds (Wing and Emanuel 2014; Holloway and Woolnough 2016; Wing and Cronin 2016), and of much lower magnitude than the clear-sky effect.

Contrastingly, in mechanism denial tests Muller and Held (2012) found that the shortwave feedbacks actually opposed aggregation. The key difference between FMSE budget analysis and mechanism denial experiments is that the latter also removes the indirect effects of a feedback. Therefore, Holloway and Woolnough (2016) hypothesised that the opposing feedback in Muller and Held (2012) was due to the circulations forced by shortwave anomalies in the moist columns.

Surface fluxes

Current research suggests that surface flux feedbacks are not essential for aggregation to occur (Tompkins and Craig 1998; Bretherton et al. 2005; Muller and Held 2012). Through sensitivity mechanism denial tests, Muller and Held (2012) found that, despite aggregation still occurring when surface flux feedbacks were removed, these feedbacks do still

favour self-aggregation: fewer simulations aggregated when the surface fluxes were homogenised. Holloway and Woolnough (2016) and Wing and Emanuel (2014) supported these results, and in particular noted that the surface flux feedbacks were most important in the early days of their experiments.

The physical mechanisms behind surface flux feedbacks can be separated into two opposing feedbacks. The first is the wind driven surface heat exchange (WISHE) feedback. This is due to increased windspeeds in the close vicinity of convecting regions, increasing surface fluxes in the already moist regions and thus acting as a positive feedback on aggregation. This feedback depends solely on variations in surface windspeed. The second, negative feedback is due to the air-sea enthalpy disequilibrium being smaller in the moist, convecting regions and therefore reducing surface fluxes, acting to suppress convection. This feedback depends on variations in $\Delta T = T_s - T_a$ and $\Delta q = q_{T_s}^* - q_v$, with terms as described in equations 1.6 and 1.7. It is the balance of these two feedbacks which determines the sign of the surface flux feedback in FMSE variance budget analysis. Wing and Emanuel (2014) derived a decomposition of equation 1.8 to give analytic formulae for these different feedbacks (see equation 10 in Wing and Emanuel 2014). In general, the positive WISHE feedback dominates in the early stages of aggregation which is why homogenising the surface flux feedbacks can reduce aggregation. In the latter equilibrium stages of simulations, the air-sea enthalpy disequilibrium feedback tends to dominate, driving a negative surface flux feedback (Wing and Emanuel 2014; Holloway and Woolnough 2016).

Advective feedbacks

As alluded to above, the role of advective feedbacks has been found to be important to the development of self-aggregation. Bretherton et al. (2005) was the first to identify that FMSE was being transported upgradient, and visualised this through a moisture-sorted stream-function. Muller and Held (2012) and Muller and Bony (2015) further corroborated this result, and emphasised its importance. In particular, they found that it was the radiative

cooling from the top of low-level clouds which drove subsidence in the dry regions and this generated a low-level overturning circulation which was responsible for transporting the high surface FMSE upgradient. In their simulations, there is also a mid-tropospheric export of low FMSE from the moist to the dry regions. Thus, these circulations positively feed back on self-aggregation.

Through the FMSE variance budget, Wing and Emanuel (2014) and Holloway and Woolnough (2016) show that the total contribution from all advective processes is a positive feedback in the early stages of self-aggregation, but that it changes sign in the latter stages of their simulations, and in Wing and Cronin (2016) the advective feedback from FMSE variance budget was found to be always negative. Coppin and Bony (2015) concluded that, whilst the overall advective feedback might be negative, there could still be local advection which favoured aggregation and that the shallow component of the circulation could still be transporting FMSE upgradient. It is also possible that the indirect effect of radiative cooling anomalies are working to transport FMSE upgradient, but that other advective processes are counteracting this. Indeed Holloway and Woolnough (2016) found that the upgradient FMSE transport was being balanced by other advective effects with the opposite sign. They also concluded that the FMSE circulation was being forced mostly through convective heating anomalies, not radiation.

Clearly, advective feedbacks contribute to self-aggregation. However, there are still disagreements in the literature and further work is still needed to identify whether they trigger aggregation or simply amplify it once direct, diabatic feedbacks have triggered it.

Moisture-memory feedback and cold pools

Another mechanism that is potentially very important for self-aggregation is the moisture-memory feedback (Tompkins 2001c). This feedback is driven by the idea that moist regions favour convection. The physical mechanism behind the feedback is still somewhat dis-

puted. There are three main hypotheses which can explain the processes driving this. The first is that convection is favoured by an anomalously moist boundary layer which occurs in the absence of strong downdrafts. Due to the slow advection of detrained cloud moisture, the humidity field close to previous convective clouds continues to moisten, creating conditions which are favourable to new clouds (Craig and Mack 2013). Secondly, when cold pools are suppressed this can also amplify boundary layer moisture close to recent convection (Jeevanjee and Romps 2013; Muller and Bony 2015; Hohenegger and Stevens 2016; Holloway and Woolnough 2016; Yanase et al. 2020; Nissen and Haerter 2021). The third explanation for the moisture feedback is due to entrainment. In a moist environment, convective entrainment would not dilute the convective plumes, and so this would favour further convection (Tompkins 2001c).

Both Muller and Bony (2015) and Holloway and Woolnough (2016) found that convection could self-aggregate in the absence of radiative feedbacks when this moisture feedback was artificially enforced by suppressing the re-evaporation of raindrops. Whilst this condition is not realistic in standard conditions, its relevance could increase in an (almost) saturated boundary layer with precipitation efficiency close to 100%. Other studies have also found that the moisture feedback tends to favour aggregation (Craig and Mack 2013; Becker et al. 2017; Tompkins and Semie 2017; Windmiller and Craig 2019). However, the extent to which the moisture feedback is essential to self-aggregation remains debated (Craig and Mack 2013; Muller and Bony 2015; Wing 2019; Yang 2019).

Gravity wave interaction

Inspired by the fact that aggregation seems to be dependent on certain boundary layer features (Jeevanjee and Romps 2013; Muller and Bony 2015; Naumann et al. 2017; Yang 2018b), Yang (2021) devised a linear shallow water model which simulates the boundary layer. This model successfully simulated convective self-aggregation, and highlighted an important role for convectively-coupled gravity waves in driving the aggregation. They

found that standing gravity waves partitioned the domain into convectively-active and inactive regions. Gravity waves were also found to influence convection in the first few days of the simulations in Wing and Cronin (2016).

Feedback sensitivity to surface temperature

As introduced earlier, the sensitivity of self-aggregation to surface temperature is contested. However, there has also been some work done to investigate, if convection does self-aggregate, if, and to what extent the self-aggregation feedbacks differ with surface temperature. In particular, Coppin and Bony (2015) found that the feedbacks driving self-aggregation in a GCM varied at high and low surface temperatures. At high temperatures they identified that the WISHE surface flux feedback was the main feedback driving aggregation. However, at lower SSTs the circulation associated with low-level radiative cooling in the dry region was found to be the dominant feedback. Contrastingly, the radiative-instability model derived in Emanuel et al. (2014) predicts that the direct clear-sky longwave feedback should be increasingly dominant with higher temperatures, due to the increase in water vapour with temperature which increases the opacity of the lower troposphere. Additionally, the relative contribution of the shortwave feedback at different SSTs has been found to vary (Holloway and Woolnough 2016; Wing and Cronin 2016).

1.2.1.3 Self-aggregation in CRMs and GCMs

For many years, differences in self-aggregation between CRMs and GCMs were mostly studied through experiments with individual models. However, through RCEMIP, it has become easier to compare how features and mechanisms might differ when convection is either explicit or parameterised.

When analysing the RCEMIP ensemble, Wing et al. (2020) found that the changes in mean climate in response to self-aggregation were consistent across CRMs and GCMs, with most

models warming, drying, and increasing longwave cooling to space with aggregation. Pope et al. (2022) also recently investigated the differences between GCMs and CRMs. The authors found that, on average, GCMs aggregate faster than CRMs from homogeneous initial conditions. They also used the FMSE variance budget method to compare the contributions from different diabatic feedbacks in driving the self-aggregation. The shortwave and surface flux feedbacks were shown to have a similar magnitude across all models, whilst the longwave-cloud interactions were, on average, twice as strong in GCMs than in CRMs.

1.2.2 Idealised versus real-world convective organisation

All of the results discussed thus far have been within the context of extremely idealised models in RCE with no inhomogeneities in the boundary conditions and no rotation. Whilst we have gained a wealth of knowledge through these highly idealised studies, an obvious question is whether these processes and feedbacks occur within the real atmosphere. Even more simply, to what extent we see convective self-aggregation in the real world is not a question that is easily answered. Thus far in this thesis the terms aggregation and self-aggregation have been used somewhat interchangeably, however we must now make a distinction between the two. Convective self-aggregation is the phenomenon we have primarily discussed so far, where convection clusters together entirely from self-generated feedbacks and circulations. Convective aggregation is a more general term which can include self-aggregation, but can also encompass convective clustering that might be forced through some external mechanism.

More recently, attempts have been made to bridge the gap between idealised simulations and real-world convective organisation. There are different methods for achieving this: some works have used observations to identify signals of aggregation within the tropics

(e.g. Tobin et al. 2012, 2013; Holloway et al. 2017; Bony et al. 2020), whilst other studies have added layers of complexity to idealised models to understand how specific real-world processes might change the occurrence, or features of convective aggregation (e.g. Khairoutdinov and Emanuel 2018; Muller and Romps 2018; Shamekh et al. 2020a; Leutwyler and Hohenegger 2021; Tompkins and Semie 2021). In particular, it has been argued that the processes driving self-aggregation could be important for understanding tropical cyclones (e.g. Khairoutdinov and Emanuel 2013; Reed et al. 2015; Wing et al. 2016; Muller and Romps 2018; Carstens and Wing 2020; Ramírez Reyes and Yang 2021), the MJO (e.g. Neelin and Held 1987; Bretherton et al. 2005; Arnold and Randall 2015; Holloway et al. 2017; Khairoutdinov and Emanuel 2018), and the ITCZ (e.g. Raymond 2000; Müller and Hohenegger 2020). In the following sections we will explore different avenues of realism to introduce the ways in which convective self-aggregation can be related to real-world organisation.

Inhomogeneous sea-surface temperatures

In typical studies on self-aggregation, the SST is homogeneous across the domain and remains fixed throughout the simulation. In the real world, gradients in the SST are known to strongly impact the organisation of convection. In particular, Tompkins (2001c) found that imposing SST anomalies leads to the migration of convective clusters towards the warm spots. Therefore, it is logical to assume that the inclusion of an SST gradient would impact the existence and formation of self-aggregation.

Over an SST gradient, the boundary layer above the warmest SSTs becomes anomalously warm and moist, driving a pressure gradient and low-level flow (Back and Bretherton 2009). If the SST is kept fixed in time, but inhomogeneous in space in idealised simulations, Shamekh et al. (2020a) showed that the warmest SSTs (termed the SST 'hot spot') cause local convective instability which drives a large-scale overturning circulation which aggregates the convection over the hot spot. They argued that this is different from the typical driving mechanism for self-aggregation, where the radiative cooling in the dry patch forces

the circulation and 'pushes' the convection to aggregate. Here, the SST gradient is instead 'pulling' the convection towards the hot spot. They also show that the strength of the large-scale overturning circulation, and the speed of aggregation, is a function of the hot spot's fractional area. Additionally, through mechanism denial tests, they found that this aggregation could occur in the absence of radiative feedbacks (unlike most self-aggregation), providing the hot spot was sufficiently warm and large.

In a spherical domain, Müller and Hohenegger (2020) studied the impact of a temporally fixed, zonally-symmetric SST gradient on aggregation. They found that convection clusters together along the warmest SSTs, resembling the ITCZ. Interestingly, they also found that after this meridional clustering happens, there is a zonal contraction of the convection. They hypothesise that this forms due to the emergence of a shallow circulation driven by self-aggregation feedbacks, although no formal feedback decomposition was performed.

Several studies have investigated the impacts on aggregation of allowing the ocean surface to dynamically interact with the atmosphere. Due to the below-cloud cooling effect of cloud shielding, one would expect that interactive SSTs could delay or prevent convection from aggregating (Hohenegger and Stevens 2016; Coppin and Bony 2018; Shamekh et al. 2020a; Tompkins and Semie 2021). Indeed, when modelling over a slab ocean⁵, both Tompkins and Semie (2021) and Shamekh et al. (2020b) find that interactive SSTs slow the onset of aggregation. This is due to the relative surface warming in the dry regions, combined with cooling in the convective regions, which creates a gradient in surface fluxes. This opposes the low-level convergence of moisture and thus slows aggregation. Once convection has aggregated however, Shamekh et al. (2020b) found that a negative SST anomaly forms in the dry patch. The results from Tompkins and Semie (2021) agreed with this, and attributed the negative anomaly to strong longwave radiative cooling and enhanced latent heat fluxes in the dry patch, which cool the ocean surface. Tompkins and Semie (2021) show that the

⁵A slab ocean is an idealised ocean model which represents the thin, well-mixed top layer of the ocean. This allows for interactive SSTs and surface fluxes.

domain separates into three distinct regions - the cold-dry zone, the convective cloudy zone, and an intermediate boundary zone of moist clear-sky air. In this intermediate zone, the absence of anvil cloud leads to the shortwave anomaly dominating over the longwave, driving increases in SSTs. This causes the convection to constantly migrate towards this boundary zone, however it cannot enter the neighbouring dry zone.

Aggregation with rotation and cyclogenesis

Studies using rotating RCE have shown that self-aggregation can present as tropical cyclogenesis (e.g. Bretherton et al. 2005; Khairoutdinov and Emanuel 2013; Wing and Cronin 2016; Muller and Romps 2018; Carstens and Wing 2020). Wing et al. (2016) investigated this cyclogenesis process using the FMSE variance budget method and compared the feedbacks with those found in regular, non-rotating self-aggregation studies. They found that there are significant contributions from longwave and surface flux feedbacks in the early stages of formation, as with self-aggregation. Contrastingly to self-aggregation though, mechanism denial tests found that the radiative feedbacks aid cyclogenesis but are not a necessary feedback. Ramírez Reyes and Yang (2021, 2022) go a step further and show that cyclogenesis can happen in rotating RCE simulations without both radiative and surface flux feedbacks. They show that cyclogenesis is associated with an increase in APE production, and attribute this to the moisture-entrainment feedback discussed above. Understanding the mechanisms behind tropical cyclogenesis and intensification is still an active area of research, but Muller and Romps (2018) highlighted that rotating self-aggregation studies can help to shed more light on the physical processes surrounding tropical cyclones and their genesis.

The MJO

The MJO was first linked to self-aggregation after Raymond (2001) suggested that the MJO is due to an instability driven by cloud-radiation interactions. He identified that, in their model of the MJO, the cloud-radiation interactions made the tropical atmosphere unstable to large-

scale radiative-convective overturning circulations. Arnold and Randall (2015) were also able to simulate the MJO. Using a GCM they initially used a typical idealised RCE set up to simulate self-aggregation. When rotation was added to their model the aggregation took the form of the MJO, centred on the equator, and thus they concluded that the MJO could be a form of convective self-aggregation but on a rotating sphere. Khairoutdinov and Emanuel (2018) found similar results. Using mechanism denial tests they confirm the results of Raymond (2001) by showing that the cloud-radiation interactions are essential for the MJO to form in their model. They also highlighted a role for the WISHE feedback in propagating the MJO-like disturbance eastwards. Observational work from the DYNAMO field campaign also found an important role for radiation and, to a lesser extent, surface fluxes in amplifying MJO variability which further links self-aggregation and MJO processes (Sobel et al. 2014). However, the processes governing the MJO's propagation and variability are still debated. For example, in their recent review of MJO theories, Zhang et al. (2020) highlight that the cloud-radiative feedback is the main feedback in only one of the four key MJO theories, a secondary feedback in one other theory and is not even included in the final two theories. Thus, significant work remains in determining the role of cloud-radiative feedbacks in the MJO and how self-aggregation and the MJO might interact.

Aggregation with a land surface

Another simplification that idealised models in RCE typically use is an aquaplanet model. Introducing land to these models increases the complexity of both the study design as well as interpreting the results. Nevertheless, in recent years some studies have implemented models to investigate how land affects clouds and precipitation in the tropics. This has been done in two ways - some have run modified RCE simulations on a land-only planet (Becker and Stevens 2014; Hohenegger and Stevens 2018), and some have included both islands and ocean in their simulations (Cronin et al. 2015; Coppin and Bellon 2019a,b; Leutwyler and Hohenegger 2021).

On a land-only planet, Hohenegger and Stevens (2018) found that the soil moisture gradients which formed at the surface homogenised the precipitation field over long time scales. Similarly to simulations with interactive SSTs, they found that as the soil dried in the dry patches, a low-level circulation converging towards the warm, dry patch was induced. Hence, once a convective cluster has formed, the drying process begins away from it such that aggregation is prevented from being maintained.

In idealised simulations containing islands, precipitation typically favours land over ocean (Cronin et al. 2015; Coppin and Bellon 2019a; Leutwyler and Hohenegger 2021). The presence of islands in RCE simulations has also been shown to impact the domain-mean temperature profile. Cronin et al. (2015) found that their simulation with an island had a warmer troposphere than their land-free simulation. The authors attribute this warming to the convection forming in the warmest and moistest areas of the boundary layer which are all over the island. This then forces the convection onto a warmer moist adiabat, the temperature of which is propagated across the domain due to the weak temperature gradient assumption typically holds in the tropics. Contrastingly, Leutwyler and Hohenegger (2021) find that the presence of islands in their simulations drives a cooling of the troposphere. The difference in these two experiments is attributed to a difference in modelling parameters. In Cronin et al. (2015), the only difference between the island and ocean is the heat capacity. Whereas in Leutwyler and Hohenegger (2021), the islands are modelled using a land-surface model, and so their soil has the ability to dry out. Thus, in land grid-cells which are precipitation free, the soil dries and limits evaporation. This leads to a warmer, but drier sub-cloud layer (unlike in Cronin et al. (2015) which has a warmer, moister sub-cloud layer). This process becomes increasingly important as the land fraction increases, meaning that for larger islands, convection will end up on a cooler moist adiabat thus cooling the domain-mean temperature. Less work has specifically investigated self-aggregation and its interactions with land, especially looking into how the mechanisms vary when a land-sea contrast is present.

Aggregation in observations

In their review on observing convective self-aggregation, Holloway et al. (2017) argue that the modelled behaviour is relevant to real-world convection and climate. They highlight that the processes identified in self-aggregation studies may also operate in nature. Recently, Bony et al. (2020) found that convective organisation, along with lower tropospheric stability, accounted for over 60% of the variance in the tropical radiation budget. Hence, they concluded that this emphasises the importance of understanding organisation and is consistent with the conclusions from idealised modelling studies that aggregation substantially influences the radiative budget of the Earth.

In the first paper to specifically investigate self-aggregation processes in observations, Tobin et al. (2012) identified similarities between organised scenes in the tropics and idealised simulations of self-aggregation using the SCAI metric. Under fixed SSTs, they found that increased organisation led to a drier free-troposphere in the non-convective environment and increased OLR by up to 30 W m^{-2} due to a reduction in mid- and upper-level clouds. These results are in agreement with self-aggregated scenes in idealised models. These results have also been supported by Tobin et al. (2013), Stein et al. (2017), Bony et al. (2020) and Masunaga et al. (2021). Not all results are as conclusive though. Tobin et al. (2012, 2013) found that increases in the OLR were compensated by decreased reflected shortwave radiation, leading to no net change in the top-of-atmosphere net radiative budget, in contrast to the results from idealised simulations, such as Wing and Cronin (2016). Additionally, Tobin et al. (2012, 2013) had contrasting results on the change in surface fluxes with increased aggregation and the low cloud response. Nevertheless, Holloway et al. (2017) also conclude that there are many aspects of observing convective aggregation which require more observational study, especially to investigate any potential SST dependence of aggregation mechanisms, and to understand the impacts of climate change on organised convection. One feature which seems robust in observations of the tropical climate is a two-peaked humidity distribution (Mapes 2001; Zhang et al. 2003; Mapes 2016), which implies the trop-

ical atmosphere tends to divide into wet and dry regions, however it gives no insight into their spatial organisation. Additionally, the relatively long time scales of self-aggregation (15-100 days) provides additional difficulties to observing aggregation, due to potential disruptions of the organisation by synoptic variability in the real world (Muller et al. 2022).

Climate sensitivity

Due to its tendency to broaden the humidity distribution and increase radiative cooling to space, studies have suggested that self-aggregation might modulate climate sensitivity (e.g. Khairoutdinov and Emanuel 2010; Becker and Stevens 2014; Cronin and Wing 2017; Becker and Wing 2020). Thus, if the degree of self-aggregation increased with warming, this could feed back on the temperature, and act as a self-regulatory feedback on tropical warming (Khairoutdinov and Emanuel 2010). Indeed, Becker and Wing (2020) showed that models in which self-aggregation increases with SST typically have a lower climate sensitivity. However, the main caveat to this relationship is that recent results imply that there is no consistent relationship between surface temperature and self-aggregation (Wing et al. 2020). Additionally, allowing SSTs to interact with convection can reduce, or even negate this effect. Coppin and Bony (2018) found that the negative aggregation-warming climate sensitivity feedback loop was offset by a positive feedback between SST and reduced low cloud cover.

The work presented across Section 1.2.2 has highlighted the multifaceted ways in which the scientific community has learnt from the results in idealised self-aggregation studies as well as identifying some key areas in which further exploration would be beneficial. Despite the evidence presented, the relevance of self-aggregation to the real world is still a highly debated topic. Improving our understanding of how different idealisations in models impact the results found is vital in order to reach a conclusion.

1.3 Aerosols and the monsoon

Monsoons refer to a seasonal change in meteorological conditions, in particular, strong seasonal precipitation cycles marked by a rainy summer and a drier winter with a seasonal reversal in prevailing winds. Historically, the monsoons have been thought to be primarily driven by a contrast in the land-sea heating where the differential warming of the land and the ocean will drive strong pressure gradients and thus force a large-scale circulation (Halley 1686; Webster 1987; Wang 1994; Webster et al. 1998). More recent work has suggested that regional monsoons are localised perturbations of a tropical convergence zone, which may sit at the equator (the ITCZ) or be pulled over a continent as a monsoon (e.g. Bordoni and Schneider 2008, 2010; Mukherjee et al. 2014; Faulk et al. 2017; Hill et al. 2019; Geen et al. 2020).

The aerosol effects on the monsoon are many and highly debated. Some theories propose that aerosols are strengthening the monsoon (Lau and Kim 2006; Lau et al. 2006; Wang et al. 2009): absorbing aerosols can strongly heat the atmospheric column, especially in the boundary layer where concentrations are highest. This boundary layer heating can lead to increased convective instability, and eventually drive an increase in the rain rate (Sarangi et al. 2017, 2018). However, Ramanathan et al. (2005) showed that aerosols are associated with a weakening of the meridional thermal contrast and thus a weakening of the Indian monsoon with Bollasina et al. (2011) also showing that anthropogenic aerosols are driving the observed decrease in Indian monsoon rainfall in the 20th century.

The monsoon and its interactions with aerosols are not widely discussed in this thesis, thus a more detailed discussion of monsoon theory and aerosol interactions is left to existing literature reviews, such as Geen et al. (2020) and Li et al. (2016). However, the modelling design used in this thesis could provide a useful analysis test-bed for investigating the

monsoon. A further discussion of this is provided in Chapter 5.

1.4 Objectives of thesis

Whilst great strides have been made in understanding the features and mechanisms of convection self-aggregation, many questions still remain, particularly regarding the application of the work in the real-world. Looking for evidence of self-aggregation in observations is made tricky due to the time scales of idealised self-aggregation far exceeding synoptic variability time scales (Holloway et al. 2017; Wing et al. 2017; Muller et al. 2022), therefore allowing for this variability to disrupt the aggregation. Additionally, more work is needed to clarify the roles of different mechanisms in the self-aggregation process, especially as the level of idealisation decreases (Hohenegger and Stevens 2018; Müller and Hohenegger 2020; Shamekh et al. 2020a). In particular, RCE is a highly idealised modelling environment, and therefore understanding how self-aggregation mechanisms and 'real-world' aggregation mechanisms interact with each other would help to evaluate the relevance of idealised self-aggregation.

In this thesis we will address some of these questions by investigating how aggregation responds to real-world forcings. We will approach this by including atmospheric heating perturbations, land, and sea-surface temperature gradients into idealised models. Incrementally increasing the complexity of idealised models allows us to isolate the direct impacts each of these processes has on the convection and its spatial organisation. We will utilise the FMSE energy budget and mechanism denial methods introduced above to investigate the role of different feedbacks on the aggregation we see in our models. The key aims of this thesis are to answer the following questions:

1. Can we force convection to aggregate by using atmospheric diabatic heating pertur-

bations, and how does this affect the mechanisms of aggregation?

2. What is the impact of land on large-scale convective aggregation?
3. How does self-aggregation behave under the influence of a large-scale sea-surface temperature gradient?

This thesis is structured as follows:

Chapter 2: Forced convective aggregation

In this chapter we investigate the concept of forced convective aggregation. In Shamekh et al. (2020a), the inclusion of SST 'hot-spots' were shown to force convection to cluster over the warm ocean anomaly. They investigated the mechanisms of this forced aggregation through mechanism denial tests and found that, whilst the aggregation was still driven primarily by radiative feedbacks as in idealised self-aggregation, the mechanisms were driven mostly from the warmest and moistest columns pulling the convection towards them, as opposed to typical self-aggregation which is driven by a radiatively-driven dry patch expansion. We expand on these ideas by investigating how diabatic heating by absorbing aerosols can drive convective aggregation. In contrast to the surface temperature anomalies in Shamekh et al. (2020a), in this chapter, we force the aggregation by using idealised plumes of absorbing aerosols concentrated in the lower troposphere. This chapter compares the features of forced aggregation to idealised self-aggregation and investigates its mechanisms using both the FMSE energy budget analysis and mechanism denial tests. The use of aerosol forced diabatic perturbations allows us to also link the results to potential impacts of absorbing aerosol events in the real world, such as biomass burning events or pollution.

Chapter 3: Aggregation in the presence of an island

Inhomogeneous surfaces have been shown to impact the existence and properties of convective aggregation, however, the interactions between land and aggregation have been

understudied. On a land-only RCE planet, Hohenegger and Stevens (2018) showed that soil-moisture gradients opposed the persistent aggregation of convection by generating circulations which opposed the aggregation circulations through the surface fluxes. Additionally, papers which used an RCE framework with both islands and ocean (e.g. Cronin et al. 2015; Coppin and Bellon 2019a; Leutwyler and Hohenegger 2021) found that convection and precipitation typically favour land, however, no work has yet provided a systematic decomposition of convective organisation mechanisms. Additionally, none of these works studied the large-scale interactions of land and aggregation, with all previous studies using limited-area CRMs. In this chapter, we add an idealised, continentally-sized island to an RCE model. Similarly to Chapter 2, we investigate how the aggregation which forms in this modelling paradigm compares to idealised self-aggregation. We look at both the early, aggregating phase of the simulation and the equilibrium, maintenance phase separately. Circulations driving the organisation are decomposed to investigate what is driving them, and results are confirmed with mechanism denial tests.

Chapter 4: Convective self-aggregation over sea-surface temperature gradients In this chapter, a different idealisation typically used in self-aggregation studies is relaxed: SST gradients. Müller and Hohenegger (2020) showed that on a convection resolving spherical domain with a zonally homogeneous meridional SST gradient, convection clusters together along the warmest SSTs, much like the ITCZ at the equator. However, they also showed that this convection then zonally contracts despite no zonal forcing in the boundary conditions. The authors argue that this contraction is a self-aggregation of the convection. Here, we use a zonally-symmetric SST gradient in a GCM to thoroughly investigate the mechanisms driving zonal clustering along the equator. This work highlights that self-aggregation feedbacks may be interacting with other large-scale forcings in the real atmosphere, particularly within the ITCZ.

Discussion and Conclusions

In this final chapter, results from across the thesis are summarised and combined into key conclusions we can take from this work. Additionally, new questions that arise from the work presented here are posed.

2 | **Forced convective aggregation**

All sorts of things can happen when you're open to new ideas and playing around with things.

STEPHANIE KWOLEK

In this chapter, GCM simulations are used to investigate if convection can be forced to aggregate together, using a large-scale diabatic heating source. The hypothesis behind this work is that if we can generate a thermally-driven circulation, then this could drive enough instability such that convection is forced to preferentially form close to the heating perturbation, thus aggregating the convection.

This chapter is based on an article published in Journal of Advances in Modeling Earth Systems:

Dingley, B., Dagan, G., and Stier, P. (2021). Forcing convection to aggregate using diabatic heating perturbations. *Journal of Advances in Modeling Earth Systems*, 13(10), e2021MS002579. doi: 10.1029/2021MS002579.

I designed the study together with the co-authors. I carried out the simulations and analyses presented, with input from the co-authors. I wrote the manuscript, and underwent the peer-review process, with contributions and approval from the co-authors.

Abstract

Tropical deep convection can aggregate into large clusters, which can have impacts on the local humidity and precipitation. Sea surface temperature (SST) gradients have been shown to organise convection, yet there has been little work done to investigate the impact of diabatic heating perturbations in the atmosphere on the aggregation of convection. Here we investigate how anomalous diabatic heating of the atmospheric column, through an idealised aerosol plume, affects the existence and mechanisms of convective aggregation in non-rotating, global RCE simulations. We show that the aerosol forcing has the ability to increase the degree of aggregation, especially at lower SSTs. Detailed investigation shows that the diabatic heating source incites a thermally-driven circulation, forced by the shortwave perturbation. The increase in aggregation is caused in part by this circulation, and in part by the longwave heating anomalies occurring due to the surface convergence of moisture and convection. At higher SSTs, longwave feedbacks are crucial for the aggregation of convection, even with the shortwave heating perturbation. At lower SSTs, convection is able to aggregate with the shortwave perturbation in the absence of longwave feedbacks. These perturbations provide a link to studying the effects of absorbing aerosol plumes on convection, for example during the Indian monsoon season. We argue that, as there is aggregation for plumes with realistic aerosol absorption optical depths, this could be an analogue for real-world organisation in regions with high pollution.

2.1 Introduction

Moist deep convection is important for distributing heat, moisture, and momentum globally, however, its intensity and evolution depend on its environment. A common method for studying tropical deep convection is modelling in a radiative-convective equilibrium (RCE)

setup. (Manabe and Wetherald 1967; Held et al. 1993). Whilst this is an idealised setup, it provides an acceptable simplification of the tropical atmosphere on large scales (Jakob et al. 2019) and has been used to study convection for many years (e.g. Manabe and Wetherald 1967; Held et al. 1993; Tompkins and Craig 1998). A specific convective organisation phenomenon that can occur when running a model in RCE is convective self-aggregation (Bretherton et al. 2005).

It has been robustly shown that interactions between longwave radiative feedbacks, moisture, and convection are essential for triggering and maintaining aggregation (e.g. Muller and Held 2012; Coppin and Bony 2015; Yang 2018a). This physical feedback relies on strong clear-sky longwave radiative cooling away from deep convective areas, which helps to develop a circulation which advects moist-static energy up-gradient to the moist convecting region (Muller and Held 2012). There is an increasing body of work suggesting the boundary layer is especially important for feedbacks involved in convective aggregation (e.g. Muller and Bony 2015; Naumann et al. 2017; Yang 2018a,b). Yang (2018a) showed through mechanism denial experiments, that removing longwave feedbacks in the boundary layer is sufficient to suppress aggregation, whilst removing the free-tropospheric feedbacks alone still enabled the convection to aggregate, verifying that the boundary layer is important for convective self-aggregation. There has been some dispute over the remaining physical drivers of aggregation, with different studies giving opposing results. Some proposed positive feedbacks include the virtual effects of water vapour (Yang 2018a), and the wind-induced surface heat exchange (WISHE) feedback (Coppin and Bony 2015). The shortwave radiative feedbacks have been found to have differing signs. Muller and Held (2012) found that interactive shortwave fluxes were not essential in triggering aggregation and that shortwave fluxes opposed the formation of aggregation. They hypothesise that this is due to increased shortwave cooling in the cloudy regions. Other studies, such as Wing and Emanuel (2014) and Holloway and Woolnough (2016) have contradicted this result, finding that there is reduced shortwave absorption in the dry regions, due to the

absorption of water vapour. It has also been shown that the dominant mechanisms can depend on the model configuration chosen, such as SST, horizontal grid resolution, or the representation of convection (Muller and Held 2012; Coppin and Bony 2015; Wing 2019).

Shamekh et al. (2020a) investigated the concept of forced convective aggregation. They used a CRM with fixed SSTs, and with SST 'hot-spots' of between 3K-5K and looked at how this forced the aggregation and whether it differed from self-aggregation. They noted an acceleration in the formation of aggregation, especially for warmer/larger hot-spots. They also saw that the inclusion of a hot-spot allowed simulations to aggregate at temperatures that they previously would not. Convective instability over the hot-spot forces a large-scale circulation and this increases the drying from subsidence outside of the anomaly.

Khairoutdinov and Emanuel (2010) found that, in their simulations, convective aggregation exhibits hysteresis: once convection has aggregated, it remains so even if the SST is subsequently dropped below their critical threshold temperature. Muller and Held (2012) also found hysteresis in their simulations, including when key mechanisms required to form aggregation are removed after the simulation has aggregated. In most convective self-aggregation studies this hysteresis feature is seen, however, Shamekh et al. (2020a) found that the aggregation that exists due to the SST hot-spots does not exhibit hysteresis, with convection disaggregating again once the hot-spot is removed.

Convective self-aggregation is formed by similar mechanisms to observed organised convection (such as mesoscale convective systems) however the link between the simulated and observed aggregation remains unclear and is one of the key questions in the study of convective self-aggregation. Many of the processes organising the convection in these idealised studies are exhibited on a much larger scale in the formation of the Madden-Julian Oscillation (MJO) (Arnold and Randall 2015), hence this is a possible real-world analogue of self-aggregation. Another avenue that has not yet been explored is the ability of strong pollution plumes to influence the organisation of convection. Roeckner et al. (2006) have

shown that plumes of absorbing aerosols in the tropics can heat the atmosphere, induce thermally direct circulations and locally increase moisture convergence and precipitation. Further, in Dagan et al. (2019) an absorbing aerosol plume was introduced into the tropics of an aquaplanet model; the plume incited a large-scale thermally driven circulation and the authors conclude that this could promote convective aggregation in the tropics.

In this chapter, we aim to utilise the results in Dagan et al. (2019) to investigate the impact of external diabatic heating on convective organisation. We introduce diabatic heating based on an idealised plume model, which is representative of aerosol radiative perturbations. The plume used (see details in Section 2.2.3) creates a strong local shortwave radiative heating perturbation. This creates a large-scale thermally driven circulation, which encourages moisture convergence near the surface and divergence in the upper atmosphere (Dagan et al. 2019). We hypothesise that this, in turn, will encourage convection to form and hence convective aggregation will form around the plume forcing. Henceforth, when this process is discussed, it is referred to as ‘forced aggregation’ and it should be noted that this differs from spontaneously occurring convective self-aggregation. In particular, we aim to answer the following questions:

1. Can the inclusion of a diabatic heating perturbation increase the degree of aggregation in GCM RCE simulations?
2. How do the mechanisms driving spontaneously formed self-aggregation differ from forced aggregation?
3. Can convection be forced to aggregate through shortwave heating perturbations when key feedbacks required for self-aggregation are removed, such as spatial gradients in longwave fluxes?

2.2 Methods

2.2.1 Model set-up

In all simulations, the ICOSahedral Nonhydrostatic (ICON) Atmospheric GCM (Zängl et al. 2015; Giorgetta et al. 2018), version 1.8, is used. The ICON GCM model uses the ECHAM6 physics packages (Stevens et al. 2013), including a bulk mass-flux convection scheme (Tiedtke 1989; Nordeng 1994), cloud cover calculated using the relative humidity (Sundqvist et al. 1989), and the PSRad radiation scheme (Pincus and Stevens 2013). Other parameterisation schemes used are the Lohmann and Roeckner microphysics scheme (Lohmann and Roeckner 1996) and the gravity wave scheme as described in Stevens et al. (2013).

ICON is run on a triangular grid, based on dividing spherical icosahedron. Grids are defined as RnBk grids, where the original icosahedron edges are divided into n equal arcs, which creates n^2 new triangles. The arcs of these triangles are then bisected k times, to recursively subdivide each triangle into 4 smaller triangles. Therefore, the total number of triangular cells in each grid is defined as

$$n_c = 20n^24^k \quad (2.1)$$

In this thesis, we employ the R02B04 grid, which has 20480 cells, with an average cell area of approximately 25000 km². This leads to an approximate equivalent grid-spacing of 160 km. The vertical resolution is set by assigning 47 stretched model levels between the surface and model top at 83 km, with grid spacings ranging from 40 m between the lowest model layers, to around 1350 m at 15 km, and 5900 m near the model top.

2.2.2 Experimental set-up

ICON is used in an RCE configuration. The RCE simulations are setup on an aquaplanet with no rotation and no diurnal cycle. The modelling parameters described next are taken from Wing et al. (2018), the RCE model intercomparison project (RCMIP) to study convective aggregation in radiative-convective equilibrium models. To initialise the RCE state, homogenised boundary conditions are set where the solar insolation is 551.58 Wm^{-2} with a fixed zenith angle of 42.05° . Together these values give a constant insolation of 409.6 Wm^{-2} . This is equivalent to the annual mean tropical insolation (Wing et al. 2018). The global ocean albedo is set to 0.07. Concentrations of tracers CO_2 , CH_4 , N_2O and O_2 are set to be constant in space and time and the O_3 profile is the same as used in Popke et al. (2013). SSTs are kept globally constant throughout each simulation at either 290K or 305K. The model spin-up is done for 1 month, with horizontally homogenised radiative fluxes, where the longwave and shortwave cooling rates are averaged horizontally at each model level and time-step. Then the domain-averaged conditions over the final 5 days of these simulations are used to initialise the simulations, following Wing et al. (2018). Each simulation is then run for 5 years. Model output is given every 5 days, as a 5-day mean. All timeseries in this chapter are therefore plotted for these 5-day means.

Most simulations have been run with interactive radiation. However to perform the mechanism denial experiments, radiative feedbacks have been turned off by horizontally homogenising the radiative cooling rates at each model level and time-step, following Muller and Held (2012). These simulations are referred to as HomogLW and HomogSW respectively. Please note that the 290K_Plume_HomogLW experiment has a plume with aerosol optical depth (AOD) = 1, and the 305K_Plume_HomogLW experiment (see Table 2.1 below) has a plume with AOD = 0.8, compared to the plume with AOD = 1.8 used in the rest of the simulations. Testing has shown that a plume of this shape and size, with single scattering albedo (SSA) = 0.8, can force an increase in the degree of aggregation at AODs of

<i>Experiment Name</i>	<i>SST</i>	<i>Plume</i>	<i>Interactive LW</i>	<i>Interactive SW</i>
290K_NoHomog	290K	×	✓	✓
290K_HomogLW	290K	×	×	✓
290K_HomogSW	290K	×	✓	×
305K_NoHomog	305K	×	✓	✓
305K_HomogLW	305K	×	×	✓
305K_HomogSW	305K	×	✓	×
290K_Plume_NoHomog	290K	✓	✓	✓
290K_Plume_HomogLW	290K	✓	×	✓
290K_Plume_HomogSW	290K	✓	✓	×
305K_Plume_NoHomog	305K	✓	✓	✓
305K_Plume_HomogLW	305K	✓	×	✓
305K_Plume_HomogSW	305K	✓	✓	×
290K_control	290K	×	×	✓
305K_control	305K	×	×	✓

Table 2.1. List of experiments

0.6 or greater (see Section 2.3.2). Also, these two simulations only homogenise the long-wave fluxes for three out of every four timesteps. Whilst this does not fully homogenise the longwave heating field, this amount of homogenising is sufficient to decrease the degree of aggregation to close to the value in our control runs. These measures are taken to ensure that the model stays in equilibrium as using high AOD and fully homogenising the longwave heating leads to excessive instabilities.

Occasionally, we reference a control run at either 290K or 305K SST. In these control simulations, we horizontally homogenise the longwave radiative cooling rates to prevent the aggregation of convection (e.g. Muller and Held 2012; Wing and Emanuel 2014; Arnold and Putman 2018). This enables us to decipher effects of aggregation, by comparing simulations to a non-aggregated base state. A list of all experiments can be seen in Table 2.1. These control simulations are the same as the HomogLW simulation at the relevant SST, (i.e., 290K_control is the same as 290K_HomogLW and 305K_control is the same as 305K_HomogLW).

2.2.3 Aerosol plume model

The aerosol plume in this chapter is prescribed using the Max Planck Institute Aerosol Climatology version 2, Simple Plume (MACv2-SP) model (Stevens et al. 2017). MACv2-SP is a parameterisation used to simplify the representation of anthropogenic aerosol distributions by prescribing the number and features of the aerosol plumes. Parameters to decide include the AOD, SSA, and plume spatial extent, and these are given as functions of geographical location, time, and wavelength. In this chapter, we remove any temporal dependence and use constant parameters for each variable. We also only use a single plume in our simulations, and in order to isolate the role of the heat perturbation we only introduce the radiative properties of the perturbation, not the microphysical effects which are also described in Stevens et al. (2017). In this chapter, unless otherwise specified, experiments are performed with a single plume at latitude = 0° , longitude = 0° , AOD = 1.8 and SSA = 0.8. This produces a strongly absorbing plume, which causes a large heating perturbation. The horizontal shape of the plumes is modelled with a Gaussian distribution with AOD reducing by a standard deviation every 10° in each direction. Hence, approximately 68% of the aerosols lie within a 10° radius of the plume centre, and 95% lie within 20° . The vertical distribution of the aerosols is determined by the kernel of Euler's β function with most aerosols occurring below 5 km (Stevens et al. 2017). This bottom-heavy vertical distribution is based on a climatology of aerosols, and ensures the modelled plumes are not unrealistically top-heavy. The vertical and horizontal distribution of the AOD is shown in Figure 2.1. It is important to note, realistic absorbing aerosol plumes can reach AODs upwards of 0.6 with SSAs of 0.8 and under (e.g. Sharma et al. 2017), with some places regularly reaching an AOD over 1 (e.g. Filonchyk et al. 2019; Kiely et al. 2019). Therefore, while the plume used here is far stronger than many aerosol plumes seen in the real world, plumes of this strength are seen in certain places (for example, Eastern China, South-East Africa, and Indonesia).

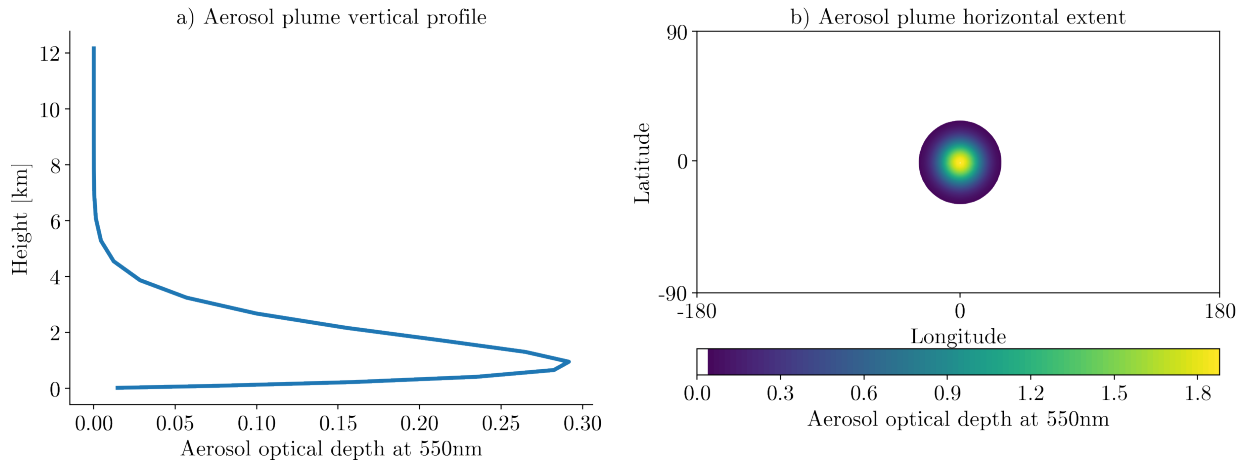


Figure 2.1. Aerosol plume, centred on latitude, longitude = (0,0), maximum aerosol optical depth (AOD)=1.8 and single scattering albedo=0.8, decreasing in a Gaussian way with a standard deviation of 10°. a) Vertical profile of aerosol optical depth (AOD) at the centre of the plume. b) Horizontal extent of the vertically integrated plume AOD, up to 3 standard deviations. This contains 99.7% of AOD.

2.2.4 Metric

Convective aggregation is associated with a moistening of the convective regions, and a drying surrounding them. This therefore causes a broadening of the moisture distribution and, in turn, an increase of the horizontal moisture variance. To compare the degree of aggregation between different simulations in this study we will therefore use the variance of the column-integrated relative humidity (σ_{CRH}^2) (Wing and Cronin 2016). In this thesis, CRH is defined as the density-weighted integral of relative humidity, integrated from the surface to the top of the troposphere. This removes the temperature dependence of the humidity and enables comparisons of the moisture between different simulations (Wing and Emanuel 2012). This metric does not have a threshold value to determine when a simulation has aggregated, it is instead used as a comparison tool to determine which atmospheres are more aggregated than others.

2.2.5 Frozen moist static energy budget

As introduced in the in Chapter 1, a useful framework for diagnosing aggregation mechanisms is the FMSE variance budget equation, defined in Wing and Emanuel (2014):

$$\frac{1}{2} \frac{\partial \hat{h}'^2}{\partial t} = \hat{h}' \text{SEF}' + \hat{h}' \text{NetLW}' + \hat{h}' \text{NetSW}' - \hat{h}' \text{Adv}' \quad (2.2)$$

Where SEF stands for surface enthalpy fluxes, which is the sum of the surface latent heat and sensible heat fluxes, NetSW and NetLW are the column shortwave and longwave radiative flux convergences respectively, and Adv is the horizontal divergence of $\hat{h}$. Each term on the right-hand side of the budget equation represents a covariance with a source or sink of FMSE. Therefore, a positive term represents a positive feedback of aggregation.

2.3 Unforced versus forced aggregation of convection

Here we analyse the model simulations 290K_NoHomog and 305K_NoHomog and compare them to 290K_Plume_NoHomog and 305K_Plume_NoHomog. Figure 2.2 shows the 5-day mean CRH after the five years of the simulations, after equilibrium is reached, for the two different SSTs, 290K and 305K. There are large differences between the amount of aggregation seen in the four simulations. 290K_NoHomog is the least aggregated, as we can see in Figure 2.2a: the moisture field is the most homogeneous of the simulations, implying the convection is scattered across the globe and there is an absence of large clusters. There is also a lack of large dry patches.

At the higher SST (Figure 2.2c), there is a more organised moisture field, with extremely wet

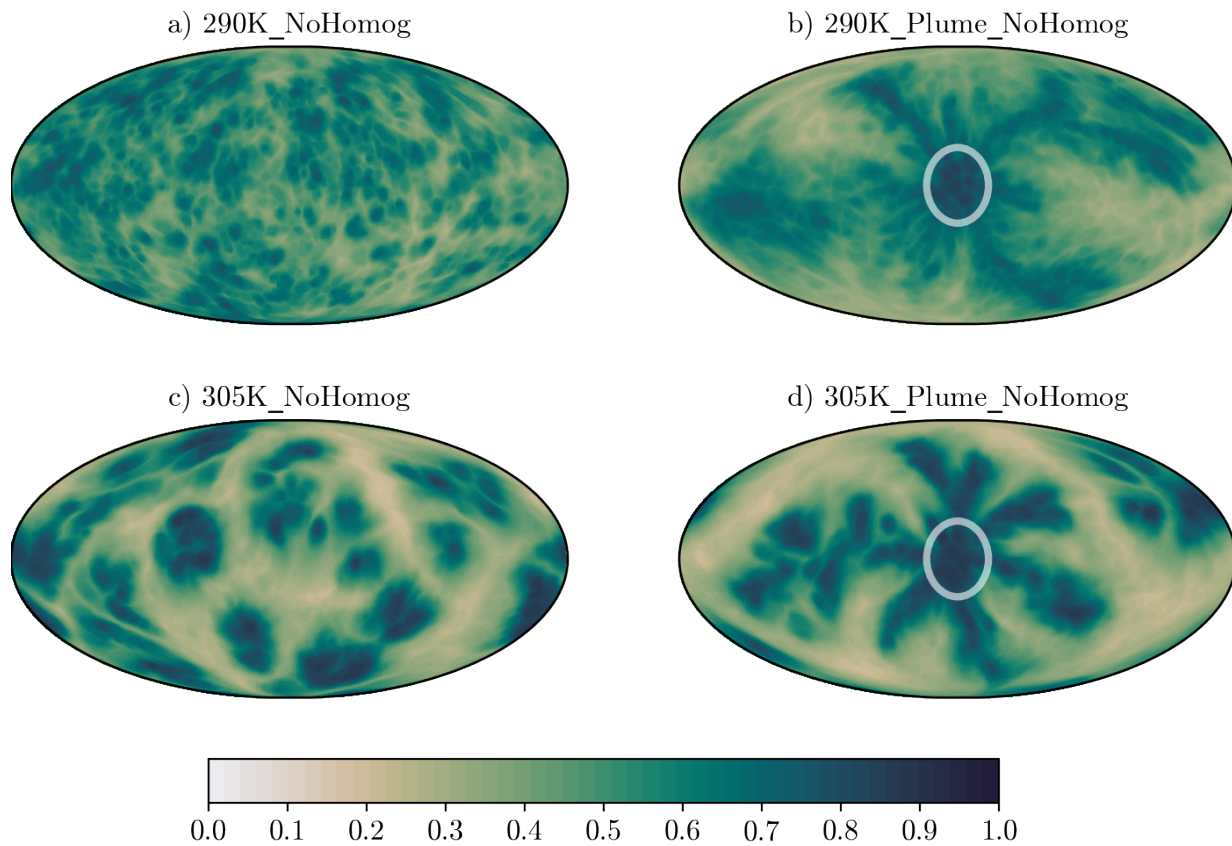


Figure 2.2. 5-day mean column relative humidity (CRH) after 5 years of ICON GCM RCE simulations. a) and c) are simulations without an aerosol plume. b) and d) are simulations with an aerosol plume with AOD=1.8 at the centre. White circle shows 20° radius around plume centre, containing 95% of AOD. a) – b) Sea surface temperature (SST)=290K, c)-d) SST=305K.

regions and contrastingly very dry regions. This shows that there are large clusters of deep convection across the globe and this simulation may be classified as aggregated. Through time these clusters are not stationary - the convective clusters do not stay in the same place, and they also grow and decay through time. In contrast to most small domain simulations (e.g. Bretherton et al. 2005; Wing and Emanuel 2014), the convection does not aggregate into a single large cluster, instead, there are multiple clusters throughout the domain in the aggregated case (Figure 2.2c). This is, however, consistent with other convective self-aggregation studies (e.g. Muller and Bony 2015; Yang 2019).

When the plume is used in the simulations at 290K and 305K, it causes a large moistening near to it, and the development of some dry patches away from it. This pattern is

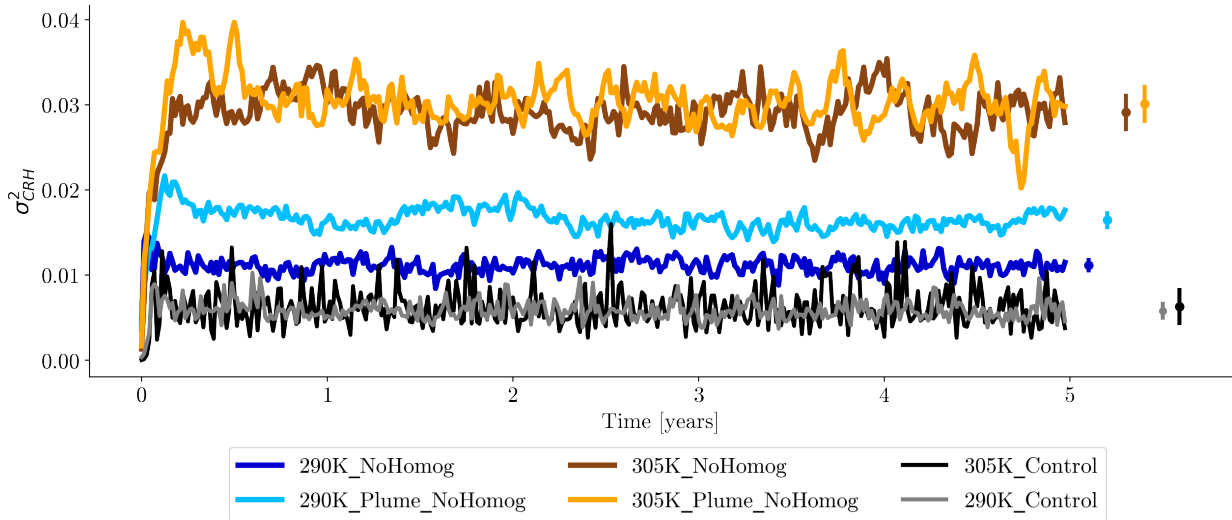


Figure 2.3. 5-day mean time evolution of variance of column relative humidity (CRH) for ICON GCM simulations in RCE. Black and grey lines show the control run at 305K and 290K SSTs, respectively. Controls are simulations run with horizontally homogenised longwave heating. Orange and brown lines for simulations at 305K SST with and without a plume, respectively. Light and dark blue lines for simulations at 290K SST with and without a plume, respectively. Circles show mean over the final 4 years of simulation, vertical bars represent one standard deviation of the 5-day mean σ_{CRH}^2 in time. The aerosol plume has AOD=1.8 at the centre.

analogous to the moisture signal convection aggregation causes. The plume forces convection to aggregate around itself. In Figure 2.2b we see the effect the plume has on the moisture field at an SST of 290K. Comparatively to the simulation 290K_NoHomog, we can see large areas of dry patches and a very moist region near the plume centre. Therefore, we qualitatively expect this simulation to have a larger degree of aggregation than the simulation without a plume. As shown in Figure 2.2d, using a plume at an SST of 305K converges convection towards it. However, here we do not see a visible difference in the horizontal moisture variance.

These findings are reinforced when looking at timeseries of our aggregation metric, σ_{CRH}^2 in Figure 2.3. All four simulations have an increased degree of aggregation, when compared to the non-aggregated control runs. The simulations at 305K with and without the plume are the most strongly aggregated, showing that adding the plume forcing to an already strongly aggregated simulation primarily causes a reorganising of the aggregated convection and does not force a significant change in the degree of aggregation. At an SST of 290K, we see

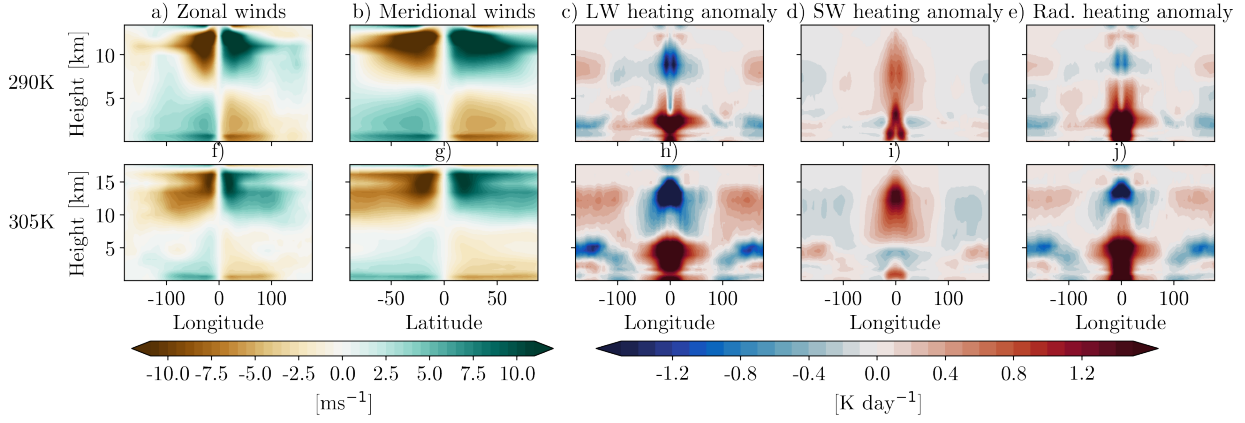


Figure 2.4. 4-year mean a) and f) Zonal winds, b) and g) Meridional winds, c) and h) longwave heating anomaly, d) and i) shortwave heating anomaly, e) and j) total radiative heating anomaly. Anomalies are taken from the global mean in each simulation. All figures show a slice at latitude=0°, except b) and g) which show a slice at longitude=0°. Top row is for simulations at 290K SST, bottom row is for simulations at 305K SST. All simulations are from ICON GCM model runs in RCE aerosol plume which has AOD=1.8 at the centre.

that, without the plume there is a small increase in the degree of aggregation comparatively to the control run, however the simulation is significantly less aggregated than that at 305K. When using a plume at 290K, we see that the addition of the plume has forced an increase in the degree of aggregation.

The plume model used for these simulations creates large shortwave heating anomalies, which have the ability to generate strong, thermally driven circulations (Dagan et al. 2019). This is the mechanism that is hypothesised to drive the increase in the degree of aggregation seen in these simulations. Figure 2.4 shows 4-year mean 3D zonal and meridional wind fields and the longwave, shortwave and total radiative heating horizontal anomalies for the two simulations with the plume. It is clear from Figure 2.4a, b, f, and g that the plume incites a truly global circulation. There is strong convergence near the surface and strong divergence in the upper atmosphere. This is driven by the radiative anomalies and the subsequent feedbacks caused by changes in clouds and water vapour including convecting heating anomalies. The plume itself incites the large shortwave heating anomalies we can see in Figure 2.4d and j. There are significant differences in the vertical profile of the shortwave heating caused by the plume. At 290K SST this heating is concentrated in

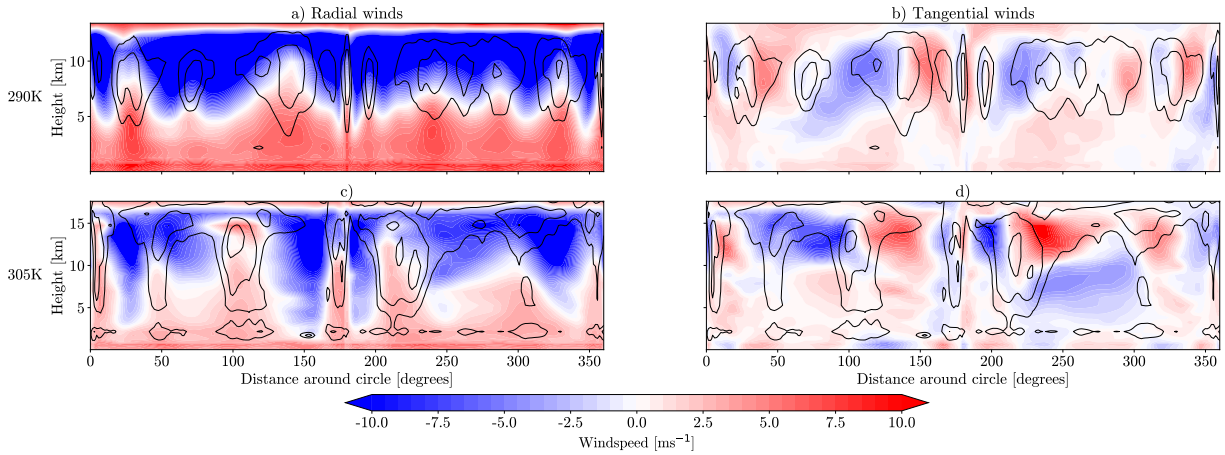


Figure 2.5. 5-day mean slices at day 720 of wind field taken at a radius of 40° around the plume centre. The radial (a and c) and tangential (b and d) fields have then been calculated. Cloud fraction contours are shown in black at (0.15, 0.4, 0.65). Positive radial winds are moving inwards, towards the plume. Positive tangential winds are moving clockwise around the plume. Top row is for simulations at 290K SST, bottom row is for simulations at 305K SST. All simulations are from ICON GCM model runs in RCE with an aerosol plume with AOD=1.8 at the centre.

the lower troposphere, while at 305K the heating is strongest in the upper troposphere.

There is also a clear signal in the longwave heating anomalies (Figure 2.4c and i). Here we see a strong negative anomaly in the upper troposphere close to the plume. This is due to the larger emissivity, increased flux divergence and relatively high temperatures near the top of the deep convective clouds formed around the plume. In the region of the plume, in the lower troposphere we see a strong longwave heating. This is due to the absorption and re-emission of longwave radiation from the bottom of the convective clouds, and the additional absorption from the high amounts of moisture in that area. In the 305K_Plume_NoHomog simulation, which is more aggregated than the 290K_Plume_NoHomog simulations, we can also see a strong negative anomaly in the longwave heating at 5 km height, around $\pm 100^\circ$ longitude. This is similar to the strong longwave cooling in the dry regions of the domain that has been shown to be vital to forming aggregation due to the boundary layer circulation it incites (e.g. Muller and Held 2012; Sessions et al. 2016).

Figure 2.5 shows slices of winds taken around a 40° radius circle, centred on the plume's maximum AOD (latitude, longitude= 0°). Radial and tangential wind contributions have then

been calculated for both 290K_Plume_NoHomog and 305K_Plume_NoHomog. In the radial wind fields (Figure 2.5a and c) the large-scale circulation can be seen. These radial winds show that there is generally convergence towards the plume centre near the surface and divergence in the upper troposphere away from the deep convection. This is consistent with the thermally-driven circulation that was shown by Dagan et al. (2019) and that can be seen in Figure 2.4. In the places where there is deep convection, the convergence extends higher into the atmospheric column, particularly prevalent in the simulation at 305K SST (Figure 2.5c). This implies the convection is being advected towards the plume at all heights. Hence, as convection pops up randomly some distance from the plume this will then converge towards the plume, and cluster together with the existing convection. This can sometimes cause aggregation to have radial branches extending out of the central cluster, for example, in Figure 2.2d. This aggregated spatial distribution can also be seen in other aggregation simulations in GCMs, such as Coppin and Bony (2015), Figure 1. The winds working tangentially to the plume also show a secondary circulation. This circulation has tangential surface convergence towards the radial convection branches and upper atmospheric divergence. This circulation helps to organise convection into lines connected to the central cluster around the plume, and helps to maintain areas of drier, clear sky in-between these lines.

2.3.1 Assessment of hysteresis

Many previous studies of convective self-aggregation have found the convective cluster to exhibit hysteresis - that is, once it has aggregated it will remain so even if the necessary feedbacks are removed (e.g. Khairoutdinov and Emanuel 2010; Muller and Held 2012). However, in the simulation 290K_Plume_NoHomog, the aggregation has been forced to occur through temperature perturbations creating thermally driven circulations. This aggregation is not necessarily maintained through the usual feedback interactions. To investigate whether the circulations driving this organisation are self-sustaining and therefore able to

maintain the aggregation when the plume is not there anymore, we ran simulations where the plume is removed after 5 years at both SSTs. We then compare the σ_{CRH}^2 at the end of these simulations, the simulations with no plume and the original 5-year simulations with the plume. We found that, after the plume has been removed, σ_{CRH}^2 drops back down to a value comparable to the simulation without a plume at an SST of 290K, and at both SSTs, the convection reverted to the geometrical patterns of the NoPlume simulations. Therefore, the aerosol plume does not generate convective aggregation that exhibits hysteresis, and the existence of the cluster is directly linked to the existence of the forcing.

2.3.2 Sensitivity to aerosol plume strength

A number of sensitivity experiments were performed to investigate the results' robustness for different aerosol radiative perturbations. A range of 7 different AODs were used, including the original AOD=1.8 and these were all compared with the experiment with no plume. The other AODs tested were 0.3, 0.4, 0.5, 0.6, 1, and 1.2. To generalise these results to different combinations of AOD and SSA (which remains fixed at 0.8 throughout this study), we discuss the plume 'strength' with respect to the aerosol absorption optical depth (AAOD), which is defined as

$$\text{AAOD} = \text{AOD} * (1 - \text{SSA}) \quad (2.1)$$

Therefore, the values of AAOD tested were 0.06, 0.08, 0.1, 0.12, 0.2, 0.24, and 0.36.

As AAOD is increased, the degree of aggregation also generally increases, except between AAOD = 0.24 and 0.36, at which point the AAOD remains steady (Figure 2.6). The three simulations with the weakest forcings (AAOD=0, 0.06, 0.08) do not show much difference in their σ_{CRH}^2 . When the AAOD is increased to 0.12 or greater there are significant increases in σ_{CRH}^2 and therefore, increases in the degree of aggregation. The simulations with an aerosol

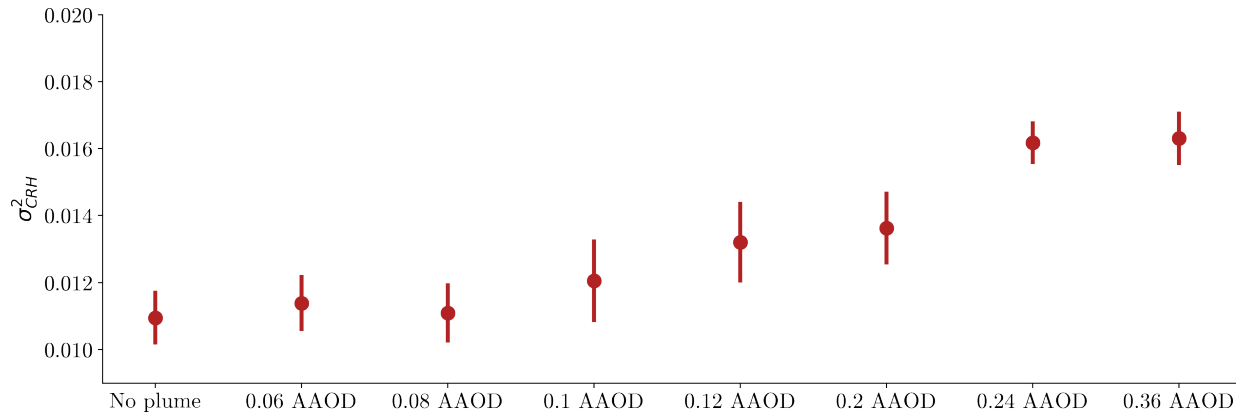


Figure 2.6. 4-year mean variance of column relative humidity (CRH) for simulations run at 290K. Vertical lines show one standard deviation around the means. All simulations are from ICON GCM model runs in RCE with an aerosol plume (except for No plume), centred on latitude, longitude = (0,0), and single scattering albedo=0.8. Simulation plume maximum absorption aerosol optical depth (AAOD) at centre increases from 0.06 to 0.36 along the x-axis.

plume AAOD of 0.24 and 0.36 show the strongest response, with the simulations with an AAOD of 0.12, and 0.2 also showing an increase in σ_{CRH}^2 compared with the simulation without an aerosol plume. From this, we note that, for the aerosol plume to have an impact on the aggregation convection at an SST of 290K, there must be an AAOD of at least 0.12. Pollution plumes seen in the real-world can have AAODs of 0.12 or greater during high pollution events, such as during biomass burning events (e.g. Sharma et al. 2017), or dust events (e.g. Filonchyk et al. 2020), and so we hypothesise that these aerosol plumes could have a local impact on convective organisation.

2.4 Physical mechanisms behind forced aggregation

2.4.1 Frozen moist static energy budget

In this section, we investigate, using the frozen moist static energy (FMSE) budget described in Section 2.2.5 (Wing and Emanuel 2014), the physical mechanisms driving the aggregation of convection in our simulations. In particular, we are interested in how the relative contributions from the shortwave feedbacks differ when using the plume to force aggregation.

Figure 2.7 compares the relative contributions of the $\hat{h}\text{NetLW}'$, $\hat{h}\text{NetSW}'$, $\hat{h}\text{SEF}'$, and $\hat{h}\text{Adv}'$, feedbacks to the overall growth rate of the FMSE variance, from equation 2.2 for the simulations at 290K and 305K SSTs, both with and without the plume. Hereafter, these feedbacks are referred to as the longwave, shortwave, surface enthalpy, and advective feedbacks, respectively. It is clear that in each simulation the strongest, positive relative contribution comes from the longwave feedbacks once the simulations have reached equilibrium. This follows previous studies, such as Coppin and Bony (2015) and Arnold and Putman (2018). In the three, more aggregated, simulations (290K_Plume_NoHomog, 305K_Plume_NoHomog, and 305K_NoHomog) the contribution from the longwave feedbacks decreases after the initial aggregating period, but still remains the strongest relative feedback. When the contribution is split into the contribution from the wettest 5% and driest 5% of columns (Figure 2.8) we can see this strong longwave feedback is primarily working in the wettest regions of the domain. These wet regions correlate with the cloudiest regions in the domain. However, it is important to note that these co-variances will be affected by the domain-mean itself. In the aggregating stage of the simulations, the relative contribution from the longwave feedback also dominates for all simulations except in 305K_Plume_NoHomog (Figure 2.7d).

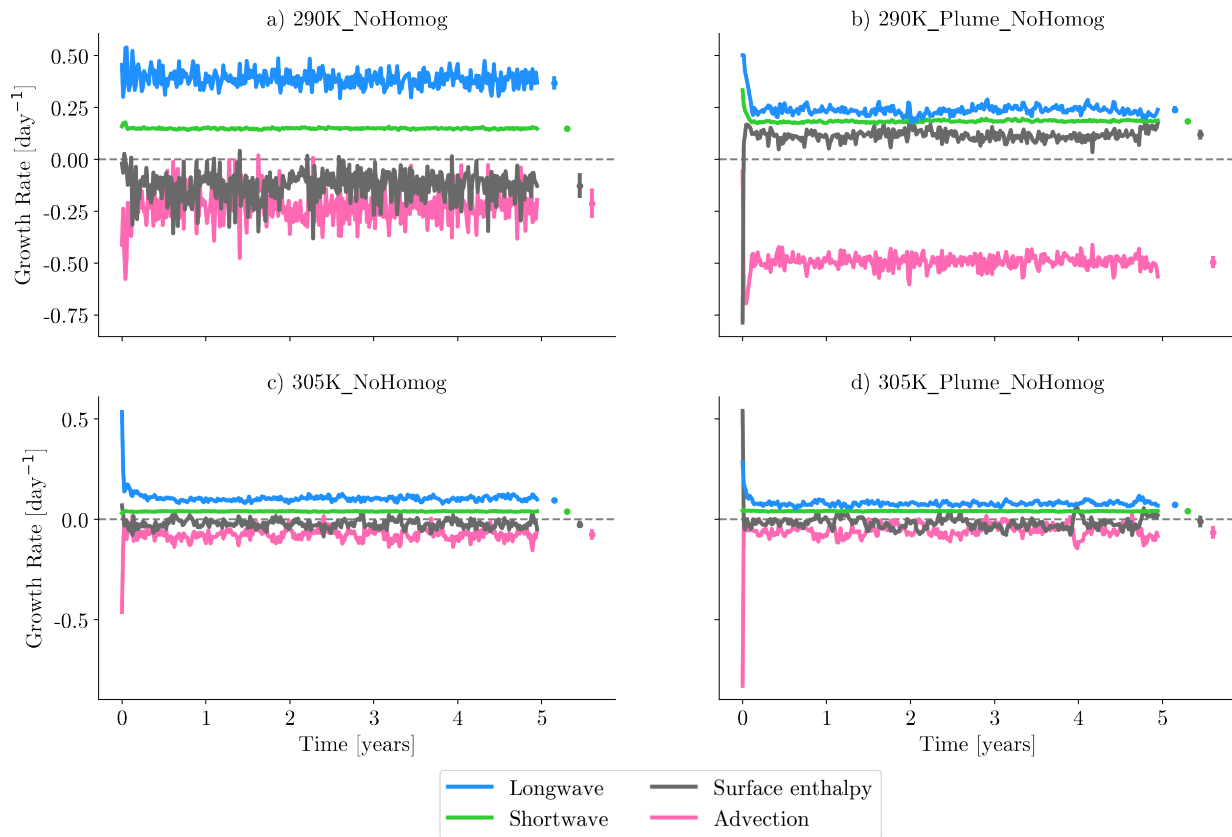


Figure 2.7. 5-day mean time evolution of domain mean feedback growth rates in the frozen moist static energy budget (FMSE). a) and c) simulations at sea surface temperature (SST) of 290K, b) and d) SST at 305K. Circles show final 4-years mean, with vertical line showing one standard deviation of the 5-day mean feedback growth rates in time. All simulations are from ICON GCM model runs in RCE. b) and d) are run with an aerosol plume with AOD=1.8 at the centre. Grey dotted line highlights $y=0$.

The relative contribution from the shortwave feedbacks is strongest in the 290K_Plume_NoHomog simulation (Figure 2.7b). Here, there is an almost equal contribution from the longwave and shortwave feedbacks. This increase comes from the inclusion of the plume, driving a large positive perturbation in the shortwave convergence. Interestingly we do not see the same dominance from the shortwave feedbacks in the 305K_Plume_NoHomog simulation (Figure 2.7d). A theory for this is given in the SHORTWAVE FEEDBACKS section below. The driver of this increase in the shortwave contribution comes mainly from the wettest columns of the domain, with the contributions in the driest columns remaining mostly equal to those in the 290K_NoHomog simulation.

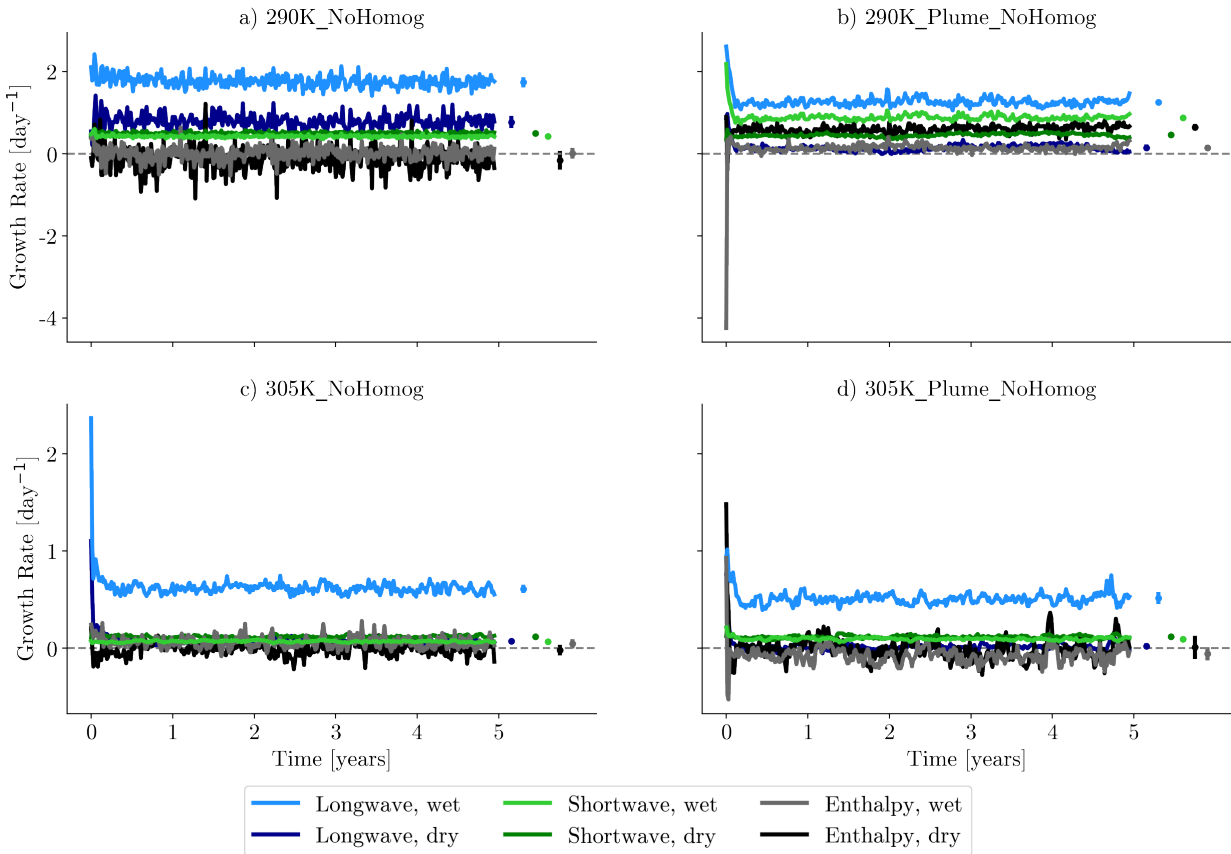


Figure 2.8. 5-day mean time evolution of mean feedback growth rates in the frozen moist static energy budget (FMSE) in the wettest 5% of columns (lighter lines) and driest 5% of columns (darker lines). a) and c) simulations at sea surface temperature (SST) of 290K, b) and d) SST at 305K. Circles show final 4-years mean, with vertical line showing one standard deviation of the 5-day mean feedback growth rates in time. All simulations are from ICON GCM model runs in RCE. b) and d) are run with an aerosol plume with AOD=1.8 at the centre. Grey dotted line highlights $y=0$.

At an SST of 305K, the contribution from the surface enthalpy fluxes is close to zero, however, at 290K we see a negative contribution in the simulation without a plume, and a positive contribution in the simulation with a plume. The sign of the enthalpy feedback is driven by the feedbacks in the driest columns in both these simulations, in particular this is driven mostly by the latent heat fluxes in these dry columns. We hypothesise that the strongly positive feedback in the simulation with the plume is due to decreased windspeeds in the driest columns furthest away from the plume. This is the positive WISHE mechanism described in Coppin and Bony (2015). For the remainder of this chapter, we will focus on the radiative feedbacks due to the direct interactions between the plume and radiative feedbacks.

LONGWAVE FEEDBACKS

The key positive feedback behind the longwave mechanism in these simulations is the reduced column longwave radiative cooling in the moist, convecting region close to the plume. This acts as a source of FMSE, and thus constitutes a positive feedback. This feedback is the same as the longwave maintenance feedback described in Wing and Emanuel (2014).

SHORTWAVE FEEDBACKS

The small, but positive, shortwave feedbacks in the plume-free runs are simple to understand: as water vapour is an absorber in the shortwave, wet columns will have higher absorption than the drier columns. This correlates well with the anomalies of $\hat{h}$, and so we see a positive shortwave feedback, both in the global mean, and at each grid cell in the domain (not shown). The increased contributions from the shortwave feedbacks in the wettest columns in 290K_Plume_NoHomog arise from the direct shortwave absorption associated with the plume. This strong shortwave perturbation, also seen in Figure 2.4d, is the driving influence of the increased degree in aggregation for this simulation. As stated before, we do not see the same increase in the shortwave contribution in 305K_Plume_NoHomog. This is likely due to the fact that, at this SST, the longwave feedbacks are sufficient to drive aggregation, as proven by the highly aggregated simulation at 305K SST without the plume. Therefore, the introduction of the shortwave perturbation at this SST drives a thermally driven circulation, which influences the shape in which convection aggregates, but is not required for the aggregation itself.

2.4.2 Mechanism denial tests

To further investigate the role longwave and shortwave feedbacks play with and without the plume in our simulations, we ran a suite of experiments where the longwave and short-

wave fluxes were homogenised in turn at each timestep, and at each model layer, following Muller and Held (2012). Shamekh et al. (2020a) found that when they forced convection to aggregate, using an SST hotspot, this induced enough convective instability on its own, that aggregation occurred in the absence of the usually necessary longwave feedbacks. Here, we are particularly interested in whether our convection can also be forced to aggregate in the absence of the longwave feedbacks.

UNFORCED SIMULATIONS

Figure 2.9 compares the CRH at the end of each 5-year simulation across this suite of experiments. Firstly, focussing on the simulations without a plume, we can see that homogenising the longwave fluxes removes all aggregation, leaving a mostly homogeneous moisture field (Figure 2.9b and h). This is expected, given the longwave feedbacks dominate in all simulations, discussed in the previous section. This is also in line with previous studies, such as Muller and Held (2012), Yang (2018a), Beucler and Cronin (2019) and others. To further prove that the removal of interactive longwave fluxes removes aggregation we can compare the timeseries of our metric, σ_{CRH}^2 , for runs with fully interactive fluxes and homogenised longwave fluxes. It is clear, from Figure 2.10, that the removal of interactive longwave fluxes significantly reduces the degree of aggregation at both 290K and 305K SST.

When shortwave fluxes are homogenised, there is little visible difference in how aggregated the moisture field is. Indeed, when the degree of aggregation is compared in Figure 2.10, we can see that, at both 290K and 305K SST there are no significant changes in σ_{CRH}^2 .

FORCED SIMULATIONS

When shortwave fluxes are homogenised with the plume in the simulations, the moisture distribution returns to roughly how it was arranged with no plume. This makes intuitive sense, as our plume model works by perturbing the shortwave absorption. When these perturbations are then homogenised across the domain, we will no longer see spatial evidence

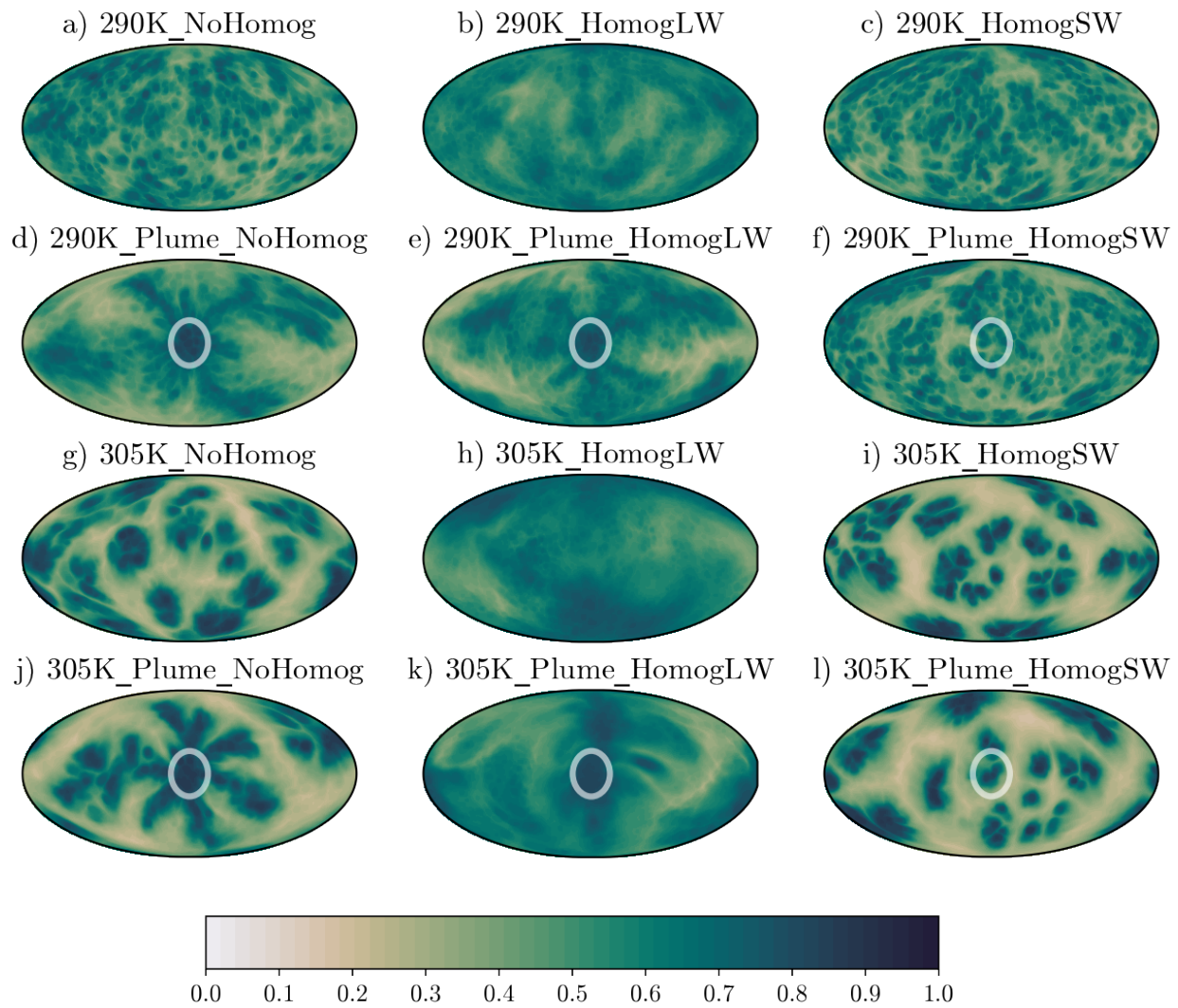


Figure 2.9. 5-day mean column relative humidity (CRH) after 5 years of ICON GCM RCE simulations. a)-c) and g)-i) are simulations without an aerosol plume. b)-d) and j)-l) are simulations with an aerosol plume, centred inside the white circle, maximum aerosol optical depth (AOD)=1.8 (except e) which has AOD=1, and k) which has AOD=0.8) and single scattering albedo=0.8, decreasing in a Gaussian way with a standard deviation of 10° . White circle shows 20° radius around plume centre, containing 95% of AOD. a)-f) Sea surface temperature (SST)=290K, g)-l) SST=305K. First column shows experiments with fully interactive radiative heating, second column shows experiments with longwave heating rates horizontally homogenised at each model level, third column shows experiments with shortwave heating rates horizontally homogenised at each model level. All homogenising is done at every timestep, except for e) 290K_plume_homogLW and k) 305K_plume_homogLW, where homogenising is done for 3 out of every 4 timesteps.

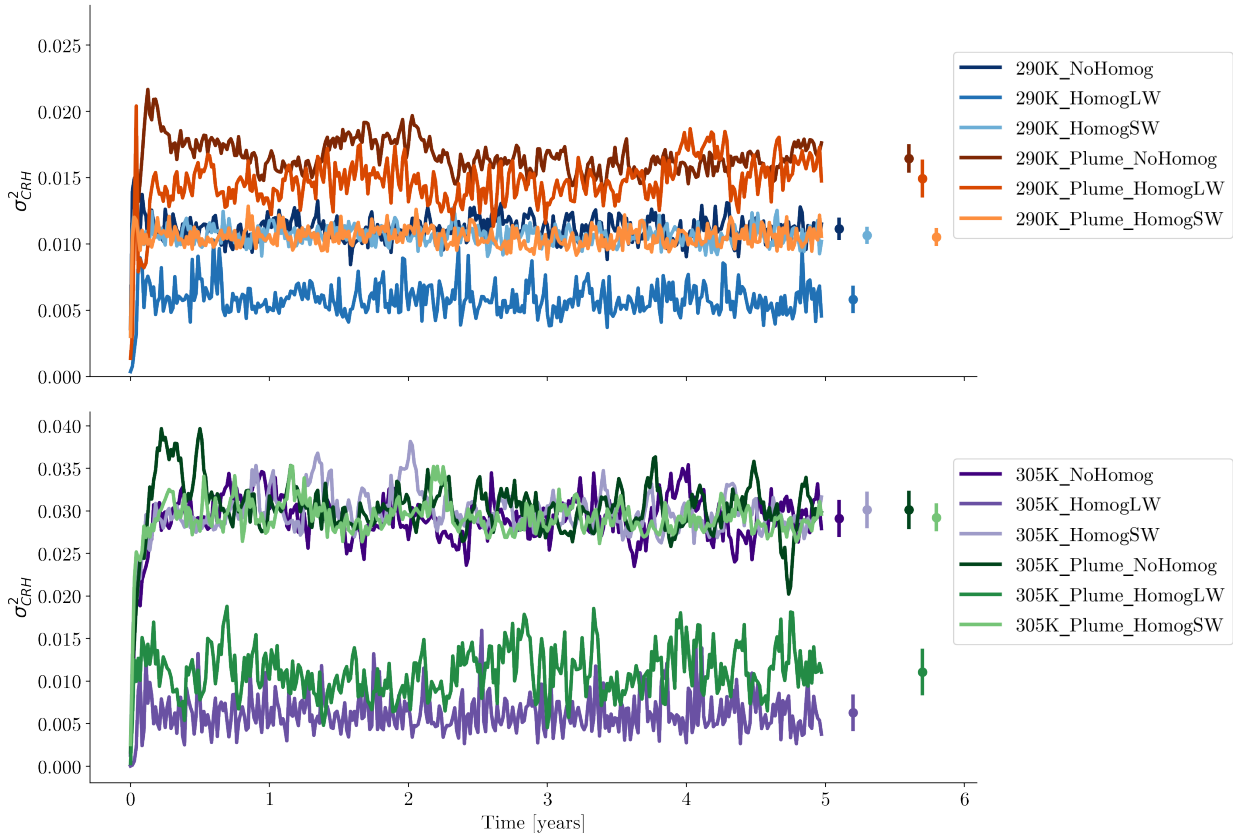


Figure 2.10. 5-day mean time evolution of variance of column relative humidity (CRH) for ICON GCM simulations in RCE. Top/bottom panel shows simulations at SST=290K/305K. Blue and purple lines show simulations with no plume, orange and green lines show simulations with aerosol plume. Darkest line in each colour shows simulation with fully interactive radiation, second darkest line shows simulations with homogenised longwave fluxes, lightest lines show simulations with homogenised shortwave fluxes. Circles show mean over the final 4 years of simulation, vertical bars represent one standard deviation of the 5-day mean σ_{CRH}^2 in time. Aerosol plume has AOD=1.8 at the centre. All homogenising is done at every timestep, except for e) 290K_plume_homogLW and k) 305K_plume_homogLW, where homogenising is done for 3 out of every 4 timesteps.

of the plume. We can see this in Figure 2.9f and l. Similarly, the degree of aggregation in these runs is equal to the equivalent runs without a plume, (Figure 2.10).

The key remaining question, is whether the shortwave perturbations induced by the plume generate a powerful enough circulation to force convection to aggregate without interactive longwave fluxes. From the evidence provided in Section 2.4.1, one might expect that we see a different response to homogenising longwave fluxes at 290K and 305K, due to the smaller shortwave contribution at 305K. First, by visual inspection of the horizontal moisture maps in Figure 2.9e and k this appears to be the case. In 305K_Plume_HomogLW (Figure 2.9k)

we can see only a small amount of evidence of the plume. Here, the homogenisation of the longwave fluxes has prevented most of the aggregation. This is further supported in Figure 2.10, where the degree of aggregation in 305K_Plume_HomogLW is far lower than that in 305K_NoHomog, and only slightly higher than the degree of aggregation in 305K_HomogLW, our original control case. In the 290K_Plume_HomogLW experiment, there is significantly more visual evidence of the plume aggregating convection in Figure 2.9e. Inspection of our metric timeseries in Figure 2.10 shows that, 290K_Plume_HomogLW has a higher degree of aggregation comparatively to 290K_NoHomog. This supports results from Shamekh et al. (2020a), who also found that they could force convection to aggregate using SST hotspots even with homogenised radiative heating. However, we still see a slight decrease in the degree of aggregation when the longwave fluxes are homogenised compared to 290K_Plume_NoHomog. This implies that, whilst not always a necessary feedback, the longwave feedbacks systematically aid the aggregation of convection with the plume and that the shortwave heating induced by the plume is not the only driver of the thermally driven circulation. The strong lower tropospheric warming in the longwave caused by the aggregation of moisture and convection around the plume is also important for maintaining the circulation.

To fully understand why the shortwave feedbacks are more effective at aggregating the convection at 290K SST with the plume (compared to 305K SST) we investigate the differences in the absolute magnitude of the circulation and radiative heating perturbations induced by the plume when longwave fluxes are homogenised (Figure 2.11). At both SSTs there is an increase in the shortwave heating perturbation near the surface when longwave fluxes are homogenised, most likely due to a reduced cloud shielding effect. The magnitude of this shortwave anomaly is greater at 290K SST than at 305K. This leads to a weaker reduction in the thermally-driven circulation at 290K. This means that, even with homogenised longwave feedbacks causing a large reduction in lower tropospheric longwave heating near to the plume, the thermally-driven circulation is being controlled mainly by the shortwave

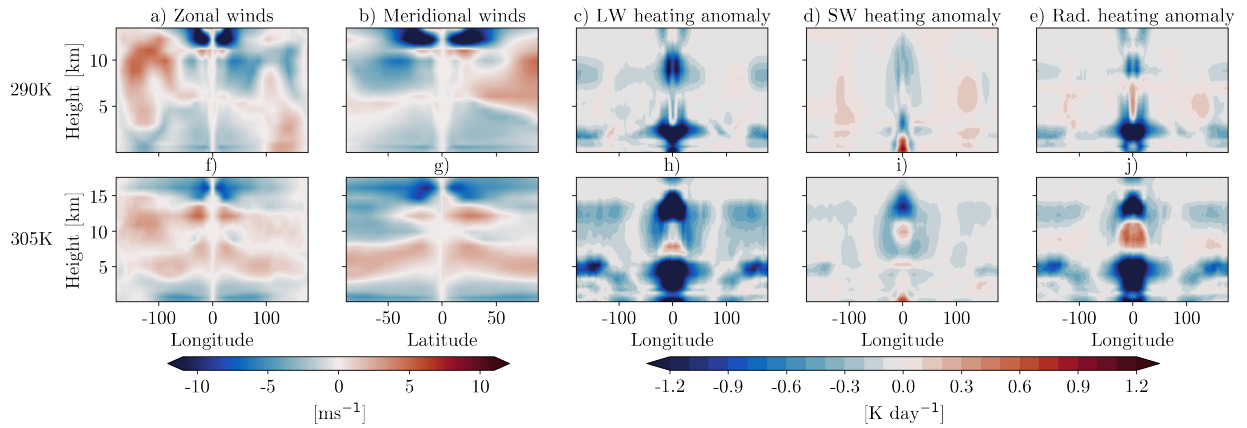


Figure 2.11. 4-year mean difference between the absolute magnitude of a) and g) Zonal winds, b) and h) Meridional winds, c) and i) longwave heating anomaly, d) and j) shortwave heating anomaly, e) and k) total radiative heating anomaly for simulations with horizontally homogenised longwave radiation minus fully interactive radiation (e.g. HomogLW - NoHomog). All figures show a slice at latitude=0, except b) and h) which show a slice at longitude=0. Top row is for simulations at 290K SST, bottom row is for simulations at 305K SST. All simulations are from ICON GCM model runs in RCE with an aerosol plume, centred on latitude, longitude = (0,0), and single scattering albedo=0.8. NoHomog simulations both have maximum aerosol optical depth (AOD) of 1.8 at the plume centre, HomogLW at 290K has maximum AOD=1, HomogLW at 305K has maximum AOD=0.8.

feedbacks at 290K SST. Also, there is some evidence in the literature that shortwave feedbacks tend to become more important at lower SSTs (e.g. Holloway and Woolnough 2016; Wing and Cronin 2016; Pope et al. 2021). The lower tropospheric shortwave heating in 290K_Plume_HomogLW, is therefore managing to drive some aggregation and so is responsible for the increase in the degree of aggregation between 290K_NoHomog and 290K_Plume_HomogLW in Figure 2.10. At the higher SST, 305K, there is some surface shortwave heating near to the plume in Figure 2.11j, however, this is extremely weak. We hypothesise that this is the reason for the increase in the degree of aggregation between the 305K control run and 305K_Plume_HomogLW being smaller than the increase between the 290K control run and 290K_Plume_HomogLW (Figure 2.10). These results are in line with the FMSE variance budget analysis in Section 2.4.1, which showed a stronger contribution from the shortwave feedbacks at the lower SST between the two simulations with the plume.

2.5 Conclusions and implications

Convective self-aggregation has been shown to occur in many different modelling setups, including in general circulation models (GCMs) with a convective parameterisation scheme. Work thus far has focused on spontaneously occurring self-aggregation. In this chapter we focus on convective aggregation in the presence of an external source of diabatic heating, representative of aerosol radiative perturbations. This plume induces a thermally-driven circulation. We were particularly interested in how the forcing affected the ability of a simulation to aggregate, and whether the mechanisms behind this forced aggregation differ from those causing a spontaneous self-aggregation.

The radiative perturbation caused by the aerosol plume forces an increase in the degree of aggregation through the generation of a large-scale circulation. This circulation is driven by strong shortwave warming due to the aerosol absorption, and enhanced by strong lower tropospheric longwave warming from the aggregation of moisture. The aggregation that is forced by this radiative plume is a superposition of two circulations. One circulation has radial convergence towards the plume in the lower atmosphere and radial divergence in the upper atmosphere. The second circulation works tangentially to the plume again with lower-level convergence and upper-level divergence, shaping the lines of convection connected radially to the central cluster formed around the plume.

The forced aggregation shown in this chapter is dependent on the aerosol plume. When the plume was removed, the convection immediately disaggregates. Therefore, in contrast to previous studies (e.g. Khairoutdinov and Emanuel 2010; Muller and Held 2012), forced aggregation does not exhibit hysteresis and is entirely dependent on the plume forcing's existence in this chapter.

Longwave feedbacks are found to be essential for forming convective self-aggregation, in

line with many previous studies (e.g. Muller and Held 2012; Wing and Emanuel 2014; Arnold and Putman 2018) at both SSTs, however, at lower SSTs, in the presence of a strong short-wave radiative heating perturbation convection can be forced to aggregate in the absence of longwave feedbacks. In addition, the contribution from surface enthalpy flux feedbacks varies at different SSTs, with a stronger contribution at lower SSTs. This is in contrast to the results from (Coppin and Bony 2015), who found the importance of surface fluxes was greater at higher SSTs. However, in these simulations, the greater importance of the surface flux feedback is directly related to the inclusion of the aerosol plume forcing. Due to the circulation induced by the plume, the WISHE feedback plays a larger role in driving the aggregation at the lower SST. When comparing the mechanisms behind unforced and forced aggregation, we find that shortwave feedbacks play a larger role in forming the aggregation at 290K SST with the plume than any other simulation. This is confirmed through mechanism denial experiments with horizontally homogenised longwave radiative heating, where convection is able to aggregate through the induced circulation, driven by short-wave heating anomalies. Therefore, we have shown that, even when aggregation is forced to organise together through a diabatic heating perturbation, the self-generated feedbacks between clouds, moisture, and longwave radiative fluxes are necessary for maintaining the high degree of aggregation. This also appears to be more relevant at higher SSTs.

We have shown that an aerosol absorption optical depth (AAOD) of 0.12 or greater is required to force simulations to aggregate at an SST of 290K, and the maximum degree of aggregation is reached at an AAOD of roughly 0.24. There are many examples of aerosol plumes with AAODs greater than 0.12 in the real world such as pollution, dust events, and biomass burning events (e.g. Eck et al. 2003; Vadrevu et al. 2015; Sharma et al. 2017; Filonchyk et al. 2020). Therefore, these events could be an important real-world analogue for convective aggregation. However, the real atmosphere contains far more complexity than is included in the model used here. Features of this complexity, such as planetary rotation, land, and an interactive sea surface, can hugely affect the lifetime and size-spectrum

of convection. Therefore, we can hypothesise that these dust and pollution events may have an effect on locally organising convection, but more work is needed to deduce how this may be manifested and what feedbacks are working in the real atmosphere.

3 | Aggregation in the presence of an island

Basically, I have been compelled by curiosity.

MARY LEAKEY

The analysis in the previous chapter showed that we can increase the degree of aggregation in a simulation by artificially forcing a large-scale thermally-driven circulation, as well as highlighting that self-aggregation feedbacks remain important, even when aggregation is forced to cluster together. We linked the results of this chapter to possible interactions between absorbing aerosols, such as those from biomass burning, and organised convection in the real world. The thermal forcing we used for those simulations was atmospheric, over a homogeneous surface. This homogeneous surface is another simplification used in idealised RCE models studying aggregation. The remaining chapters move on to investigate how inhomogeneous surfaces can impact aggregation. In this chapter, we include a land-surface to study how land might interact with aggregated convection and its associated large-scale circulation.

This chapter is based on an article published in *Journal of Advances in Modeling Earth Systems*:

Dingley, B., Dagan, G., Stier, P., and Herbert, R. (2023). The impact of a land-sea contrast on convective aggregation in radiative-convective equilibrium. *Journal of Advances in Modeling Earth Systems*, 15, e2022MS003249. <https://doi.org/10.1029/2022MS003249>

I designed the study together with the co-authors. I carried out the simulations and analyses presented, with input from the co-authors. I wrote the manuscript, and underwent the peer-review process, with contributions and approval from the co-authors.

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 often 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 idealised models are in the real atmosphere. We approach this question by adding a 'continentally-sized', idealised 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 necessary 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 $\mathcal{O}(10,000 \text{ km})$. These results highlight that the mechanisms of idealised aggregation remain relevant when land is included in the model, and therefore

these mechanisms could help us understand convective organisation in the real-world.

3.1 Introduction

Idealised climate models are a useful tool for studying moist convection in the tropical climate. In these models rotation, land, the diurnal cycle, and sea surface temperature (SST) gradients are often removed. In this simplified configuration, any imbalances caused by radiative cooling is balanced by convective heating. This balance is known as radiative-convective equilibrium (RCE) (Manabe and 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 of the tropical atmosphere (e.g. Manabe and Wetherald 1967; Held et al. 1993; Tompkins and Craig 1998; Robe and Emanuel 2001; Stephens et al. 2008; Khairoutdinov and Emanuel 2013; Wing et al. 2020).

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 organisation of convection, such as SST gradients (Müller and Hohenegger 2020; Shamekh et al. 2020a; Tompkins and Semie 2021) and land-sea contrasts (Sato et al. 2009; Cronin et al. 2015; Leutwyler and Hohenegger 2021). There is 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 and Randall 2015; Davis 2015; Wing et al. 2016; Khairoutdinov and Emanuel 2018; Muller and Romps 2018), and the diabatic

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

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

Previous investigations of islands in an RCE model have shown that convection and precipitation tend to favour land (Cronin et al. 2015; Wang and Sobel 2017; Coppin and Bellon 2019a; Leutwyler and Hohenegger 2021). Land has also been found to have an impact on the domain-mean tropospheric temperature in an RCE simulation. Cronin et al. (2015) found that the presence of an island increased the tropospheric temperature comparatively to an all-ocean simulation, and this warming increased monotonically with island size. They postulate that this is due to the clouds forming at the warmest and moistest areas (which are over the island), pushing deep convection towards a moister adiabat. Contrastingly, Leutwyler and Hohenegger (2021) found that the presence of islands has a tendency to cool the troposphere, with larger islands having a larger cooling effect. Hohenegger and Stevens (2018) discussed two pathways with which land, and the associated surface fluxes could influence the generation of circulations. The first was that moist soil favours convection (Findell and Eltahir 2003; Gentine et al. 2013), creating a positive feedback where enhanced precipitation maintains soil moisture. The second pathway was that, if a soil-moisture gradient can form, sensible heat gradients will also form, generating an opposing low-level circulation from moist to dry regions which can act to destabilise the convection. In their work over a land-only planet, Hohenegger and Stevens (2018) found the latter pathway dominated, preventing the persistent aggregation of convection. Leutwyler and Hohenegger (2021) also attributed the ability of tropical islands to cool the troposphere in their simulations to the same mechanism and identified that this was the key difference between their work and the work of Cronin et al. (2015), where land was simply modelled as a patch of ocean with a heat capacity anomaly. Thus it seems likely that the results of Leutwyler and Hohenegger (2021) are more realistic. This also links to known soil-moisture versus radiation-limited flux mechanisms - soil moisture-limited regimes are those where the main control on evapotranspiration is the soil moisture, whereas radiation-limited regimes are those when evaporative fraction is independent of soil moisture content (Seneviratne et al. 2010). Thus, with the more simplified set-up of Cronin et al. (2015), they are likely always

in an energy-limited regime, whilst in the work of Hohenegger and Stevens (2018) and Leutwyler and Hohenegger (2021), soil moisture is providing a first-order control on evapotranspiration, and therefore surface fluxes will have a greater impact on the circulations.

The Tropical Rain belts with an Annual cycle and a Continent Model Intercomparison Project (TRACMIP; Voigt et al. 2016) devised another idealised modelling framework in order to investigate clouds, circulation and precipitation. In their project, simulations with a zonally-symmetric, meridional SST gradient were performed which included a slab ocean and an idealised land continent along with both a seasonal and diurnal cycle in insolation. They find that adding a land continent led to a domain-mean cooling of 0.1 - 1.8 K. In particular, Biasutti et al. (2021) found that the initial energy perturbation to the land surface leads to a significant warming of the continent, despite the land's relatively higher albedo, whilst in equilibrium the land warms a little at the equator, but the continent is mostly cooler than the surrounding ocean surface. The authors hypothesise that the local feedbacks between clouds and radiation are likely important at maintaining these surface temperature anomalies due to low atmospheric humidity, and that albedo only has a minor impact.

Previous studies of islands in an RCE simulation have focused mainly on the effect the land-sea contrast has on the diurnal cycle of convection, precipitation and temperature profile more than the mechanisms behind any organisation 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 large island (between the size of Africa and South America) on aggregation. In this chapter we aim to answer the following questions:

1. How does the inclusion of an idealised 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?

3.2 Methods

3.2.1 Model set-up

In all simulations, we employ the ICOSahedral Nonhydrostatic (ICON) Atmospheric GCM (Zängl et al. 2015; Giorgetta et al. 2018), version 1.8. The same model parameterisation schemes as in Chapter 2 are used, along with the same model grid.

The JSBACH4 land model (Jungclaus et al. 2022) is a dynamic global vegetation model and offers a full representation of soil-vegetation-atmosphere interactions. The surface energy budget and soil thermal layers over land are implicitly coupled to ICON through the vertical diffusion scheme. There are four soil layers which descend to roughly 4.5 m depth; heat and water dynamics are defined on these soil levels.

Each grid cell over land is divided into two sections: a "tiled" fraction, and the fraction of the non-ice covered grid-cell that is inhospitable to vegetation (for example, rocky terrain or sandy desert). The tiled fraction of the grid box is then further separated into different surface types to represent sub-grid scale heterogeneity: a glacier, or one of 11 plant functional types (Reick et al. 2013).

3.2.2 Experimental set-up

The atmospheric experimental set up in this chapter matches the configuration in Chapter 2. However, we now only use the higher SST of 305K. In these simulations we use a model time step of 15 minutes, with radiation calculated every 90 minutes. We also tested a radiation time steps of 30, 45, and 60 minutes and the results were qualitatively similar. The simulations described in this chapter were run for two years.

Land in our simulations is represented by a large, circular island, located at latitude = 0° longitude = 0° with a radius of 40° (giving the land an area of $35.7 \times 10^6 \text{ km}^2$). All land grid cells are completely covered by vegetation, with no glaciers. Surface properties have been set to average tropical rainforest-like values, with tropical broadleaf evergreen vegetation covering the island, to mimic tropical warm conditions. Rainforest surface properties are taken from the JSBACH4 initialisation 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 3.1. Soil temperature is the only property not set using Amazon rainforest equivalent values. Soil temperature is initialised as equal to the SST at all model levels, following Leutwyler and 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. Another sensitivity test was performed for the vegetation type. For this test we changed from rainforest land parameters, to grass parameters (see Table 3.1). The results of this test were again, quantitatively similar to the rainforest experiment, and can be found in Section 3.3.1.1. The island has an elevation of 0 m everywhere, to remove effects on convection and its organisation from topography.

<i>Parameter Name</i>	<i>Rainforest</i>	<i>Grass</i>
Soil type	Mixture of loam and clay (FAO flag 4)	Loam (FAO flag 3)
Plant functional type	4	7
Thermal diffusivity	$7.1 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$	$7.4 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$
Leaf area index	8.928	2
Root depth	1.351 m	1 m
Vegetation albedo	0.122	0.3
Roughness length	1.871 m	0.05 m
Soil depth (to bedrock)	2.194 m	3 m
Heat capacity	$2.36 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$	$2.25 \times 10^6 \text{ J m}^{-3} \text{ K}^{-1}$
Heat conductivity	$1.68 \text{ W m}^{-1} \text{ K}^{-1}$	$1.67 \text{ W m}^{-1} \text{ K}^{-1}$
Soil porosity	0.456 m m^{-1}	0.459 m m^{-1}

Table 3.1. Surface properties used to initialise the JSBACH4 land model within the ICON GCM for the rainforest and grass experiments.

To test the impact of the radiative feedbacks on aggregation, we perform mechanism denial tests, where the longwave or shortwave heating rates are horizontally homogenised in turn, at each model level and each time-step. These experiments will hereafter be referred to as Land-HomogLW and Land-HomogSW respectively. Surface fluxes remain interactive for all simulations.

Finally, in order to contextualise our results with existing self-aggregation studies, we will compare our simulations to both an aggregated and a non-aggregated RCE simulation without land. In Chapter 2 we showed that, at an SST of 305K aquaplanet ICON GCM RCE simulations (that are otherwise identical to the above Land-NoHomog) strongly self-aggregate with interactive radiative fluxes, and do not aggregate with homogenised longwave radiative heating (see Figure 2.9g and h respectively). Thus, these are the simulations we will use to compare our results to (hereafter NoLand-Aggregated, and NoLand-NotAggregated respectively). A table describing all experiments in this chapter can be found in Table 3.2.

<i>Experiment Name</i>	<i>Land</i>	<i>Interactive LW</i>	<i>Interactive SW</i>
Land-NoHomog	✓	✓	✓
Land-HomogLW	✓	×	✓
Land-HomogSW	✓	✓	×
NoLand-Aggregated	×	✓	✓
NoLand-NotAggregated	×	×	✓

Table 3.2. List of experiments

3.2.3 Analysis methods

In order to compare the relative degree of aggregation of different simulations, we again use the variance of column-integrated relative humidity (CRH; σ_{CRH}^2) metric (Wing and Cronin 2016). We also tested results using the variance of frozen moist static energy. For all simulations, results were qualitatively similar.

Finally, to help us identify important feedbacks driving aggregation in our simulations, we will also use the frozen moist static energy (FMSE) variance budget again, as defined by Wing and Emanuel (2014):

$$\frac{1}{2} \frac{\partial \hat{h}'^2}{\partial t} = \hat{h}' \text{SEF}' + \hat{h}' \text{NetLW}' + \hat{h}' \text{NetSW}' - \hat{h}' \text{Adv}' \quad (3.1)$$

3.3 Results

3.3.1 Land-centred aggregation

Convection primarily forms over the island throughout our Land-NoHomog simulation (Figure 3.1a, c), driving large moisture gradients, with the moistest columns of the domain consistently over the island, and the driest columns typically furthest away from the island (Figure 3.1b, d). Aggregation can be seen between 5-10 days after the simulation start. Convec-

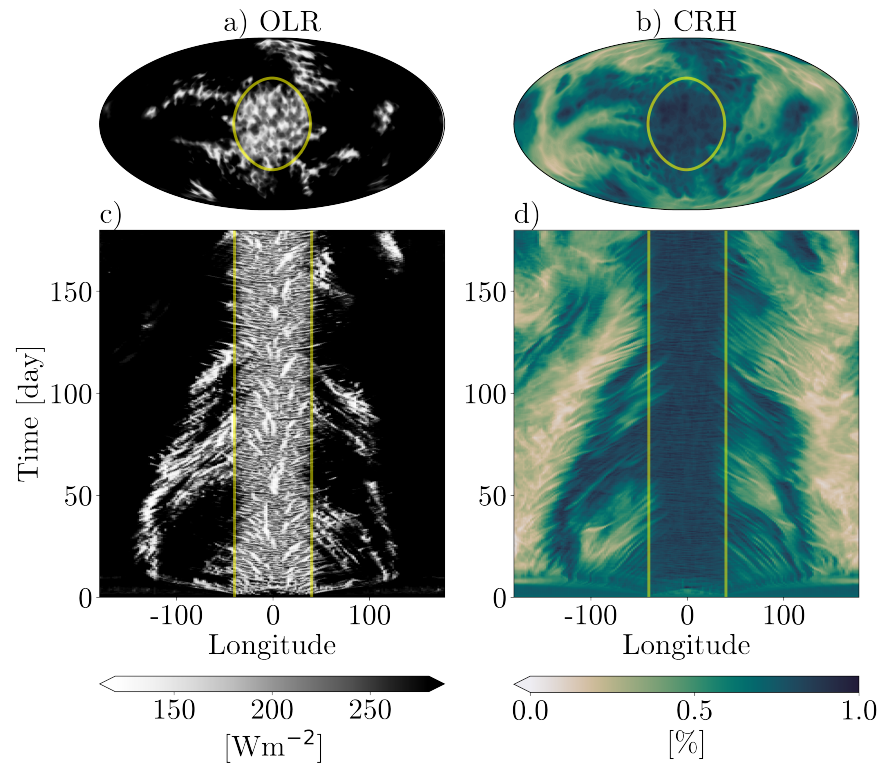


Figure 3.1. a), b): 4-hour mean snapshots of a) outgoing longwave radiation (OLR) and b) column relative humidity (CRH) on day 100 of the simulation. c), d): Hovmöller plots of c) OLR, and d) CRH over the first 180 days of the Land-NoHomog simulation, taken as a zonal slice through latitude=0°. The yellow lines show the coasts of the 40° radius island.

tion continues to aggregate until approximately day 70, when atmospheric equilibrium and therefore equilibrium in the moisture variance is reached (Figure 3.2). Convection which is triggered over the island itself, typically forms at the centre of the island and is advected towards the coastline of the island.

We earlier introduced the two pathways with which land, and the associated surface fluxes could influence the generation of circulations from Hohenegger and Stevens (2018). In our simulations, despite the use of a dynamic vegetation model where soil-moisture gradi-

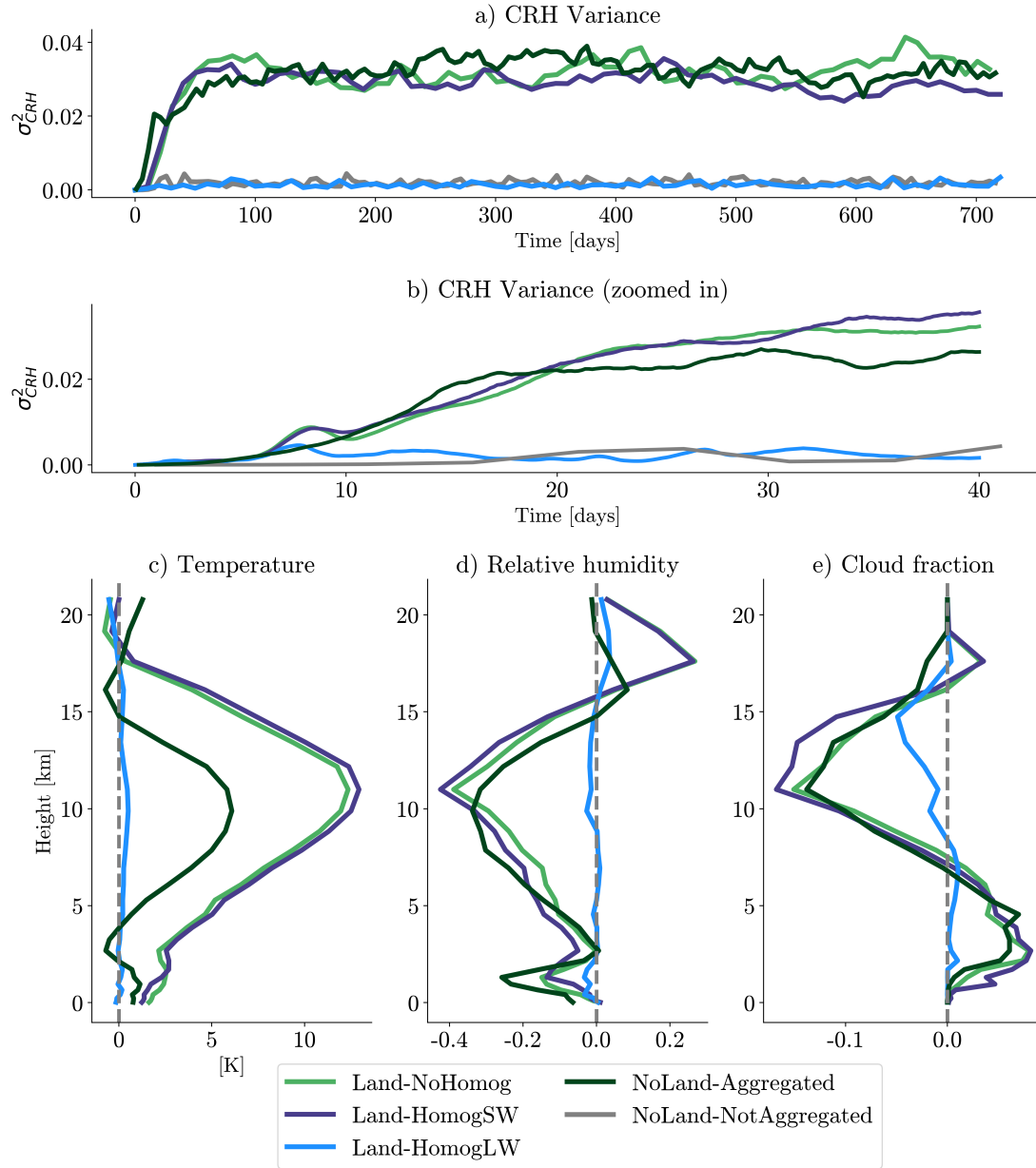


Figure 3.2. a)-b) Time evolution of variance of domain-mean column relative humidity (CRH; σ_{CRH}^2). c)-e): Domain-mean vertical profiles of c) temperature, d) relative humidity, e) cloud fraction, difference from NoLand-NotAggregated, time-averaged over days 100-720 of the simulations.

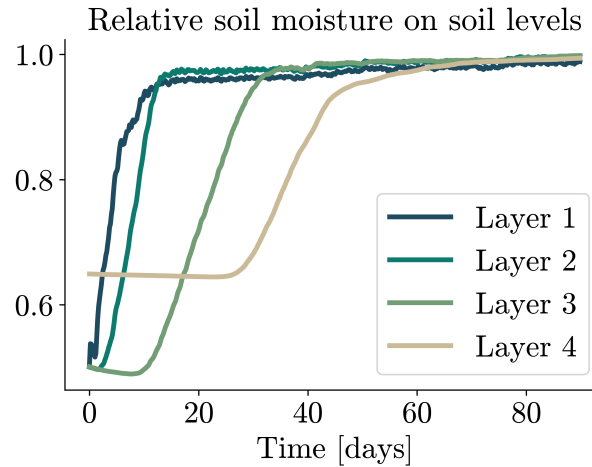


Figure 3.3. Timeseries of the soil moisture, relative to field capacity in each of the four soil layers over the first 90 days of the Land-NoHomog simulation. Layer 1 is the surface layer (0 m - 0.065 m), layer 2 (0.065 m - 0.319 m), layer 3 (0.319 m - 1.232 m), and layer 4 (1.232 m - 4.134 m).

ents could form, the persistent cluster of cloud covering the island prevents this, and thus we remain in the first pathway, where evaporation is not limited by soil-moisture (Koster et al. 2004; Seneviratne et al. 2006, 2010). This is evident from Figure 3.3, where we can see that the relative soil moisture (mostly) increases in all soil layers from the start of the simulation. After approximately 50 days, the soil column is almost completely saturated. The water budget is balanced in this model through surface runoff, drainage at the bottom of the soil column, and a small surface water convergence. In this simulation, there is approximately 1 mm of surface water for most of the simulation, and with the rainforest vegetation type, drainage provides the largest moisture sink. Thus, despite the more advanced modelling configuration, our island becomes closer to the saturated island simulation of Cronin et al. (2015).

Figure 3.2 shows a comparison of the domain-mean properties of this simulation (Land-NoHomog) with the NoLand-NotAggregated simulation, and the NoLand-Aggregated simulation. We can see that compared to the NoLand-NotAggregated simulation, there is a strong domain-mean warming, free-tropospheric drying, and a decrease in high level clouds. This is consistent with the results of many previous self-aggregation studies (e.g. Cronin and Wing 2017; Wing et al. 2020). The Land-NoHomog shows similar domain-mean effects

of aggregation to the NoLand-Aggregated simulation, with Figure 3.2a showing the same degree of aggregation between these two simulations. There is also little change in the amount of free-tropospheric drying and reduction in high cloud fraction between the runs with/without land, but there is slightly less drying of the lower troposphere and an increase in tropopause height when land is present. Despite these similarities between the simulations with/without land, there is a much stronger domain-mean warming throughout the troposphere in the Land-NoHomog simulation. This would happen, if the convection in the simulation with land is on a warmer moist adiabat than the convection in the simulation without land. This is true in our simulations as the Land-NoHomog has convection forming over a warmer lifting condensation level than the NoLand-Aggregated experiment. Also supporting this is in our Land-NoHomog simulation, the boundary layer equivalent potential temperature θ_e) is significantly warmer than in the NoLand-NoHomog simulation. Our result here agree with Cronin et al. (2015), but not with Leutwyler and Hohenegger (2021), as would be expected from the soil-moisture analysis above.

It is clear from Figure 3.1 that there is a large-scale circulation being generated and maintained over the island in the Land-NoHomog simulation, and that this is likely responsible for the aggregation of convection throughout our simulation. It has been shown before that the self-aggregation of convection is generally driven by self-generated radiative circulations. These circulations have often been shown to start as an anomalous patch of dry sky, which then grows and pushes the convection to cluster together (Muller and Held 2012; Coppin and Bony 2015; Muller and Bony 2015; Holloway and Woolnough 2016), a mechanism for which longwave radiative feedbacks are generally essential both for triggering and maintenance. We investigate here whether the convection is aggregated through the same mechanisms as self-aggregation. We will study this first by discussing the thermodynamics responsible for triggering the circulation, and then for maintaining the circulation.

Figure 3.4 shows some of the key physical quantities driving the circulation over the first 40

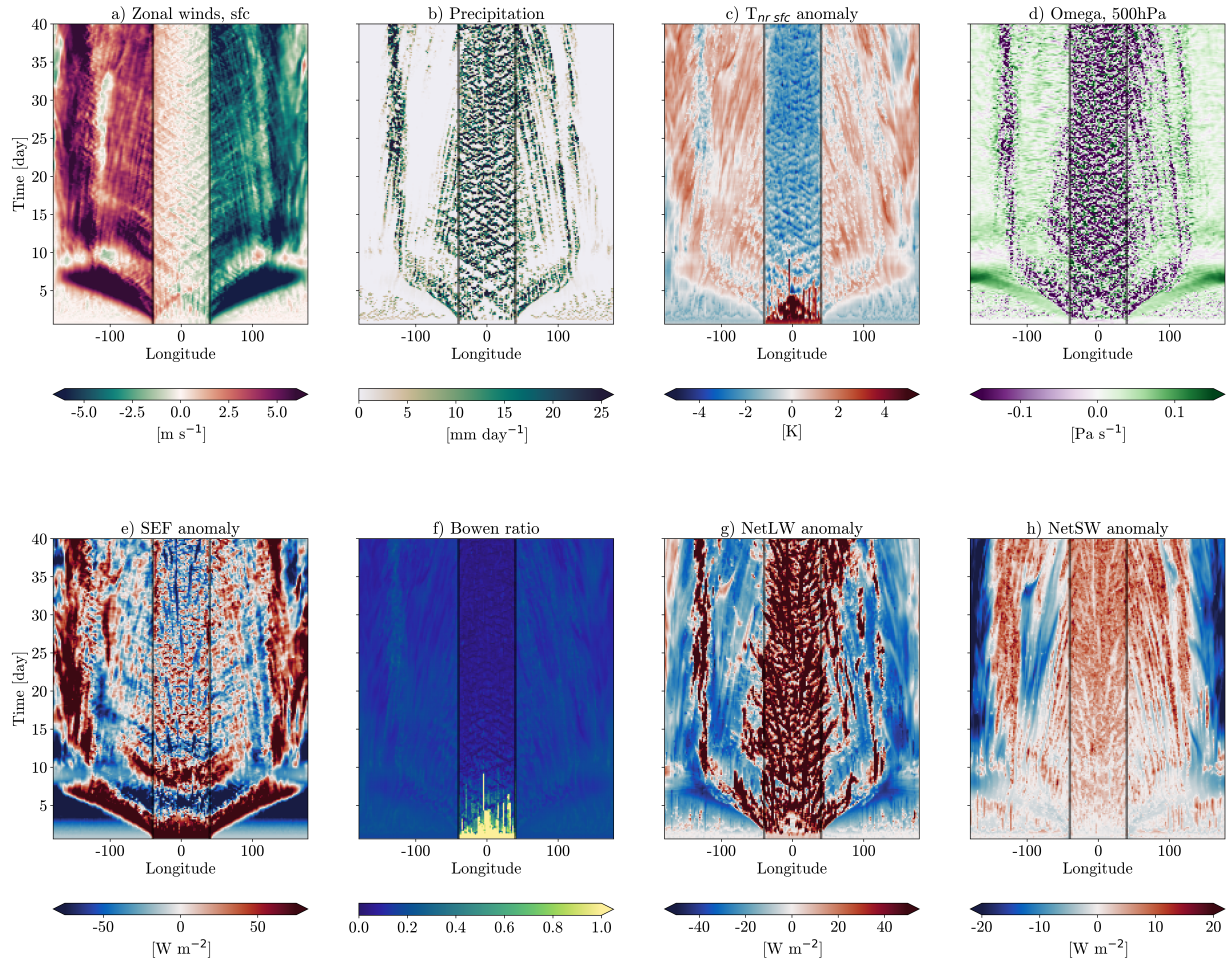


Figure 3.4. Hovmöller plots of a) Surface zonal winds, b) Precipitation c) Near-surface temperature anomaly d) Omega at 500 hPa, e) surface enthalpy flux (latent heat flux (LHF) + sensible heat flux (SHF)) anomaly, f) Bowen ratio (SHF/LHF), g) NetLW anomaly, h) NetSW anomaly, over the first 40 days the Land-NoHomog simulation, taken as a zonal slice through latitude=0°. The black lines show the coasts of the island. NetLW and NetSW are the column longwave and shortwave radiative flux convergences respectively. Anomalies are calculated from the horizontal mean.

days of our simulation. Figure 3.4a illustrates the aforementioned circulation, and its extent. We can see that the surface winds are converging towards the island at every oceanic point, with approximate speeds of 3 ms^{-1} once aggregation has been reached (roughly 10 days after simulation start). This circulation is being triggered initially by very strong sensible heat flux spatial anomalies as indicated by a strongly positive SEF spatial anomaly in Figure 3.4e and a Bowen ratio above one in Figure 3.4f at the start of the simulation. This drives high near-surface temperature spatial anomalies which cause strongly negative boundary layer density anomalies, and hence positively buoyant air over the island. The land-sea

thermal contrast also causes surface winds. The circulation described here is analogous to the well documented sea-breeze circulation (Miller et al. 2003), which subsequently triggers convection (Kingsmill 1995; Carbone et al. 2000; Crook 2001). The convection starts at the edge of the island, and as the surface circulation grows in strength, moves inwards until the whole island is covered by convecting air (Figure 3.4d). These results highlight that boundary layer processes are likely important for the initiation of aggregation, supporting recent results from other studies (e.g. Muller and Bony 2015; Naumann et al. 2017; Yang 2018a,b). In particular, Muller and Bony (2015) showed that the boundary layer advection of FMSE was vital for the self-aggregation of convection. We will show later in the chapter that this process is also a key driver of aggregation in these simulations.

The convection over the island triggers a gravity wave propagating at 30 ms^{-1} at 500 hPa, which acts to eliminate horizontal density gradients in the free-troposphere. This gravity wave is responsible for propagating the temperature of the warmer moist adiabat that the convection is on to the rest of the domain, consistent with the weak temperature gradient approximation (Sobel et al. 2001; Leutwyler and Hohenegger 2021). Evidence of this wave can be seen in Figure 3.4, especially in Figure 3.4d as a wave of subsiding air moving outwards away from the island, and in the time scale of the inward-moving convection over the island in the initial triggering phase (Figure 3.1c). The subsidence associated with this wave causes a strong drying of the columns far away from the island (Figure 3.1d), which completes the process of aggregation. Figures 3.4g and h show that in the initial two day period during which this circulation is being spun-up, the horizontal anomalies in both column longwave and shortwave radiative fluxes are minimal. Thus, it seems from Figure 3.4 that the circulation which aggregates the convection is triggered in this simulation with land primarily through surface fluxes, mostly the sensible heat flux. Once the convection starts to form, the longwave radiative spatial anomalies grow, implying that longwave feedbacks play an important role in our circulation, but are less important for the circulation to be triggered initially.

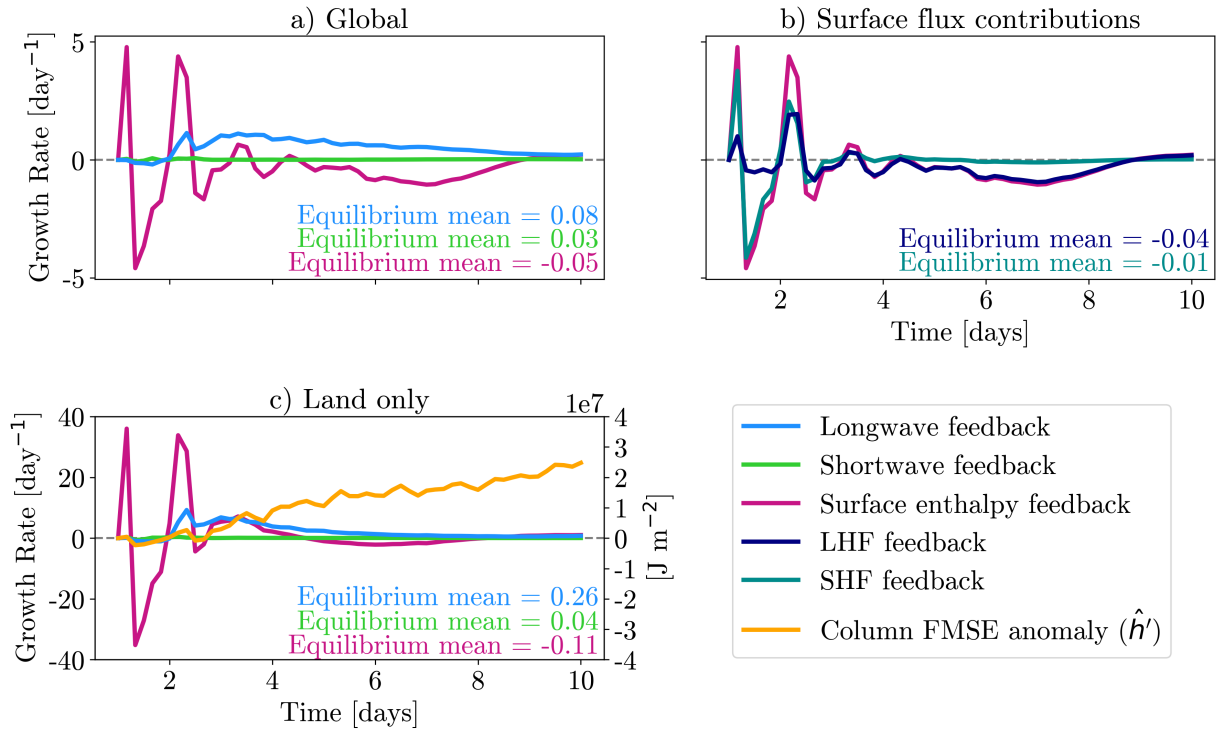


Figure 3.5. Timeseries of diabatic terms in FMSE variance budget (Eq. 3.1) over first 10 days of the Land-NoHomog simulation. a) Averaged globally, b) Globally-averaged surface flux contributions, c) averaged over the island only. c) also includes the land-averaged values of $\hat{h}'$, on the right-hand y-axis. Light blue lines show longwave feedback, green lines show shortwave feedback, pink lines show surface enthalpy feedback, navy blue lines shown latent heat flux (LHF) feedback, teal lines show sensible heat flux (SHF) feedback, orange line shows $\hat{h}'$. Mean values over days 90-180 (when the simulation is in equilibrium) of each feedback are given in the text on each plot (colour of text corresponds to feedback line colour).

If we investigate the feedbacks in the first ten days through the FMSE variance budget method, we can see similar results (Figure 3.5). For all feedbacks, the values are driven primarily by the value of the feedbacks over land, therefore we also show the feedbacks averaged over the land tiles only (Figure 3.5c). In the first three days, the surface enthalpy feedback is the dominant term driving FMSE variance with the sensible heat flux feedback providing the largest contribution (Figure 3.5b). Slightly misleadingly, both the globally-averaged and land-averaged term oscillates between positive and negative values. This is due to the oscillation in the land-averaged $\hat{h}'$ term. The sign of the surface enthalpy flux horizontal anomaly, however, remains positive (Figures 3.4e and f), acting as a source of FMSE over the island consistently in the first three days of the simulation. Thus, we ar-

gue that the surface fluxes drive the aggregation of convection over land in the earliest days of our simulation. After two days, the longwave feedback begins to increase, and it becomes the dominant positive feedback after three days of simulation. The contribution from the longwave feedback then remains the strongest, positive feedback throughout the remainder of the simulation. This is in agreement with the analysis above, where we identified that horizontal anomalies in the column longwave radiative flux convergence over land are large and positive after the initial triggering of the circulation. Thus, the FMSE variance budget feedback decomposition analysis supports our conclusion that it is the surface fluxes which are primarily responsible for triggering the aggregation processes, but the longwave feedbacks become increasingly important, and remain the strongest positive feedback in the equilibrium feedback.

After this initial aggregating period, convection remains persistently over the island (Figures 3.1c, d, 3.4b, and d). A key difference between the way that the land and ocean are modelled, is that the land surface energy budget is closed, whilst the oceanic surface energy budget is not. This means that the land surface can change temperature, whilst the ocean temperature is fixed. Thus, once convection has formed, due to shortwave cloud shielding, the land surface temperature cools (Figure 3.4c - note that this is near surface temperature, but reflects the behaviour of the surface temperature). Nevertheless, the surface zonal winds (Figure 3.4a) show that the circulation does not reverse towards the now warmer ocean anomalies, and convection remains aggregated. To investigate the mechanisms driving this equilibrium stage of our simulation, we analyse time-averaged, 3D zonal cross-sections of various physical quantities (Figure 3.6). Figure 3.6a again shows the global circulation that is keeping the convection aggregated together, i.e. surface convergence towards the island centre with strong upper tropospheric divergence away from the island. Figure 3.6b shows the vertical motions associated with convection, and Figures 3.6c and d show the aggregated moisture and cloud water content fields. Importantly, the surface convergence allows for an advection of high surface FMSE towards the convective cluster (Figure 3.6e), which

has previously been shown to be an important process driving aggregation (e.g. Muller and Held 2012; Muller and Bony 2015).

Inspecting the 3D horizontal virtual temperature anomalies in Figure 3.6f reveals that the near-surface negative temperature anomalies in Figure 3.4c are confined to less than 500 m above the surface. Above this, there is still a temperature gradient with warmer anomalies over the island than ocean, and therefore the circulation aggregating the convection is still being thermally-driven. However, initially this circulation was being driven by the land-sea thermal contrast caused by the land surface heating up. This poses the question, what is now driving the thermal anomalies over the island? Figure 3.6h illustrates the strong gradients in longwave flux convergence anomalies in the lower troposphere, which are positive over the island and negative away from the island. These gradients drive the temperature gradient in Figure 3.6f and are responsible for driving the maintenance of the global circulation. This mechanism is the same as is discussed in previous studies (e.g. Wing et al. 2017). Also supporting this, there is a higher θ_e anomaly over land than ocean throughout the troposphere. The shortwave heating anomalies also show a pattern one would expect - negative anomalies in the lower troposphere representing the effects of cloud shielding and positive anomalies in the upper troposphere due to absorption by water vapour and clouds. However, the overall horizontal radiative heating anomaly pattern is driven by the longwave radiative feedbacks (Figure 3.6j). These results agree with the conclusions from the FMSE variance budget analysis, which showed that the longwave feedbacks, especially those over the island, are the strongest mechanisms driving aggregation in the equilibrium stages of our simulation (Figure 3.5). Therefore longwave feedbacks are important for maintaining the island-centred circulation and therefore maintaining the aggregation of convection over the island.

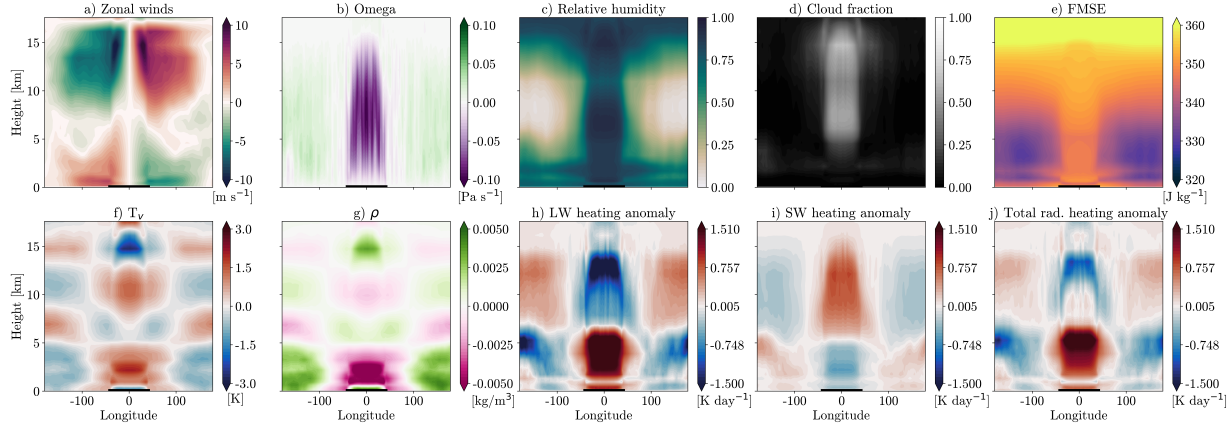


Figure 3.6. a) Zonal winds, b) Omega, c) Relative humidity, d) Cloud water content, e) Frozen moist static energy (FMSE), f) Virtual temperature anomaly, g) Density anomaly, h) Longwave radiative heating anomaly, i) Shortwave radiative heating anomaly, and j) Total radiative heating anomaly. Plots are zonal slices taken at latitude 0° , averaged over days 100-720 of the Land-NoHomog simulation. Island is located between longitudes $\pm 40^\circ$, as indicated by thick black line. Anomalies are calculated from the horizontal mean.

3.3.1.1 Vegetation sensitivity test

To test the sensitivity of our results to the vegetation chosen, we have run an additional experiment where the land initial and boundary conditions are set to grass-like parameters instead of tropical rainforest ones. Typically, rainforests are characterised by greater evapotranspiration and roughness lengths and a lower albedo than other vegetation types (Shuttleworth 1989). As shown in the results in above, surface fluxes can have a large impact on convection and precipitation and thus these changes in surface parameters could also impact our results. In particular, we showed that the high surface fluxes, driven by the sensible heat flux in the first three days of the simulations triggered convection and thus determined the location of our aggregation.

For the following results we used the land parameters from the short grass experiment in Bell et al. (2015), with the JSBACH4 PFT flag 7, and loamy soil (FAO flag 3). A table listing the parameters for both the rainforest and grass experiment can be found in Table 3.2.

The results found earlier in the chapter mostly hold when the vegetation was changed to

grass. Figure 3.7 shows the same fields as in Figure 3.4, but for our grass experiment. It is clear that, after the first two days, the two simulations are extremely similar. Similarly, we can examine the driving feedbacks derived from the FMSE variance budget for both experiments to again see very similar results (Figure 3.8). The main differences between the two experiments lies in the first two days of the 2m temperature, the Bowen ratio, and thus the relative surface flux contribution from latent and sensible heat. Whilst in our rainforest experiment the land initially became far warmer than the surrounding oceans, here we see a weaker, though still positive temperature anomaly over land. There is also a much lower Bowen ratio over land for the grass experiment, although the surface enthalpy flux anomaly is of a similar magnitude. This implies that, instead of the sensible heat fluxes initially driving the aggregation, here we see that it is the latent heat fluxes acting as a FMSE source over land. This is confirmed in the FMSE variance budget plots in Figure 3.8. Figure 3.8a shows that the surface flux feedbacks are again the main driver of aggregation in the first day with the longwave feedbacks dominating after that. Equally, Figure 3.8b confirms that it is the latent heat fluxes driving this surface flux feedback. Figure 3.7h shows that the NetSW anomaly is greater in the earliest few days than in the rainforest experiment (Figure 3.4h). This is due to the higher albedo of the grass vegetation which therefore reflects more of the incoming solar radiation while the island is cloud free at the start of the simulation. Thus, less shortwave is absorbed at the surface which is why we see a smaller near surface temperature anomaly and hence surface energy balance is reached by a lower Bowen ratio. After the first day, convection begins to be triggered over the island, and the same feedbacks as in the rainforest experiment, namely the longwave radiative fluxes, begin to dominate once more.

Thus, even with different vegetation driving a different partitioning of the surface fluxes, we still see convective aggregation preferably forming over the island in our simulations. The location of this aggregation is driven by surface fluxes, with the surface enthalpy feedback being the dominant term in the FMSE variance budget in the first 1-2 days of both grass

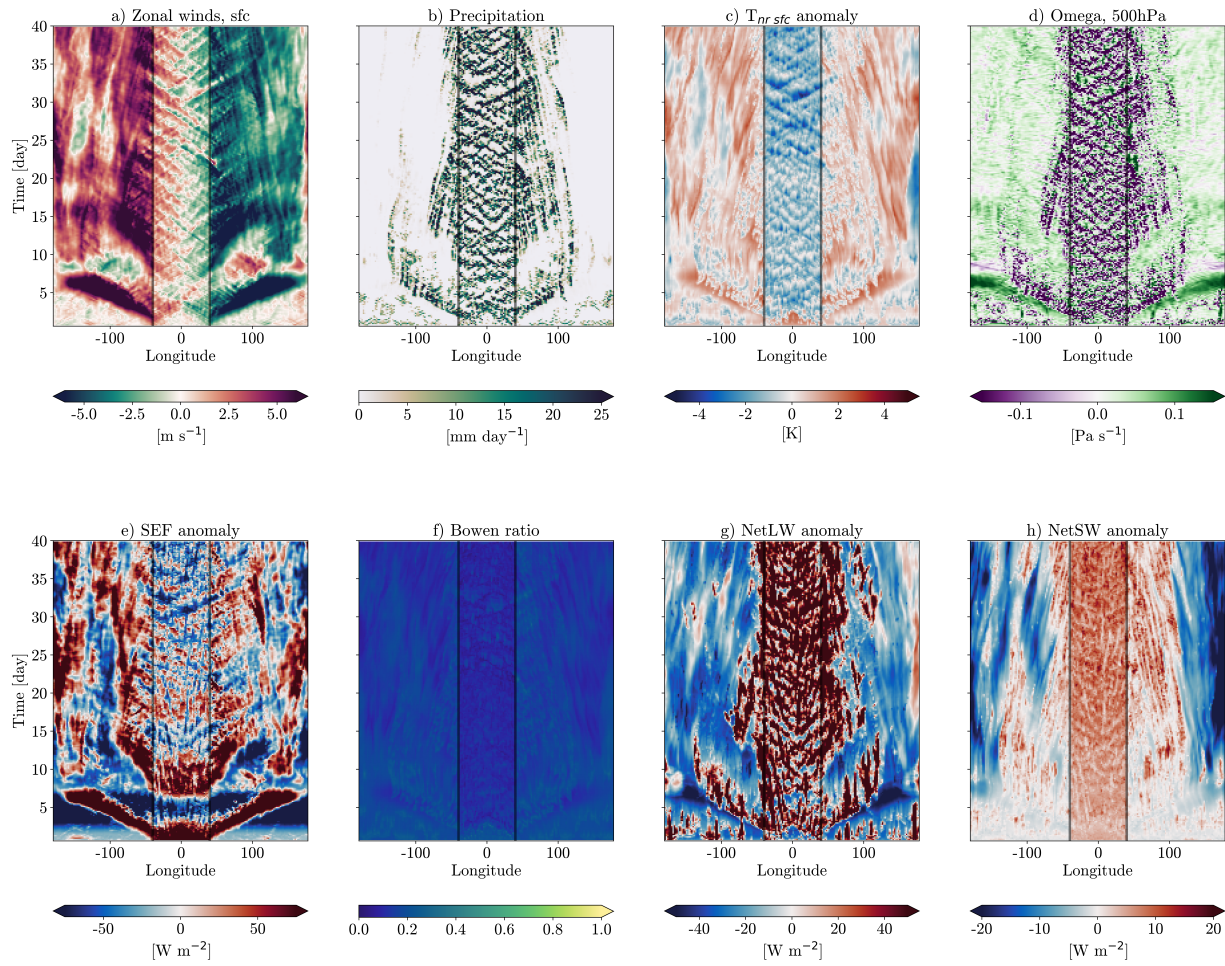


Figure 3.7. Hovmöller plots of a) Surface zonal winds, b) Precipitation c) Near-surface temperature anomaly d) Omega at 500 hPa, e) surface enthalpy flux (latent heat flux (LHF) + sensible heat flux (SHF)) anomaly, f) Bowen ratio (SHF/LHF), g) NetLW anomaly, h) NetSW anomaly, over the first 40 days the simulation with grass vegetation, taken as a zonal slice through latitude=0°. The black lines show the coasts of the island. NetLW and NetSW are the column longwave and shortwave radiative flux convergences respectively. Anomalies are calculated from the horizontal mean.

and rainforest simulations. After this initial period, the longwave feedbacks become the strongest feedback.

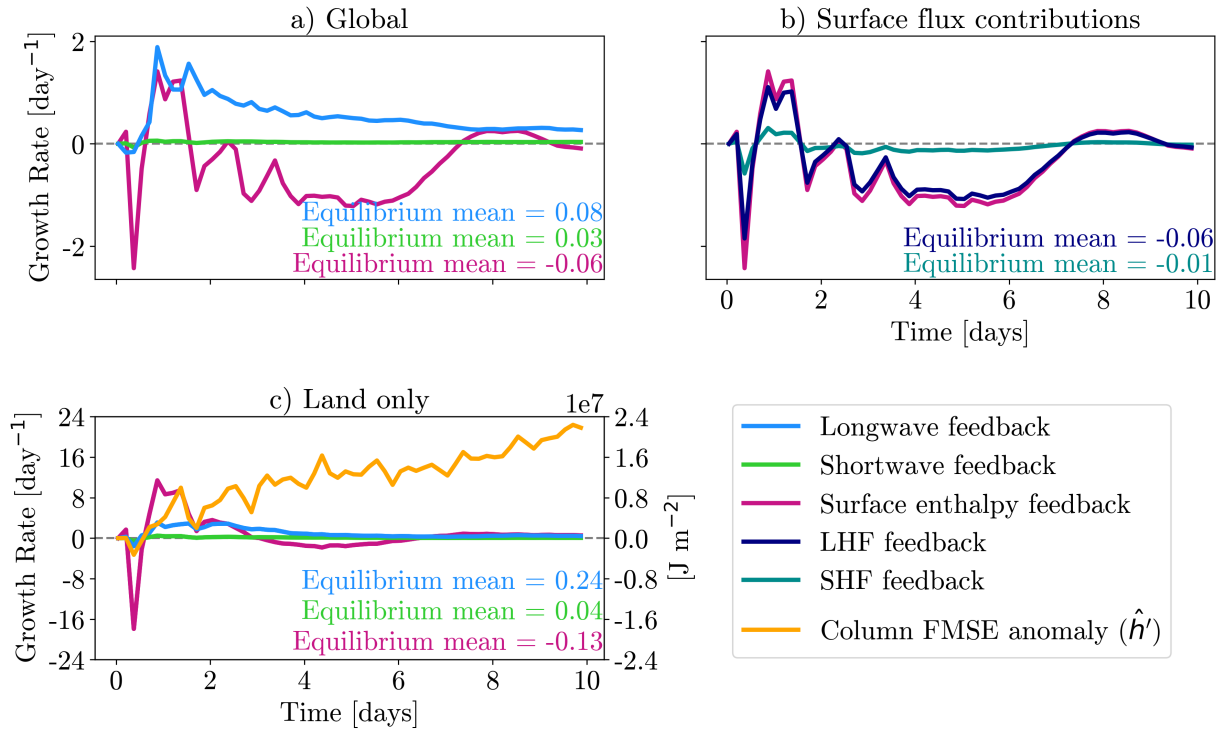


Figure 3.8. Timeseries of diabatic terms in FMSE variance budget (Eq. 3.1) over first 10 days of the simulation with grass vegetation. a) Averaged globally, b) Globally-averaged surface flux contributions, c) averaged over the island only. c) also includes the land-averaged values of $\hat{h}'$, on the right-hand y-axis. Light blue lines show longwave feedback, green lines show shortwave feedback, pink lines show surface enthalpy feedback, navy blue lines shown latent heat flux (LHF) feedback, teal lines show sensible heat flux (SHF) feedback, orange line shows $\hat{h}'$. Mean values over days 90-180 (when the simulation is in equilibrium) of each feedback are given in the text on each plot (color of text corresponds to feedback line color).

3.3.2 Mechanism denial tests: Does convection aggregate over land in the absence of horizontal radiative flux anomalies?

In order to test our radiative heating hypothesis, we analyse the results from our mechanism denial tests. These tests allow the radiative heating rates to change through time, but remove the horizontal gradients, thought to be responsible for maintaining the aggregation of convection. Figure 3.2a shows that homogenising the shortwave heating has had little impact on the overall degree of aggregation, whereas homogenising the longwave

heating has decreased the degree of aggregation down to the same degree as the NoLand-NotAggregated experiment. If we inspect the first 40 days of the simulations more closely (Figure 3.2b) then we can see that the CRH variance increases similarly in the first 7 days of each simulation with land, then it is after this that the degree of aggregation drops in the Land-HomogLW simulation. This supports the findings in the previous section that the surface fluxes are driving the spin up of the circulation, with longwave feedbacks taking over as the dominant feedback after this.

Additionally, in the 3D domain-mean fields of temperature, relative humidity, and cloud fraction (Figures 3.2c-e), the Land-HomogSW simulation mirrors the Land-NoHomog simulation, and the Land-HomogLW simulation mostly mirrors the NoLand-NotAggregated simulation. This also implies that the large domain-mean effects in Land-NoHomog discussed earlier are due to the aggregation process, not due to the inclusion of land itself.

The results from Figure 3.2b suggest that the circulation that is triggered in Figure 3.4 would also be triggered in the absence of longwave feedbacks, but that it is not being maintained, as we are seeing less impact of aggregation on the moisture distribution, domain-mean cloud fraction, and temperature. Indeed, if we study Hovmöller diagrams of the Land-HomogLW simulation (Figure 3.9) we can see that this appears to be true. The same circulation spin up can be seen by the land-sea thermal contrast in Figure 3.9c, and the subsequent gravity wave induced subsidence in Figure 3.9d, however, without the convection triggering longwave feedbacks over the island, this circulation is not maintained, and instead the horizontal motion is now being dominated by wave-like motions across the globe (Figure 3.9a). This wave also travels at roughly 30 ms^{-1} , as in our original simulation. These waves travel away from the island, passing through each other at the island's antipode, creating a surface circulation which alternates between land-centred and ocean-centred and repeats periodically approximately every 15-25 days. At the points of strongest surface-level divergence away from the island (for example, around day 20 in Figure 3.9a), the surface

windspeeds over land increase, creating a warm, dry anomaly over the centre of the island, above which there is clear-sky (Figure 3.9h). This point dries due to the increased windspeeds and the subsidence associated with the diverging circulation, and warms because of the increased surface shortwave absorption due to the clear-sky above as well as the increased windspeeds again. This warm anomaly then triggers new convection, resulting in the same thermally-driven circulation and subsequent gravity wave mechanism discussed. These results were also tested for simulations which were started from the equilibrium aggregated state shown in Figure 3.1, and then had the longwave heating rates homogenised. The results for this were the same as in Figure 3.2 and 3.9.

From the precipitation, vertical pressure velocity, and OLR fields (Figures 3.9b, d, and h), convection is less organised throughout the Land-HomogLW simulation than in our original Land-NoHomog simulation, due to an increase in oceanic convection. However, over the island we still see persistent convection, as in the Land-NoHomog simulation, except during the brief suppression period at the peak of the ocean-centred circulation. Therefore, there is clearly another mechanism responsible for organising convection over land other than the longwave radiative fluxes. However, this mechanism is not driving the same level of moisture variance as in our Land-NoHomog simulation

To further understand why we do not see a partitioning of the moisture field like many other self-aggregation studies we turn to 3D zonal slices of the equilibrium circulation, in Figure 3.10. The surface zonal winds in Figure 3.9a showed that there was no longer a large-scale, land-centred circulation being maintained in the Land-HomogLW simulation, however, Figure 3.10a shows that there is still a large-scale overturning circulation, however it no longer extends to the surface. We now have land-centred convergence starting at approximately 4 km, with similar upper-tropospheric outflow as in Land-NoHomog. The structure of the virtual temperature anomaly has also changed - the large positive anomaly in the lower troposphere in Land-NoHomog has been significantly weakened and the strongest hori-

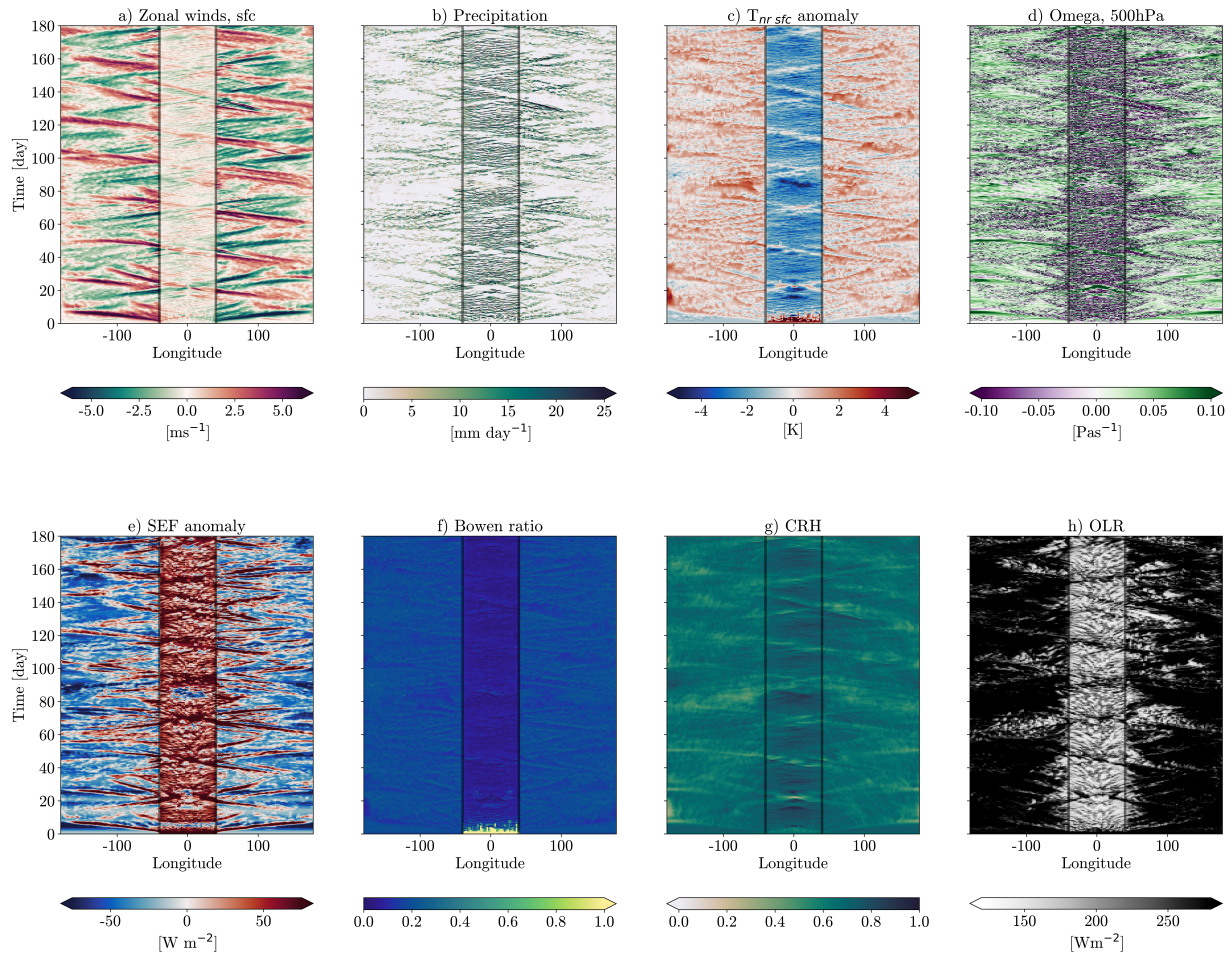


Figure 3.9. Hovmöller plots of a) Surface zonal winds, b) Precipitation c) Near-surface temperature anomaly d) Omega at 500 hPa, e) Surface enthalpy flux (latent heat flux (LHF) + sensible heat flux (SHF)) anomaly, f) Bowen ratio (SHF/LHF), g) Column relative humidity, h) Outgoing longwave radiation, over the first 180 days of the Land-HomogLW simulation, taken as a zonal slice through latitude= 0° . The black lines show the coasts of the island. Anomalies are calculated from the horizontal mean.

zonal anomaly in Land-HomogLW is now between 7-10 km, likely driven by the shortwave heating anomaly and convective heating (Figure 3.10i). The driving feedback thus combines these results: island-based convection will have upper-tropospheric outflow, which must re-converge due to mass conservation. This convergence is towards the strongest virtual temperature anomaly, which is elevated in comparison to the Land-NoHomog simulation. Therefore, gravity-wave dominated, horizontal winds in the boundary layer are somewhat disconnected from this large-scale overturning circulation, although the gravity wave motion still impacts the zonal winds at higher altitudes with wave speeds superimposed on

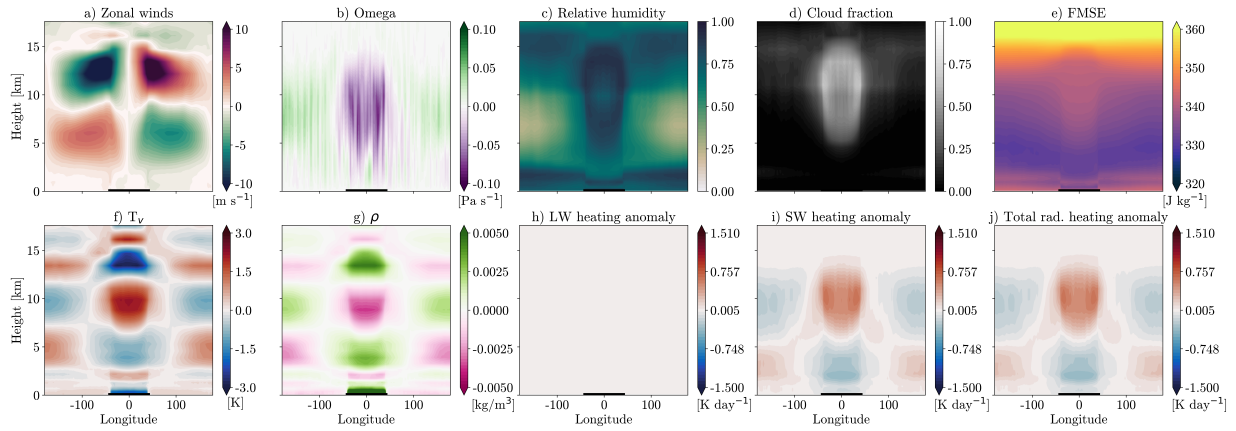


Figure 3.10. a) Zonal winds, b) Omega, c) Relative humidity, d) Cloud water content, e) Frozen moist static energy (FMSE), f) Virtual temperature anomaly, g) Density anomaly, h) Longwave radiative heating anomaly, i) Shortwave radiative heating anomaly, and j) Total radiative flux convergence anomaly. Plots are zonal slices taken at latitude $=0^\circ$, averaged over days 100-720 of the Land-HomogLW simulation. Island is located between longitudes $\pm 40^\circ$, as indicated by thick black line. Anomalies are calculated from the horizontal mean.

the background large-scale circulation. This elevated large-scale circulation also means that the advected FMSE is of much lower energy, therefore acting as a negative feedback on aggregation in the Land-HomogLW simulation. Thus, these results indicate that this near-surface advection of FMSE is possibly the key for convective aggregation to affect the energy budget by driving a broadening of the moisture distribution, supporting the results of Muller and Held (2012) and Muller and Bony (2015).

To conclude, it is difficult to quantify whether the Land-HomogLW simulation is aggregated or not - it could be labelled as either based on how we choose to define aggregation. Is convective self-aggregation simply the geometrical organisation of convection, or is it the geometrical organisation combined with large-scale climatological impacts, such as the broadening of the moisture field? Nevertheless, we have shown here that by removing the horizontal gradients in longwave radiative fluxes, convection is less spatially organised with increased oceanic convection compared with the Land-NoHomog simulation. Also, in the absence of these longwave feedbacks any spatial organisation which does occur is unable to drive the large-scale changes to the domain-mean climate which are usually caused by increased aggregation, due to changes in the height of FMSE advection.

3.3.3 Sensitivity to island size

In order to test our results' sensitivity to the island size, we ran an ensemble of simulations where the island radius was increased from 10° to 80° in 10° increments. The winds, near-surface temperature, OLR and CRH Hovmöller plots for these experiments are shown in Figure 3.11. The standard result we've seen in this study, that convection will preferentially form over the island, forced by a large thermally-driven circulation mostly holds at all island sizes. The extent of the circulation is much smaller in the 10° island simulation, as are the maximum horizontal windspeeds. This circulation extent grows, reaching across almost the whole globe in the simulations with island sizes between 20° and 50° . Along with this the convective cluster also grows to cover the whole island, leading to cool near-surface temperature anomalies over the island, due to the cloud shielding effect. Interestingly, above 50° the circulation stops growing in extent, and the convective cluster stops growing in size. At 60° , 70° , and 80° the convective cluster stays mostly the same size as the cluster in the 50° simulation, and so is no longer covering the whole island. This results in clear sky patches around the convective cluster, leading to large near-surface temperature anomalies. There is also a reduction in the horizontal extent of the zonal winds.

We speculate that these results could point to a maximum size of aggregation cluster which would cover approximately 20% of the globe. Indeed, if we calculate the average fraction of the globe which is convecting by dividing the area of the domain that has a negative vertical pressure velocity (ω) at 500 hPa by the total domain area, we find that approximately 25% of the globe is convecting at all times in all of the simulations once aggregated. This is in contrast to the NoLand-NotAggregated simulation, in which there is approximately 37% of the globe which is convecting on average. Thus, the island is not causing an increase in the amount of convection when aggregated, but simply determining the locations at which convection preferentially forms. In the largest island simulations, when there is very little convection outside of the island area, this leads to a maximum cluster size of $\mathcal{O}(10,000\text{km})$,

approximately the diameter of the 50° island. Matsugishi and Satoh (2022) investigated the natural length scale of convective aggregation in global models, and at an SST of 305K they estimated this to be approximately 2000km. Yang (2018b) also found that a typical length scale of self-aggregation is $\mathcal{O}(2000\text{km})$. Our results find a much larger size of convective cluster, however this is not a 'natural' length scale, but instead a length scale due to the forcing presence of the island. Thus, it appears that when an inhomogeneity forces convection to aggregate together, it can lead to an increase in the length scale of aggregation. Interestingly, the typical scale of the MJO, a phenomenon that has previously been linked to convective aggregation (Arnold and Randall 2015; Khairoutdinov and Emanuel 2018), is also $\mathcal{O}(10,000\text{km})$, potentially indicating a relationship between our work and large-scale aggregation in the real-world. Therefore, we recommend further work investigates aggregation length scales, particularly in models with increasing complexity, as our results indicate that forcings which are often excluded from more idealised aggregation studies could have a large impact on the spatial scale of organisation.

3.4 Discussion and Conclusions

Using the ICON GCM, we ran RCE experiments which included a large, continental-sized island to investigate how the inclusion of land affects the phenomenon of convective aggregation. The island here represents a tropical rainforest-like land mass, with no elevation and no large-scale imposed winds, surrounded by a constant SST of 305K.

We showed that the inclusion of an idealised island in these global RCE simulations causes the convection to aggregate persistently over the island. This aggregation takes approximately 5-10 days to form spatially, however, it takes closer to 70 days for the model to reach statistical equilibrium, and therefore for the maximum degree of aggregation to be reached. The aggregation in these simulations causes similar domain-mean effects as

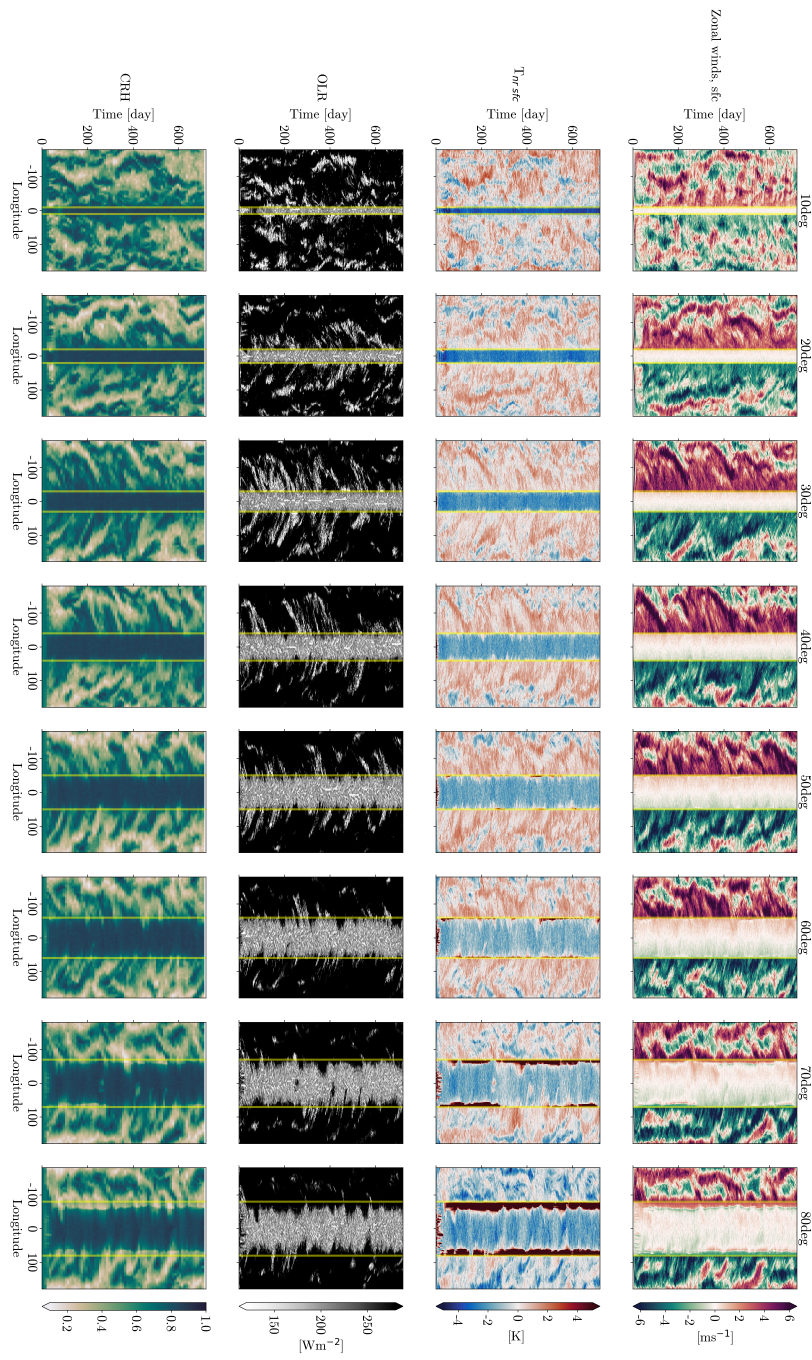


Figure 3.11. Hovmöller plots of a)-h) Surface zonal winds, i)-p) Near-surface temperature anomaly, q)-x) Outgoing longwave radiation, y)-ff) Column relative humidity for 720 days RCE simulations with different land sizes. Land sizes increase from 10° (column 1) to 80° (column 8) in 10° increments. Anomalies are calculated from the horizontal mean.

self-aggregation has been shown to have before. This includes a domain-mean warming, free-tropospheric drying and a reduction in the high cloud amount compared to a non-aggregated simulation (e.g. Bretherton et al. 2005; Coppin and Bony 2015; Wing and Cronin 2016; Cronin and Wing 2017). One key difference between self-aggregation, and this land-forced aggregation is the domain-mean temperature profile. As in Cronin et al. (2015), we find that aggregation over the island causes a large increase in the domain-mean temperature, much greater than the temperature increase seen in an aquaplanet self-aggregated simulation (Figure 3.2). This is due to a warmer cloud-base temperature in the land simulation, which drives the convection onto a warmer moist adiabat. This warmer moist adiabat is then propagated to the rest of the domain through convectively-triggered gravity waves. The similarity of our results to Cronin et al. (2015) occurs because the soil on our island rapidly becomes saturated, as is typical for tropical rainforests (Nepstad et al. 1994; Schenk and Jackson 2005), thus locking the simulation into a radiative-limited flux regime, rather than a soil-moisture limited one. Soil is therefore never able to dry and induce the low-level circulation reversal as seen in Hohenegger and Stevens (2018). In the more complex modelling framework of TRACMIP (Voigt et al. 2016), inclusion of an idealised continent drove a domain-mean cooling across all models. Their simulation design included a zonally-symmetric, meridional SST gradient, slab ocean, and seasonally varying insolation. The main driver of this cooling in their experiments was the development of a large cold 'tongue' to the west of the continent due to low-level advection from the 'winter' portion of the continent. Whilst originally seasonally driven, this anomaly develops into a persistent annual feature due to feedbacks between the cold SST, atmospheric humidity, and temperature (Biasutti et al. 2021). Thus, despite significant differences between our study and TRACMIP, there are some similarities in the ability of the land to drive an initial perturbation, which can then be maintained through atmospheric feedbacks.

The aggregation seen in these simulations is maintained by a radiatively-driven, thermally-direct circulation. We showed that the circulation is initially triggered by a strong land-sea

thermal contrast at the surface, driving a sea-breeze circulation, which has been shown to have important impacts on convection and precipitation over tropical islands, particularly in the Maritime Continent (Miller et al. 2003; Leutwyler and Hohenegger 2021). In our simulations, we found that the sea-breeze circulation triggers convection (Kingsmill 1995; Carbone et al. 2000; Crook 2001), first at the edge of the island before being triggered increasingly inland. This convection then incites a gravity wave, moving at approximately 30 ms^{-1} outwards from the island. Gravity wave induced subsidence dries the columns furthest away from the island, and saturated cloud detrainment in the vicinity of the convection moistens locally, which forms large gradients in the CRH (Lane and Reeder 2001). Once these atmospheric moisture gradients form, radiative feedbacks start to dominate the maintenance of the circulation through the strong longwave heating within the cloud layer. These longwave anomalies drive a strong virtual temperature gradient in the lower troposphere, which then causes the radiatively-driven circulation to persist throughout the simulation, despite negative near-surface temperature anomalies over the island.

We tested these results through mechanism denial experiments, which confirm the importance of longwave feedbacks for both the formation and maintenance of aggregation. When longwave heating rates are horizontally homogenised, aggregation is significantly reduced, with increased oceanic convection and reduced moisture variance. Surface convergence is no longer maintained. Instead, shortwave heating and convective heating drives a mid-tropospheric virtual temperature anomaly which causes a large-scale thermally-driven circulation, although one that is elevated above the boundary layer. In the absence of boundary layer convergence, the advection of FMSE upgradient is reduced, leading to lower FMSE in the convective cluster. Muller and Bony (2015) found that an upgradient advection of FMSE was essential for aggregation. Here, we see that convection can still be organised spatially, but without this upgradient advection, the organisation no longer drives large-scale climatological changes.

Thus, we have concluded that surface fluxes are the dominant feedback in initially driving aggregation in the presence of a land-sea contrast, and therefore also determine the location of aggregation. However, longwave heating by the convection is necessary for maintaining a large-scale circulation with convergence in the boundary layer. Through our experiments, it seems that this boundary layer convergence is extremely important for enabling convective aggregation to broaden the moisture distribution.

This study extends current understanding by demonstrating that even when land is included in an RCE model (with no diurnal cycle) which could therefore change the mechanisms of aggregation through an increased importance of surface fluxes, longwave feedbacks still drive necessary feedbacks for convective aggregation to cause domain mean changes to the moisture distribution and therefore the energy budget. These results are of course subject to the idealisations made in this study - for example, would the inclusion of a diurnal cycle allow for a nocturnal reversal of the land-sea breeze, thus disrupting the large-scale, radiatively-driven circulation? Cronin et al. (2015) found that the diurnal cycle induced nocturnal surface cooling was insufficient to destabilise the deep overturning circulation, leading to a time-mean, island-centred circulation, although their study excluded the potential effects of soil moisture. We postulate that, given that our land-surface remains cooler throughout our simulations once aggregated, and given the long time scales associated with soil drying (e.g. Bruno et al. 2006; Teuling et al. 2006), it is likely that in the time-mean our results would still hold in the presence of a diurnal cycle. However, confirming this requires further work outside the scope of this experiment, and we recommend this as an avenue for future study.

The results we have presented in this chapter mostly scale with island size, until islands have a radius greater than 50° with the large-scale circulation roughly increasing in extent with island size, and the resulting convective cluster always covering the entire island. For all experiments, convection covers roughly 25% of the globe, however with increasing

island size, this convection is increasingly centred on the island. This means, for the largest island sizes, the convective cluster is no longer able to cover the whole island. This work thus points to a maximum size of convective cluster in a global domain, something that has been a recent topic of interest (Arnold and Putman 2018; Yang 2018b; Beucler and Cronin 2019). We highlight that the framework used in this study could provide some interesting insights to this work concerning the spatial-scale of aggregation to encourage further work in developing a theoretical understanding of what sets the scale of aggregation in more complex modelling environments.

We present this chapter as an investigation of the impacts land-sea contrasts have on convective aggregation in a global configuration, and provide it as a useful addition to the growing literature on connecting idealised aggregation studies to the manifestation of real-world convective organisation (e.g. Tompkins 2001a; Arnold and Randall 2015; Hohenegger and Stevens 2016; Holloway 2017; Hohenegger and Stevens 2018; Muller and Roms 2018; Becker and Wing 2020; Beucler et al. 2020; Bony et al. 2020; Müller and Hohenegger 2020; Shamekh et al. 2020a). We have shown that, whilst the shape and scale of aggregation change when a continentally-sized island is included in an idealised RCE world, many of the features of aggregation remain the same, including its effects on the large-scale environment and the feedbacks driving the formation and maintenance of aggregation. However, our results indicate that the surface fluxes cannot be ignored, especially in the initial triggering of organised systems. It can be difficult to draw conclusions on how results shown in this and other similar studies might be manifested in the real-world, due to the experiment's highly idealised configuration. To that end, there are many extensions to this chapter that we feel will help to further elucidate the relationship between idealised aggregation and its real-world manifestations, including investigating the effects of the diurnal cycle, SST gradients and rotation on the results presented here.

4 | Convective self-aggregation over sea-surface temperature gradients

It is the reason why doing research is challenging as well as attractive. It is like being lost in a jungle and trying to use all the knowledge that you can gather to come up with some new tricks, and with some luck, you might find a way out.

MARYAM MIRZAKHANI

In the previous chapter, we found that the presence of a continentally-sized island in our GCM forced convection to aggregate over it. This aggregation displayed many similarities to the forced aggregation found in Chapter 2, and these will be discussed in detail in Chapter 5. For this chapter, we include another 'real-world' feature to our original RCE model: a meridional sea-surface temperature (SST) gradient. Here, we investigate how self-aggregation feedbacks interact with the feedbacks associated with the SST gradient to analyse how these aggregation feedbacks may be interacting with circulations and convection in the real-world.

This chapter is based on an article being prepared to be submitted to Journal of the Atmospheric Sciences:

Dingley, B., Hohenegger, C., Dagan, G. and Stier, P. (2023). Physical mechanisms driving the

zonal clustering of convection along the equator. *Journal of the Atmospheric Sciences*, *in preparation*.

I designed the study together with the co-authors. I carried out the simulations and analyses presented, with input from the co-authors. I wrote the manuscript, with contributions and approval from the co-authors.

Abstract

The self-aggregation of convection occurs under idealised, spatially homogeneous boundary conditions, however how it relates to real-world organised convection remains an open question. Here, we study self-aggregation mechanisms under the increased complexity of inhomogeneous boundary conditions: meridionally varying sea-surface temperature (SST) gradients. Convection converges along the equator coincident with the peak SSTs, resembling the ITCZ. Recent work has hypothesised that self-aggregation feedbacks may play a role in driving a zonal contraction of these equatorial clouds. We show that this zonal clustering is driven by interactions between longwave radiative, clouds, and water vapour, with contributions from advective and surface flux feedbacks. Direct shortwave feedbacks are diagnosed as small through the integrated transient frozen moist static energy variance budget, but the interactions between shortwave radiation and circulations are shown to be important. These results verify that convective self-aggregation feedbacks could play an essential role in zonally distributing clouds in the ITCZ, potentially impacting the regional distribution of precipitation and the atmospheric energy budget. Therefore, further understanding the role of self-aggregation feedbacks on the ITCZ is vital for understanding the tropical rain belt.

4.1 Introduction

There is much debate about how the results from idealised aggregation studies relate to real-world convective organisation. Many studies have taken a step towards reality by changing boundary conditions of idealised studies, such as at the surface. An inhomogeneous surface has been shown to affect the onset and lifetime of aggregated convection (Tompkins 2001a; Cronin et al. 2015; Hohenegger and Stevens 2016; Müller and Hohenegger 2020; Shamekh et al. 2020a,b; Leutwyler and Hohenegger 2021; Dingley et al. 2022). Persistent sea surface temperature (SST) gradients organise convection over the warmer SSTs due to the locally warmer and moister boundary layer which drives a pressure gradient and low-level flow (Back and Bretherton 2009; Müller and Hohenegger 2020; Shamekh et al. 2020a), and a larger θ_e driving more convective instability. In a large spherical domain, Müller and Hohenegger (2020) found that an equatorial convergence line forms when forced by a meridional SST gradient, which resembles the inter-tropical convergence zone (ITCZ). However, this convergence line subsequently contracts zonally, which the authors attribute to self-aggregation feedbacks in the tropical region. Whilst typically local SST gradients drive the zonal distribution of convection along the ITCZ, the work of Müller and Hohenegger (2020) highlights that self-aggregation feedback mechanisms could also play an important role in defining the zonal extent of the ITCZ.

Another similarity between self-aggregation and the ITCZ is the importance of radiative cooling. It has been robustly shown that radiative cooling has a large impact on the ITCZ (e.g. Byrne and Schneider 2016; Harrop and Hartmann 2016; Albern et al. 2018; Dixit et al. 2018; Talib et al. 2018; Voigt et al. 2021). Harrop and Hartmann (2016) examined the role of cloud radiative effects on the ITCZ, finding that the cloud radiative effect robustly contracts the ITCZ meridionally and reduces the double ITCZ problem. This has subsequently been attributed to lower tropospheric heating due to upper tropospheric clouds (Dixit et al. 2018).

This heating drives a net import of FMSE, a similar feedback mechanism to the one identified in self-aggregation studies. Increased zonal clustering of convection along the equator has also been linked to a widening of the tropical rain belt, highlighting that changes in zonal distributions of rainfall can also impact the meridional rainfall pattern (Popp and Bony 2019). However, the mechanisms driving the zonal clustering of the ITCZ in the absence of zonal SST gradients remain understudied. In this chapter we thoroughly investigate the role of convective self-aggregation in zonal clustering at the equator and decompose the key feedbacks driving this using a variation on the FMSE variance budget (see Section 4.2.2.)

4.2 Methods

4.2.1 Model description

In this chapter, We use the a similar configuration of ICON, with the same grid and parameterisations as in previous chapter. However, here we add a meridional SST gradient. As we are interested in zonal clustering along the highest SSTs, most analysis presented here is performed for the equatorial slice, averaged over $\pm 10^\circ$ latitude. The initial temperature and humidity profiles are taken from a non-aggregated RCE simulation. In order to break symmetry, we add random noise in the lowest four model levels. This simulation design closely resembles the one designed for the RCE model intercomparison project (RCEMIP; Wing et al. 2018), although with the added SST gradient, and allows for analysis from day 0 of the simulation as the model begins from a state close to equilibrium. For this initialisation simulation, aggregation is prevented by horizontally homogenising the longwave radiative fluxes.

To investigate the effects of spatially varying SSTs, we perform experiments using the zonally uniform "QOBS" distribution (Neale and Hoskins 2000) with 5K added to the SST everywhere. This profile has a maximum SST along the equator of 305K, and a minimum

SST of 278.15K poleward of 60°. The additional 5K allows for the equatorial SST to be 305K, a temperature where the ICON GCM has been shown to strongly aggregate (Wing et al. 2020; Dingley et al. 2021).

4.2.2 Feedback decomposition

In order to investigate the relevant aggregation feedbacks in our simulations, we use a variation on the frozen moist static energy budget (FMSE) method, following Wing and Emanuel (2014) and Beucler et al. (2019). For this method, the FMSE (h) is defined as,

$$h = gz + C_p T + L_v q_v - L_f q_{ice} \quad (4.1)$$

where gz is the geopotential ($J\ kg^{-1}$), C_p is the specific heat capacity of dry air ($J\ K^{-1}\ kg^{-1}$), T is the temperature (K), L_v is the latent heat of vaporisation ($J\ kg^{-1}$), q_v is the water vapour mixing ratio ($kg\ kg^{-1}$), L_f is the latent heat of fusion ($J\ kg^{-1}$), and q_{ice} is the ice mixing ratio ($kg\ kg^{-1}$). We also define $\hat{h}$ as the density-weighted integral of h over the troposphere. Then, following Bretherton et al. (2005) and Wing and Emanuel (2014), the FMSE variance budget can be written as:

$$\frac{1}{2} \frac{\partial \hat{h}'^2}{\partial t} = \hat{h}' \text{NetLW}' + \hat{h}' \text{NetSW}' + \hat{h}' \text{SEF}' - \hat{h}' \text{Adv}' \quad (4.2)$$

Where SEF stands for surface enthalpy fluxes, which is the sum of the surface latent heat and sensible heat fluxes, NetSW and NetLW are the column shortwave and longwave radiative flux convergences respectively, and Adv is the horizontal advection of $\hat{h}$ (defined as $\nabla_h \cdot \bar{u} \hat{h}$, the horizontal divergence of the density weighted vertical integral of FMSE flux). In Eq. 4.2, primes represent the horizontal anomaly from the global mean. This methodology allows us to compare how anomalies in the three diabatic sources/sinks of FMSE, along with horizontal divergence anomalies correlate with anomalies in $\hat{h}$, and in turn, whether

these are driving an increase/decrease in FMSE variance and thus an increase/decrease in aggregation.

The meridional SST gradient forces a large-scale circulation with convergence towards and ascent over the warmest SSTs, which converges moisture at the equator. Due to this, there is persistently high $\hat{h}$ at the lowest latitudes, even within the equatorial dry patches, compared to the highest latitudes. In order to analyse zonal variation and zonal sources/sinks of FMSE driving zonal clustering along the equator it is therefore useful to separate the $\hat{h}$ into its time mean value ($\overline{\hat{h}}$), and the local anomaly from the time mean ($\hat{h}_T$) (Beucler et al. 2019). We will also refer to $\hat{h}_T$ as the transient FMSE. Therefore, we can define

$$\hat{h}(x, y, t) = \overline{\hat{h}}(x, y) + \hat{h}_T(x, y, t). \quad (4.3)$$

Indeed this can be done for any variable:

$$\alpha(x, y, t) = \overline{\alpha}(x, y) + \alpha_T(x, y, t), \quad (4.4)$$

and using this, Beucler et al. (2019) (Eq. 5 in their paper) derived the transient FMSE budget as

$$\frac{\partial \hat{h}_T}{\partial t} = \text{NetLW}_T + \text{NetSW}_T + \text{SEF}_T - \text{Adv}_T. \quad (4.5)$$

Then, in the same vein as the FMSE variance budget derivation from Wing and Emanuel (2014), we can subtract the horizontal mean of Eq. 4.5 from the full form of the equation to obtain a time rate of change of the anomaly of $\hat{h}_T$. Multiplying this by $\hat{h}'_T$ gives us a budget for the spatial variance of transient vertically integrated frozen moist static energy:

$$\frac{1}{2} \frac{\partial \hat{h}_T'^2}{\partial t} = \hat{h}'_T \text{NetLW}'_T + \hat{h}'_T \text{NetSW}'_T + \hat{h}'_T \text{SEF}'_T - \hat{h}'_T \text{Adv}'_T. \quad (4.6)$$

Finally, terms are normalised by the horizontal mean $\hat{h}_T'^2$, to give terms in units of day^{-1} . This budget can be interpreted similarly to the FMSE variance budget from Wing and Emanuel

(2014): a positive feedback is increasing the variance in the transient FMSE variance. Therefore, when analysed zonally across the lowest latitudes, as done in this study, a positive feedback will drive an increase in zonal aggregation. Hereafter, we will refer to the $\hat{h}'_T \text{NetLW}'_T$ term as the longwave feedback, $\hat{h}'_T \text{NetSW}'_T$ term as the shortwave feedback, $\hat{h}'_T \text{SEF}'_T$ as the surface flux feedback, and $\hat{h}'_T \text{Adv}'_T$ as the advective feedback. The feedbacks may also be referred to as the transient longwave feedback (for example), though the term transient will be used interchangeably.

The second feedback decomposition method we use is a mechanism denial method in order to investigate the role horizontal gradients in radiative fluxes play in the organisation of convection. For this, we perform experiments where the longwave and shortwave radiative fluxes are set with zonally-averaged values. These values are calculated as the longwave/shortwave radiative flux averaged zonally and temporally over the final year of the simulation with fully interactive radiation. Please also note that due to a bug in the ICON model, longwave radiative fluxes are only replaced for two out of every three time steps. However, this level of homogenisation is sufficient for our conclusions.

Henceforth, we will describe the three simulations performed for this study as NoHomog (simulation with fully interactive radiation), HomogSW (simulation with homogenised shortwave cooling), and HomogLW (simulation with homogenised longwave cooling).

4.3 Physical mechanisms of zonal clustering

4.3.1 Similarities to self-aggregation

We will begin by analysing the results from the NoHomog simulation. As is expected, convection forms preferentially along the equatorial zone of our simulations (Figure 4.1a), al-

though there is evidence of zonal clustering due to the patch of the equator which has higher OLR, and thus reduced high cloud. When we study the evolution of the equatorial outgoing longwave radiation (OLR), precipitation, and column relative humidity (CRH) through time, we can see that this zonal clustering is a persistent feature through time in the NoHomog simulation (Figures 4.1a-d), supporting the results found in Müller and Hohenegger (2020).

This clustering is mostly present as a large, persistent dry patch, marked by swaths of increased OLR and decreased humidity and precipitation, persisting for hundreds of days at a time. Different from typical self-aggregation, most of the equator remains covered by convection with a smaller fraction dominated by a drier atmosphere. In more idealised, self-aggregation studies we typically see one large convective cluster covering 20-30% of the domain surrounded by extremely dry air. Therefore, in this study we will generally talk of the dry patches as indicators of aggregation, as opposed to clusters of convection, and as such we define a metric which can help us to define a dry patch.

For this definition, we will make use of transient variables, as defined in Equation 4.4. A grid cell is categorised as being within a dry patch when its transient precipitation is negative. This definition sufficiently identifies the dry patches in this simulation as they are not stationary in time, and thus a dry patch is marked by lower than average rainfall. To ensure we only detect sufficiently large, persistent dry patches and not stochastic drying of grid cells that quickly re-moisten, we apply two extra criterion for dry patches: that they persist for at least 30 successive days and their spatial extent covers at least 4° longitude. These values are chosen based on our model temporal and spatial output. 30 days in succession is three consecutive output time steps, and similarly 4° longitude is also three model equatorial grid-cells. We tested similar metrics with positive transient OLR, or negative transient CRH and both gave qualitatively similar results. Varying the choice of parameters for this metric, such as ensuring dry patches persist for 40 days, or only cover 2° longitude also gave us

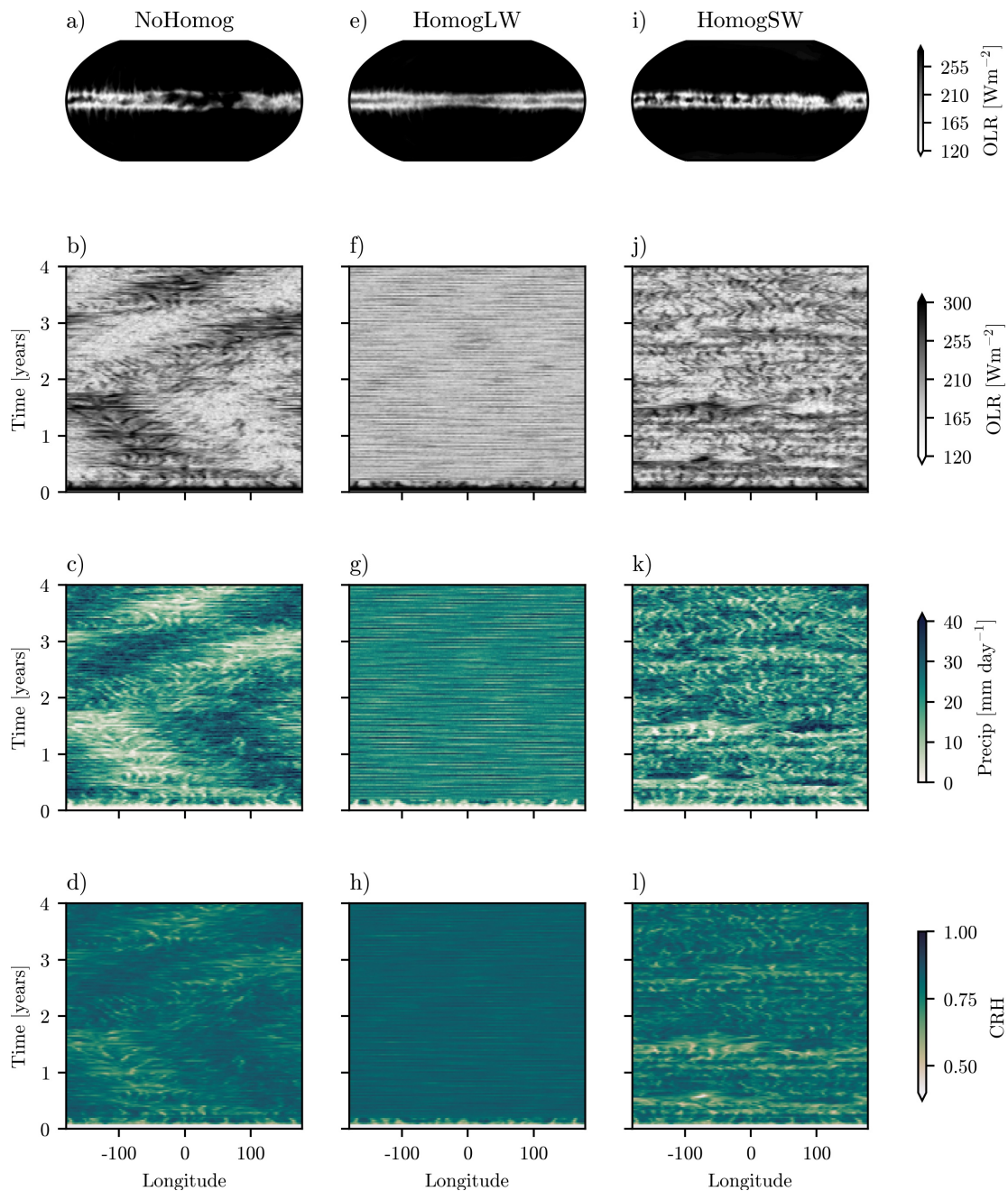


Figure 4.1. Top row: snapshots of outgoing longwave radiation (OLR) after 600 days of simulations. All other rows: Hovmöller plots over four years of a zonally-homogeneous aquaplanet simulation with a meridional sea-surface temperature gradient. Second row: OLR; third row: precipitation; fourth row: column relative humidity. Hovmöller plots are taken as an equatorial zonal slice averaged over latitude $\pm 10^\circ$. Left column (a-d) are for the NoHomog simulation with interactive radiative fluxes; middle column (e-h) are for the HomogSW simulation where shortwave cooling is horizontally homogenised; right column (i-l) are for the HomogLW simulation where longwave cooling is horizontally homogenised. Second, third, and fourth rows show model output averaged every 10 days

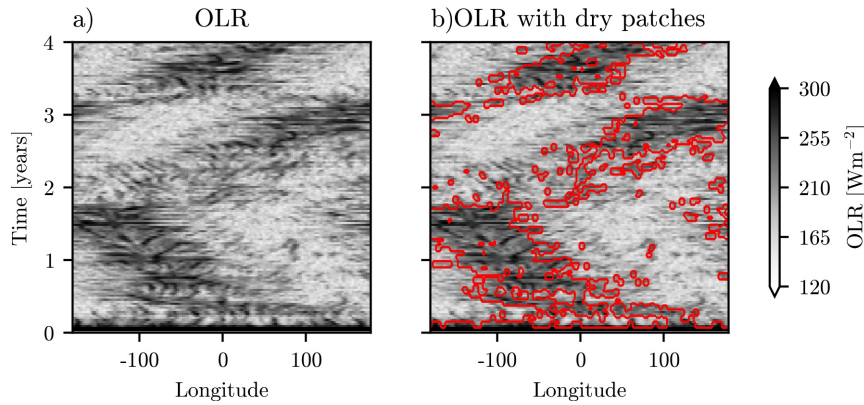


Figure 4.2. Outgoing longwave radiation Hovmöller plots of a zonally-homogeneous aquaplanet simulation with a meridional sea-surface temperature gradient for the NoHomog simulation with interactive radiative fluxes. Red lines in figure b) outline dry patches, which are defined as areas with negative transient precipitation, which persists for 30 days successively and has a spatial extent of 4° longitude.

qualitatively similar results. The OLR field with dry patches outlined is shown in Figure 4.2. We can see that the metric performs well at capturing the dry patches where there is reduced deep convection as the red lines in Figure 4.2b enclose the large swaths of increased OLR.

To understand the feedbacks driving the development and persistence of these dry patches, we will now inspect the feedbacks derived from the transient FMSE budget analysis (Figure 4.3).

4.3.1.1 Longwave feedbacks

The longwave feedbacks are positive across the equatorial region, and strongest within the dry patches (Figures 4.3a-c). This is consistent with identified feedbacks in previous self-aggregation studies, and can be attributed to the reduction of clouds and moisture within these dry patches. There is a negative anomaly in the transient column convergence of longwave radiation in the dry patches which is present in both the clear- and cloudy-sky fields, although the cloudy-sky anomaly is larger in magnitude (not shown). These dry patches have a reduction in the longwave absorption driven by a decrease in deep cloud amount, so providing a sink of FMSE and driving the magnitude of the clear-sky feedback.

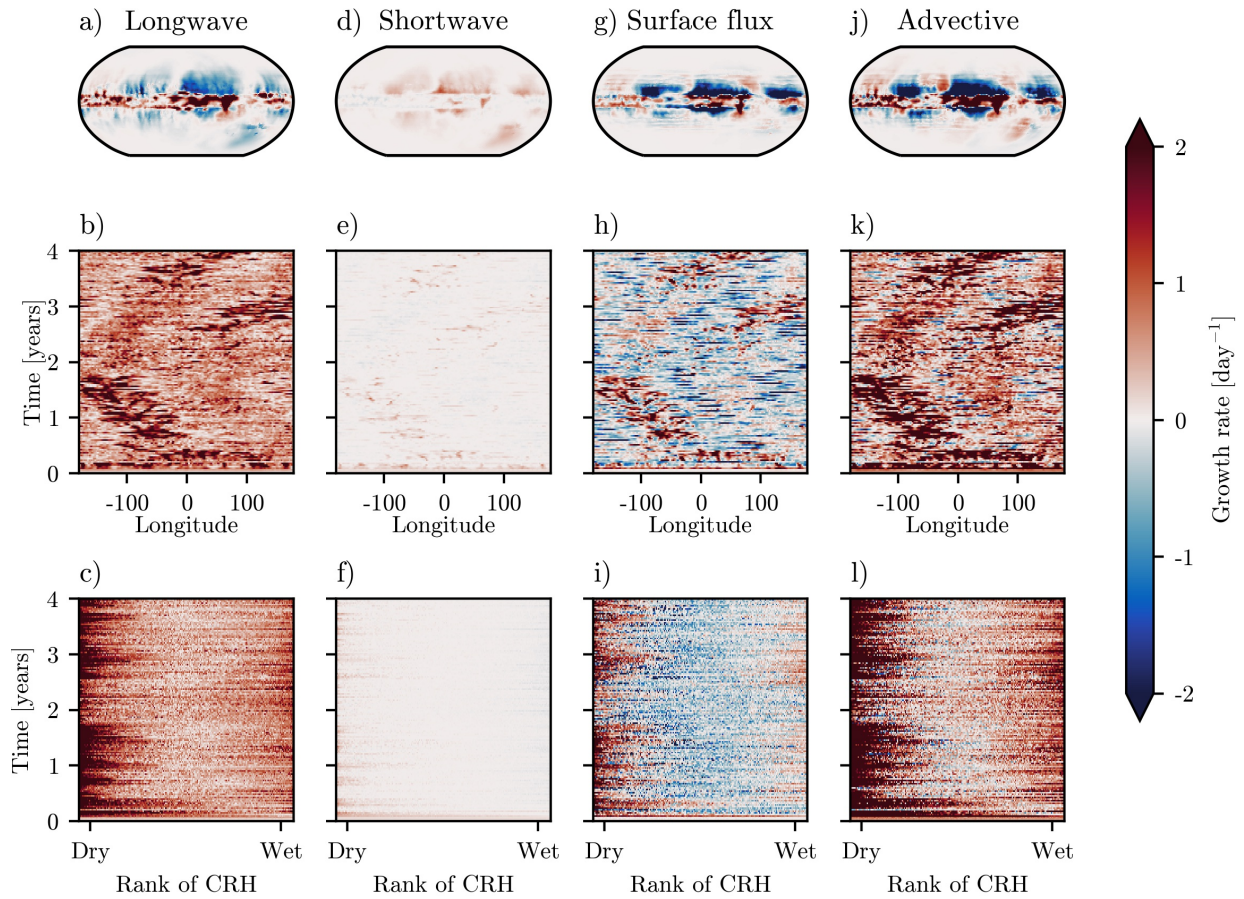


Figure 4.3. Correlations between vertically integrated transient FMSE anomalies and a)-c) transient column longwave convergence anomalies (the longwave feedback), d)-f) transient column shortwave anomalies (the shortwave feedback), g)-i) transient surface enthalpy flux anomalies (the surface flux feedback), j)-l) transient horizontal convergence of FMSE anomalies (the advective feedback), as calculated from Eq. 4.6. Top row shows a global snapshot at day 600 of simulations. Second and third rows show Hövmöller diagrams for an equatorial zonal slice averaged over latitude= $\pm 10^\circ$. Second row is plotted as time against longitude, third row is sorted into moisture space with time plotted against the column's rank of column relative humidity. All plots for the NoHomog simulation with interactive radiative fluxes.

The clear-sky feedback also contributes to this clustering process in the driest columns through a reduction in the longwave absorption by water vapour. Although weaker in magnitude, the equivalent effects are also working outside of the dry patches, where there is increased moisture and deep cloud. The shortwave feedback is also positive across the equator, although it is extremely weak and therefore the direct diabatic feedback driven by water vapour shortwave absorption has minimal effect on the zonal aggregation.

We can also use the sensitivity tests where the zonal longwave and shortwave feedbacks are switched off in turn and investigate any subsequent zonal clustering that forms. Following the conclusions from the FMSE budget analysis above, we expect a decrease in the zonal clustering without longwave feedbacks (HomogLW), and minimal changes in the organisation in the absence of shortwave feedbacks (HomogSW). The results of these experiments are shown in the second and third columns of Figure 4.1.

We can see that, in Figures 4.1e-h for the HomogLW simulations, all zonal clustering has disappeared, and the OLR, the precipitation, and the CRH are mostly homogeneous across the equatorial region. Additionally, in Figure 4.4 some key aggregation features are investigated. With increased aggregation, one would expect to see broadened OLR, humidity and precipitation distributions. A metric which can capture some of these features of aggregation is the variance of CRH (σ_{CRH}^2 ; Wing and Cronin 2016). We can see that when longwave cooling is homogenised, there are narrower OLR, CRH, and precipitation distributions along with a significantly significant decrease in σ_{CRH}^2 (as tested with a t-test at 99% confidence), all consistent with a decrease in the zonal aggregation.

4.3.1.2 Shortwave feedbacks

Figures 4.3 d-f show that the shortwave feedbacks are very small throughout the simulation. Thus we would expect that removing the zonal gradients in shortwave fluxes would have

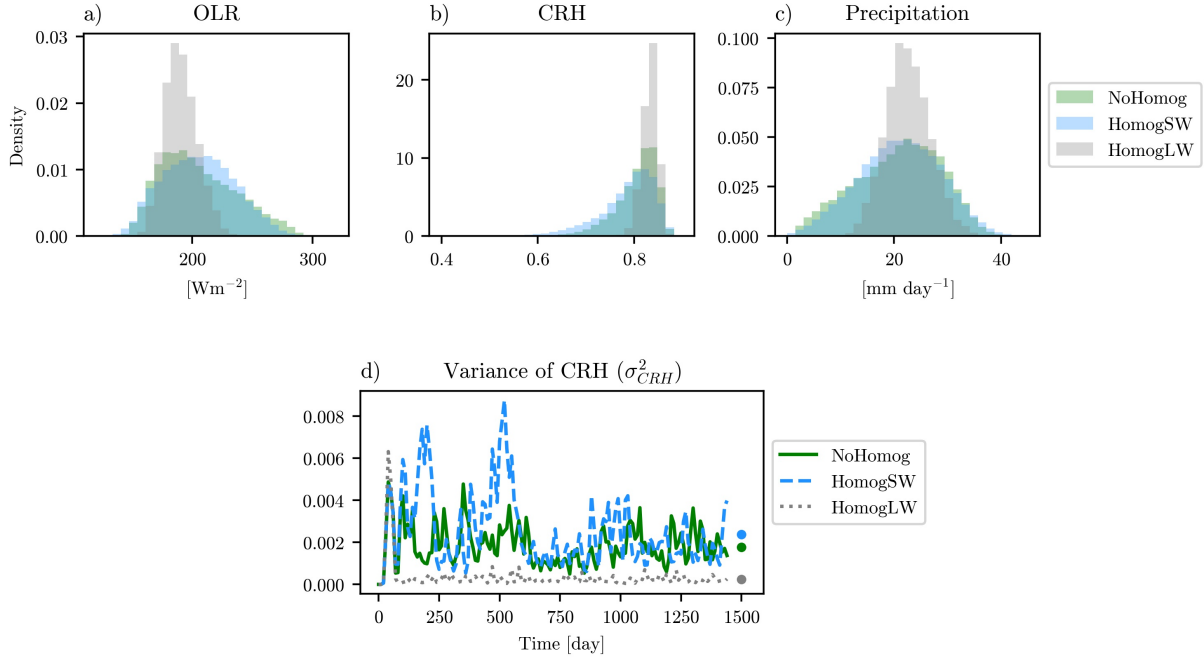


Figure 4.4. Top row: Probability density histograms for a) outgoing longwave radiation, b) column relative humidity, c) precipitation, where green represents the NoHomog simulation with interactive radiative fluxes; blue represents the HomogSW simulation where shortwave cooling is horizontally homogenised; grey represents the HomogLW simulation where longwave cooling is horizontally homogenised. d): timeseries of variance of column relative humidity (σ_{CRH}^2) for the same three simulations. Dot at day 1500 shows the average of σ_{CRH}^2 over years 1-3 (days 360-1440). All plots are calculated for the mean of the equatorial slice between latitude= $\pm 10^\circ$ of each simulation.

a minimal impact. However, the results from the HomogSW simulation in Figures 4.1 i-l show a very different manifestation of aggregation compared to the NoHomog simulation in Figures 4.1 a-d. There is still clustering, but it is on a smaller length and timescale than the clustering in the NoHomog simulation. Thus, despite the small shortwave feedback that the transient FMSE variance budget diagnoses, it appears that the total impact of the shortwave feedbacks is much greater.

Additionally, when comparing the histograms of these fields in Figure 4.4, we can see that the distributions of OLR, precipitation, and CRH are all similar to the NoHomog simulation, with a slight broadening of the CRH distribution in HomogSW. In agreement with this, the σ_{CRH}^2 is, on average, greater for HomogSW than NoHomog. This increase in σ_{CRH}^2 is also statistically significant. Inspecting σ_{CRH}^2 along its timeseries shows that there is large tem-

poral variability in σ_{CRH}^2 for HomogSW, with the largest values aligning with the times when there are the largest dry patches. This indicates that dry patches are able to become more dry in the HomogSW simulation. Thus, in the absence of shortwave feedbacks, aggregation is able to become more intense (with stronger moisture variability) but is shorter lived.

Some possible reasons for these results differing from the FMSE variance budget results above are that the FMSE budget is calculated from vertically integrated fields, and thus can fail to capture variations within the atmospheric column (Yao et al. 2022). Also, indirect feedbacks between shortwave anomalies and circulations are encapsulated in the advective term of the FMSE transient variance budget, instead of the shortwave feedback term. Thus, the key role of shortwave radiation could also be an indirect effect of shortwave radiative anomalies impacting on the circulations.

Nevertheless, this analysis highlights two important feedbacks. The first is that shortwave feedbacks can constrain the drying caused by zonal clustering. The second is that shortwave feedbacks lengthen the lifetime of dry patches which form. A possible mechanism which links these two effects:

1. A drier dry patch has reduced CRH locally
2. Lower near surface humidity enables larger differences in near surface water vapour and surface saturation water vapour (hereafter Δq) to form,
3. This will locally increase surface fluxes,
4. The Air-Sea Enthalpy Disequilibrium (ASED) term of the surface flux feedback decomposition will begin to dominate, which acts to remove these enthalpy gradients and re-moisten the dry patches.

The feedback loop above shows that, if shortwave feedbacks prevent more extreme drying during aggregation, this would allow convective clusters to persist for longer.

Another interesting feature we can pick out from Figures 4.4a-c is that, despite the differences in time and length scale of the self-aggregation in NoHomog and HomogSW, the aggregation drives similar changes in the equatorial-mean effects of aggregation. For example, the NoHomog and HomogSW simulations show a similar amount of broadening of the OLR distribution when compared to the HomogLW simulation (Figure 4.4a), despite the manifestations of aggregation looking very different between NoHomog and HomogSW. This implies that the length scale of aggregation does not linearly scale with the large-scale effects of aggregation.

4.3.1.3 Surface flux feedbacks

The surface enthalpy fluxes in Eq. 4.2 are primarily driven by variations in windspeed and the thermodynamic disequilibrium between the sea surface and the near-surface atmosphere. Wing and Emanuel (2014) partition the surface enthalpy term of Eq. 4.2 into three terms: the wind driven term representing the WISHE feedback, the thermodynamic disequilibrium term representing the ASER feedback, and an eddy term representing surface flux variations due to the product of the previous two terms. They found that the surface flux feedbacks are mostly driven by the first two terms and so we will focus on those here. The ASER is driven by differences in the temperature at the surface and the lowest model level (hereafter referred to as ΔT), and Δq . Additionally, Wing and Emanuel (2014) show that the WISHE feedback acts as a positive feedback on self-aggregation as it increases surface fluxes close to existing convection and thus the high FMSE regions, whilst the ASER acts as negative feedback with reduced surface fluxes in the convective regions. In Figures 4.3g-i we can see that the surface flux feedbacks are typically positive in the dry patches and mostly negative outside these regions with some positive contributions in the moistest columns. To further understand this, it is useful to examine the key variables which drive the surface flux feedback decomposition terms from Wing and Emanuel (2014), namely

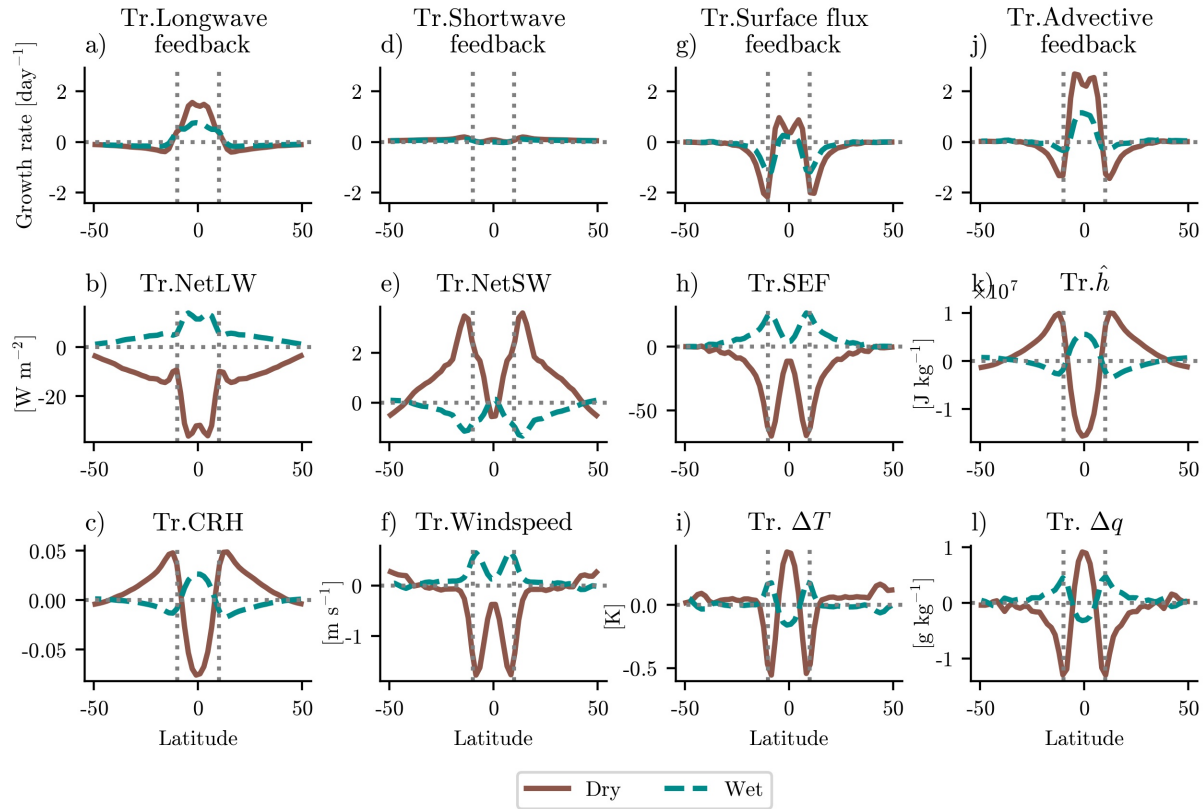


Figure 4.5. Meridional slices of variables composited on the condition of whether a slice passes through a dry patch at the equator (Dry) or not (Wet). Averaged over all meridional slices in time and longitude. Top row shows transient feedbacks of a) longwave, d) shortwave, g) surface flux, j) advective terms as calculated from the transient FMSE variance budget (Eq. 4.6). Second row shows terms which have been combined to calculate the transient feedbacks: b) transient NetLW, e) transient NetSW, h) transient surface enthalpy fluxes, k) transient integrated FMSE ($\hat{h}$). Third row shows c) transient CRH, f) transient surface windspeeds, i) transient ΔT , l) transient Δq . ΔT is the difference in the temperature at the surface and the lowest model level. Δq is the difference in surface saturation water vapour and near surface water vapour.

surface windspeeds, ΔT , and Δq .

To allow us to investigate how different fields change when a dry patch is present or not, we can composite meridional slices on the condition that they do or do not pass through a dry patch at the equator. This has been done for the fields presented in Figure 4.5, for the feedbacks in the transient FMSE budget terms and their individual components (Figures 4.5a-b, d-e, g-h, and j-k), CRH (Figure 4.5c), and the three terms above (Figure 4.5f, i, and l). We can see that, in the tropical region between $\pm 10^\circ$ latitude, it is variations in the surface windspeeds which are defining the positive sign of the surface enthalpy feedback. The

windspeeds within the dry patches are reduced due to a reduction in the overall large-scale meridional circulation. This is because, when a dry patch forms at around 0° it generates an opposing circulation to the large-scale circulation which diverges in all directions, including north and south. Therefore, this growth opposes the background circulation and reduces the windspeeds in the equatorial region, and hence reduces surface fluxes. This acts as a positive feedback on aggregation as it lowers the surface flux source of FMSE in the lower FMSE regions. This feedback 'overpowers' the negative ASER feedback, which is opposing aggregation in the lowest latitudes (Figure 4.5i and l).

4.3.1.4 Vertically-resolved analysis

As alluded to in previous sections, one drawback of the FMSE variance budget analysis is that it uses vertically integrated values. Whilst the method has allowed us to deduce some important results, it is still useful to investigate aggregation using the full vertical fields. In particular, this section will explore the vertical profile of the radiative heating rates to further investigate why our FMSE budget analysis suggested a weak role for the shortwave feedbacks, whereas the mechanism denials tests found a much larger impact of them. Additionally, a brief investigation of changes in the zonal advection of FMSE will be presented.

In Figure 4.6 we can see vertical slices of our NoHomog simulation. These are time-averaged over the periods of the simulation with the greatest proportion of dry patches and thus when the simulation is most strongly aggregated. Figure 4.6a) shows that when the simulation is more aggregated, there is more longwave cooling in the drier columns of the domain throughout the mid to low troposphere. This is consistent with the reduced humidity and cloud shown in Figures 4.6e and f, and is typical of a more aggregated domain. Inspecting the transient shortwave radiative heating (Figure 4.6b shows that when there is a more aggregated domain, there is increased shortwave heating in the mid to low troposphere in the dry columns. This is due to the reduced deep cloud in these regions,

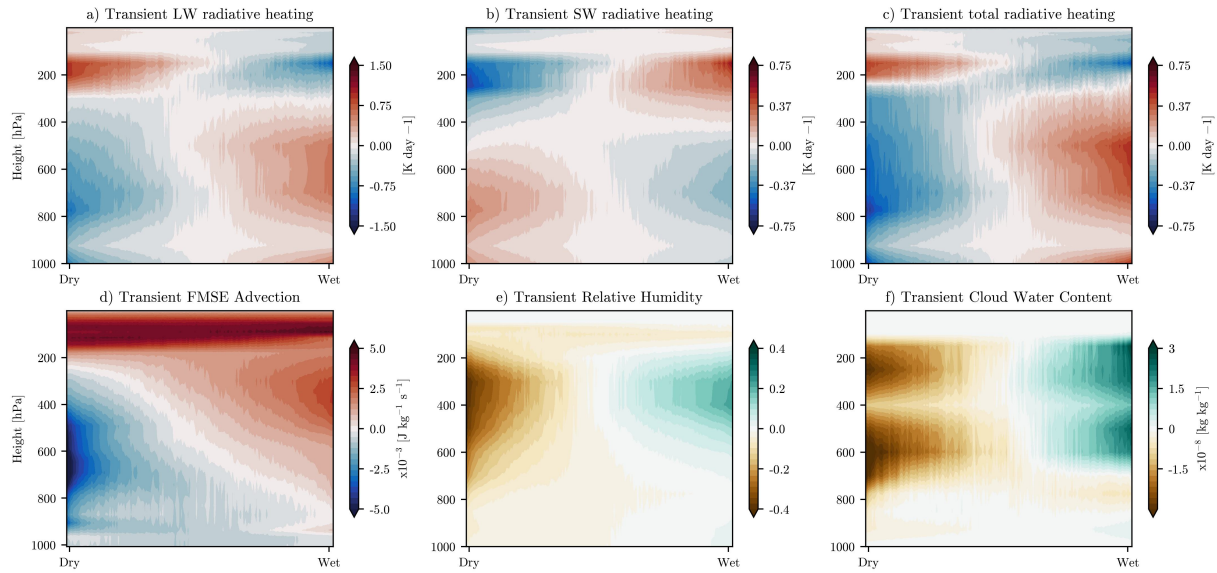


Figure 4.6. Vertical slices of 3D zonal fields, moisture sorted by column relative humidity values from dry to moist on x-axis. a) Transient longwave radiative heating rate, b) Transient longwave radiative heating rate, c) Transient total radiative heating rate, d) transient frozen moist static energy (FMSE) zonal advection ($-\mathbf{U}\nabla h$), e) Transient relative humidity, f) Transient cloud water content. All plots are averages over $\pm 10^\circ$ latitude equatorial slice and are a time average over the times when dry patches cover over 30% of the equator.

allowing more shortwave radiation to penetrate into the lower layers of the atmosphere. In the upper troposphere, we can see there is less shortwave heating in the dry columns. This is due to the reduced upper tropospheric humidity. When we performed the FMSE budget analysis, the transient shortwave feedback was positive everywhere. Therefore, the integrated NetSW term is negative in the dry regions, implying that the sign of the NetSW term is dominated by this upper tropospheric signal. These vertical slices provide some extra context, showing that the sign of the transient shortwave radiative heating will oppose the sign of the transient FMSE in the middle and lower troposphere. Thus, the reason our HomogSW simulation showed such different results to those we expected from the FMSE budget analysis could be due to different feedbacks dominating at different heights of the atmosphere. This shows the importance of using multiple feedback decomposition methods when performing aggregation mechanism analysis.

Investigating vertical slices also allows us to briefly examine the role of FMSE advection

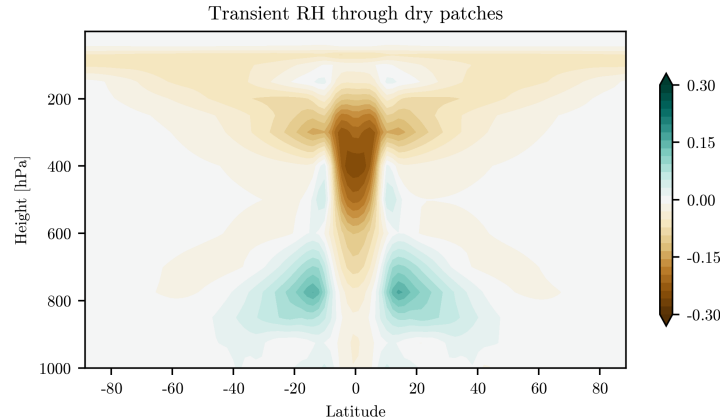


Figure 4.7. Height-latitude plot of the transient relative humidity. Plot is averaged over all times and longitudes at which meridional slices pass through an equatorial dry patch.

in this simulation. Figure 4.6d shows the transient advection of FMSE by zonal winds (i.e. $-U\nabla h$) during the more aggregated periods of the simulation. It is clear that the advection is negative throughout the boundary layer, implying there is increased upgradient horizontal transport of FMSE in the lowest levels of the atmosphere. Matching this, there is also an increased downgradient transfer of FMSE in the highest levels of the troposphere. These results support the findings of previous aggregation studies (e.g. Muller and Held 2012; Muller and Bony 2015). However, more work is required to determine if this feedback plays a role in triggering aggregation, or whether it is simply amplifying the aggregation which is triggered by diabatic feedbacks.

4.3.1.5 Meridional moisture export

When Müller and Hohenegger (2020) investigated the zonal aggregation of convection along a zonally-symmetric, meridional SST gradient, they found that the convective cluster exported moisture meridionally in the mid-troposphere. The authors highlighted some similarities between this moisture export and the phenomenon of atmospheric rivers (e.g. Newell et al. 1992; Zhu and Newell 1998; Ralph et al. 2011). In our work, we also see a mid-tropospheric moisture export. This is evidenced in Figure 4.5c. In the meridional com-

posites of CRH, we can see there is a moister sub-tropics surrounding the dry patches. The vertical profile of the relative humidity shows that a positive moisture signal is present in the mid-troposphere (Figure 4.7), thus our work partially supports the findings from Müller and Hohenegger (2020). The key difference between the two studies is which part of the domain the moisture export is happening from - in these simulations the export is from the dry patches, whereas in Müller and Hohenegger (2020) the export is from the convective cluster itself.

4.4 Discussion and Conclusions

In many convective self-aggregation studies, idealised models with homogeneous boundary conditions are used (e.g. Muller and Held 2012; Wing and Emanuel 2014; Muller and Bony 2015; Holloway and Woolnough 2016). This provides a useful simplification of the tropical climate in order to study the interactions of deep convection and circulations. However, the idealised nature of these models makes it difficult to interpret how the results would be applied in the real-world. Here, we have increased the complexity of an idealised RCE model to include a zonally-symmetric, meridional SST gradient and analysed the physical mechanisms driving the zonal aggregation of convection over the equatorial region.

We used both the transient FMSE variance budget, based on work from Beucler et al. (2019) and mechanism denial tests to find that self-aggregation feedbacks between longwave radiation, water vapour, and clouds are necessary for triggering aggregation to form, as in more idealised self-aggregation studies (e.g. Muller and Held 2012; Wing and Emanuel 2014; Becker et al. 2017; Yang 2018a). These feedbacks are driven primarily by the reduction in longwave cloudy-sky absorption within the dry patches. We also found that increased aggregation is accompanied by an increased zonal advection of FMSE, in line with previous self-aggregation studies (e.g. Muller and Held 2012; Muller and Bony 2015).

The role of shortwave feedbacks is slightly more complex. Direct shortwave feedbacks as calculated by transient FSME budget are small, but through mechanism denial tests we showed that removal of the zonal gradients in shortwave fluxes shortened both the time and length scales of aggregation formed. Therefore, as hypothesised by Holloway and Woolnough (2016), we suggest that shortwave feedbacks have a strong indirect effect on self-aggregation, especially in the presence of an SST gradient, which is supported by the vertical profile of the shortwave flux. In particular, our results suggest that the shortwave feedbacks are necessary for maintaining larger-scale dry patches. A full understanding of this feedback is important, and we recommend this is prioritised in future studies. Additionally, we showed that, despite the differences in time and length scale of the aggregation in the HomogSW simulation, the equatorial-mean effects of aggregation, such as a broadened humidity distribution are similar between NoHomog and HomogSW when compared to the not-aggregation HomogLW simulation. This implies that the length scale of aggregation does not linearly scale with the large-scale effects of aggregation.

The work we have presented here highlights an important role for interactions between radiation, moisture, and surface fluxes in driving the zonal clustering of convection along the equator. The similarity of our results to previous self-aggregation feedback analysis (e.g. Wing and Emanuel 2014; Coppin and Bony 2015; Muller and Bony 2015; Holloway and Woolnough 2016; Becker et al. 2017; Yang 2018a) suggest that the observed zonal clustering of convection along the equator could be impacted by convective self-aggregation. Whilst the primary driver of convective convergence in the tropics is typically variations in surface temperature (Back and Bretherton 2009), the results shown here imply that the potential role of self-aggregation feedbacks should not be ignored.

Clarifying the mechanisms controlling the spatial and temporal extent of clustering is important for improving our understanding of self-aggregation. The work presented here points towards contributions from shortwave radiation and surface fluxes being controlling

factors for this. Importantly, using only one feedback decomposition method would have led us to misdiagnosing the relative importance of the shortwave feedback. We therefore recommend future mechanism testing in aggregation studies use multiple methodologies in their work to prevent potentially spurious conclusions.

With aggregation having impacts on both the intensity and spatial distribution of precipitation, further analysis of these processes could provide key understanding of the mechanisms involved in determining the scale and lifetime of convective clustering in the real atmosphere, particularly within the ITCZ. As this is a highly idealised study, it can be difficult to fully quantify how the feedbacks identified above would interact in more complex atmospheres. In particular, how do these feedbacks interact with rotation and land? Answering such questions provide an interesting and important extension of our work, especially due to the drastic effects changes in regional precipitation have for people living within the ITCZ.

5 | Discussion and Conclusions

One never notices what has been done; one can only see what remains to be done.

MARIE CURIE

Convective self-aggregation is a manifestation of convective organisation, which can occur in highly idealised models. In the past decade, significant progress has been made to understand how it forms, how it is maintained, and how it affects the environment of its model domain. Whilst there are remaining questions within these topics, one overarching query that is not yet well understood is how highly idealised self-aggregation relates to real-world convective organisation. In this thesis, my goal was to investigate how previously identified self-aggregation mechanisms and feedbacks interact with organisation which is forced by more realistic forcings. I approached this problem by adding different 'real-world features' into idealised radiative-convective equilibrium (RCE) models, from which they are typically absent. In this chapter, I will first summarise the work presented in this thesis, before giving some general concluding remarks and identifying recommended avenues for future work.

5.1 Summary of thesis

The main question I sought to answer in **Chapter 2** was “*Can I force convection to aggregate by using atmospheric diabatic heating perturbations, and how does this affect the mechanisms of aggregation?*”. For this, I forced a thermally-direct circulation by adding a plume of strongly absorbing aerosol into the ICON general circulation model (GCM). The simulation was run in an RCE configuration, with no rotation, no land, no diurnal cycle, and with homogeneous and constant sea-surface temperatures (SSTs). This set-up was designed to be as close to other self-aggregation studies in order to make the comparison of results easier. Whilst the concept of forced aggregation by a thermally-direct circulation had been previously defined by Shamekh et al. (2020a), their work differed from mine in two key ways: their work generated the circulation through SST anomalies, and their work was done in a cloud-resolving model (CRM). I instead, utilised the results of Dagan et al. (2019), who showed that using an absorbing aerosol plume generated a thermally-direct circulation, to investigate how an atmospheric diabatic heating perturbation in an otherwise homogeneous environment would affect the convective aggregation. In particular, I was interested in how the forced aggregation interacted with self-aggregation and any differences in the mechanisms behind the organisation. Also, I used two different SSTs, as Coppin and Bony (2015) found differing contributions from self-aggregation feedbacks at different SSTs in a GCM. I found that, at an SST of 305K with no plume, convection strongly self-aggregates, whilst at 290K there is minimal aggregation. This is expected as results from RCEMIP showed that self-aggregation in GCMs often shows a strong dependence on SST (Becker and Wing 2020).

When the aerosol plume was included in the simulations, I showed that the thermally-direct circulation forced convection to aggregate around the plume. In addition to the convective cluster around the plume, there were radial branches of convection connected to the central cluster, forming a star-shaped cluster of convection. This spatial pattern occurs

due to the superposition of two circulations: the radial thermally-direct circulation driven by the aerosol plume, and local tangential circulations which locally organise each radial branch of convection. The 'star-shaped' convective cluster forms at two different SSTs, 290K and 305K, however at 290K, the plume drives a large increase in the degree of aggregation, whilst at 305K there is no change. Therefore, the inclusion of the heating perturbation can increase the degree of aggregation, but only for a non- or weakly-aggregated simulation. For a simulation which strongly aggregates without the forcing, the plume changes the geometry of the clustering but does not drive a change in the amount of aggregation.

When investigating the important feedbacks driving the aggregation at both SSTs, with and without the cluster there were some similarities to previous self-aggregation studies and some key differences. Longwave feedbacks are typically found to be essential for self-aggregation (e.g. Muller and Held 2012; Wing and Emanuel 2014; Holloway and Woolnough 2016; Pope et al. 2021), a result which I found to hold true for the simulations at 305K. The frozen moist static energy (FMSE) variance budget identified that longwave feedbacks drive the largest growth rate in the FMSE variance, and mechanism denial tests showed that aggregation is prevented without interactive longwave radiative fluxes. However, at the lower SST of 290K with the plume, I found different contributions from the different feedbacks. Whilst the longwave feedbacks are still the largest term in the FMSE variance budget decomposition, the relative contributions from the shortwave and surface enthalpy feedbacks are greater than in other simulations. In agreement with this, when the longwave radiative fluxes are horizontally homogenised, the plume can still force some aggregation.

There are many drivers of thermally-driven circulations in the tropics, from SST anomalies (e.g. Shamekh et al. 2020a; Silvers and Robinson 2021), and absorbing aerosol plumes (e.g. Dagan et al. 2019; Williams et al. 2022), to land-sea breezes driven by differential heating of land and ocean during daytime (Stull 2006). I have shown that absorbing aerosols could impact the aggregation of convection, and previous studies have found similar results for other

thermally-forced circulations (e.g. Tompkins 2001c; Coppin and Bellon 2019a; Shamekh et al. 2020a; Leutwyler and Hohenegger 2021). My results suggest that even when aggregation is forced to occur, there are still large contributions from self-aggregation feedbacks such that sometimes the forcing cannot aggregate convection together on its own. This significant result supports work in existing literature that have found important contributions to phenomena like the ITCZ (e.g. Voigt et al. 2014; Talib et al. 2018; Lau et al. 2020) and tropical cyclones (e.g. Ruppert et al. 2020; Yang et al. 2022) from feedbacks similar to those discussed in this thesis. However, if self-aggregation mechanisms are contributing to forced aggregation, this would make disentangling self-aggregation processes in observations more difficult than currently thought. On the other hand, trying to observe self-aggregation has been difficult as synoptic variability likely disrupts potential convectively-generated circulations at time scales faster than self-aggregation has been shown to occur. However, if this hypothesis is true, new studies could look for signatures of self-aggregation within more easily observed forced convective organisation events.

In **Chapter 3**, I added a different 'real-world forcing' to our simulations: land. The impact of land on self-aggregation is one of the biggest unanswered questions within the aggregation community. In recent years some studies have included land in these idealised modelling frameworks which has led to interesting results on the impact of land on temperature profiles and precipitation (Cronin et al. 2015; Leutwyler and Hohenegger 2021) over small islands. However, no studies have specifically investigated how aggregation mechanisms are impacted by the presence of a land-sea contrast. Also, existing studies have exclusively used CRMs for their research, however, this limits the size of land mass which can be included in a model. Therefore, these two open questions are what motivated me to ask *"What is the impact of land on large-scale convective aggregation?"*

My study design was similar to that of the simulations in Chapter 2 which do not include the aerosol plume. This gave me a good understanding of the equilibrium state convection

reaches if the land is not present. As I wanted to see how land impacts aggregation, I used the higher SST of 305K, as at this temperature, convection is strongly self-aggregated in the absence of land. The representation of land in this chapter was an idealised, circular, flat, continentally-sized island which was initialised with tropical 'rainforest-like' parameters.

I found that convection aggregates persistently over our island, leading to domain-mean warming, drying, and reduction in high-cloud amount, as with previous, more idealised self-aggregation simulations (e.g. Muller and Held 2012; Wing and Emanuel 2014; Cronin and Wing 2017; Wing et al. 2020; Zhang et al. 2021). The aggregation over land is triggered by surface fluxes, where sensible heating causes a land-sea thermal contrast, which in turn drives a land-sea breeze circulation. This circulation converges over the land, triggering convection. Although there are some differences, this is similar in many ways to the mechanisms driving the aggregation shown in Chapter 2: a thermally-direct circulation is spun up which causes convection to organise nearby, and convection is suppressed away from the heating source, although there are differences in the way the thermally-direct circulation is triggered.

After the initial triggering, the surface temperature anomaly field reverses with positive anomalies over the ocean and negative ones over land. Previous self-aggregation studies have shown that, when surface temperature pattern reverses like this, convection typically propagates towards the warmest surface temperatures (e.g. Tompkins 2001c; Hohenegger and Stevens 2018). Therefore, one would expect the convection to propagate towards the now comparatively warmer ocean. However, convection remains clustered over the negative temperature anomalies over land. I attributed this to radiative feedbacks between longwave fluxes and convection. The lower-tropospheric cloud longwave absorption is able to maintain an equivalent potential temperature gradient, which continues to drive the land-centred circulation. When testing this result, horizontally homogenising the longwave radiative fluxes effectively removed this virtual temperature gradient in the lower-

troposphere, and thus removed the surface level land-centred convergence. Without this convergence, I showed that near-surface FMSE was no longer advected upgradient which prevented the broadening of the moisture distribution that is typical of self-aggregation (e.g. Bretherton et al. 2005; Coppin and Bony 2015; Bony et al. 2016; Wing and Cronin 2016; Becker et al. 2017; Wing et al. 2020).

The work in Chapter 3 reinforced the key conclusion from Chapter 2, which is that self-aggregation feedbacks remain vital in maintaining clusters of convection, even if the initial clustering is triggered by a large-scale forcing. Also, in both chapters, the large-scale effects of self-aggregation such as the broadening of the moisture distribution and reduction in high-cloud amount also happen if the aggregation is initially forced. With the convection remaining locked over the land, I was also able to show a potential limit to the maximum size of convective cluster, in line with previous scaling work (e.g. Craig 1996). This scaling is remarkably similar to the typical length scale of the Madden-Julian Oscillation (MJO), a phenomenon self-aggregation has been linked to in the past (Arnold and Randall 2015; Khairoutdinov and Emanuel 2018). These two studies which simulated an MJO-like disturbance did so in a highly idealised framework, close to RCE but with rotation. Whilst I make no claim that our convective cluster is a representation of the MJO, especially as our simulations are non-rotating, it is interesting that the potential length scales are so similar. Therefore, I recommend a future line of research that further investigates the links between self-aggregation and the MJO. This could help us to understand not only a potential real-world manifestation of self-aggregation but also the length scale of self-aggregation. Understanding this scaling would clarify how we might observe self-aggregation in the future. Further discussion of future research directions can be found in Section 5.3.

Another potential interaction between forced- and self-aggregation has previously been documented by Müller and Hohenegger (2020). They showed that convection zonally aggregates in a cloud-resolving spherical domain with a meridional SST gradient and attributed

this to self-aggregation feedbacks. Therefore, I wanted to first verify that this zonal aggregation also occurs with parameterised convection, and do a detailed analysis of the feedbacks driving the self-aggregation. Thus, **Chapter 4** answers the question *"How does self-aggregation behave over the influence of a large-scale sea-surface temperature gradient?"*. As with each of the previous two chapters, I found that longwave feedbacks are essential for zonal aggregation to occur, and these generate a circulation which increases the up-gradient advection of FMSE when the equator is more aggregated. The role of shortwave feedbacks was found to impact the length and time scales of the aggregation indirectly, through interactions between shortwave radiation and the circulation. Additionally, I found that zonal aggregation has similar equator-mean effects to the domain-mean effects of idealised self-aggregation, such as a broadened moisture distribution and an increase in longwave cooling to space. These domain-mean effects occurred regardless of the time and length scales of aggregation. Finally, I showed that zonal aggregation is associated with a mid-tropospheric meridional moisture export. Müller and Hohenegger (2020) also found this moisture export, although in their simulations moisture was primarily exported from the convective cluster, whereas in my simulations the moisture export is from the dry patches. Altogether, these results point to zonal aggregation being a manifestation of self-aggregation in an incrementally more realistic atmosphere. Whilst in the real tropical atmosphere, the primary driver of zonal clustering is surface temperature gradients, the work I have presented in Chapter 4 implies that self-aggregation could play an important role in zonal clustering and therefore should not be ignored. Further, the conclusions from Chapters 2 and 3 have highlighted that self-aggregation feedbacks might be amplifying aggregation originally driven by a large-scale forcing. Therefore, it is also possible that, despite real-world zonal clustering being triggered by surface temperature gradients, self-aggregation mechanisms are playing a role in amplifying and maintaining the organisation.

However, in the presence of the meridional SST gradient, there are some differences between our zonal self-aggregation and more idealised self-aggregation. Firstly, in our study

there is still some convection covering most of the equator, even during periods which have increased aggregation due to the equatorial moisture convergence forced by the SST gradient. Secondly, I also showed that when self-aggregation forms it manifests as a dry patch, typically existing for hundreds of days in succession, covering 30-40% of the equator at the peak of aggregation. This differs from typical self-aggregation, where the dry patches generally expand to cover over 50% of the domain (e.g. Coppin and Bony 2015; Bony et al. 2016; Becker et al. 2017). Indeed, in Chapter 3 I showed that aggregated convection seems to only cover approximately 25% of the domain at any time. Thus, the work in Chapter 4 has shown that self-aggregation could be important for driving zonal clustering along the equator. However, as has been shown before, the tropical regions have a constant import of near-surface FMSE driven by the Hadley circulation (e.g. Rhiel and Malkus 1958; Neelin and Held 1987; Needham and Randall 2021). It is likely that this net import of FMSE is therefore driving the differences between more idealised self-aggregation, and the self-aggregation along the equator in this model with an SST gradient.

5.2 GCMs and parameterised convection

The work presented across this thesis uses a relatively coarse GCM with parameterised convection. The RCE model intercomparison project (RCEMIP) has robustly shown that both GCMs and CRMs self-aggregate, and that this aggregation drives similar domain-mean responses (Wing et al. 2020). However, other studies have shown differences in some features of aggregation between models with explicit and parameterised convection. As introduced in Chapter 1, Becker and Wing (2020) found that GCMs almost always show an increase in aggregation with warming in the RCEMIP ensemble, whereas CRMs showed no consistent response to SST. Additionally, Coppin and Bony (2015) found that the feedbacks driving self-aggregation in a GCM varied at high and low surface temperatures. At high temperatures they identified that the WISHE surface flux feedback was the main feedback driving aggre-

gation. However, at lower SSTs the circulation associated with low-level radiative cooling in the dry region was found to be the dominant feedback. Finally, Pope et al. (2022) found that the GCMs in the RCEMIP ensemble have stronger cloud-longwave radiation interactions than CRMs, and that typically resulted in faster aggregation in GCMs versus CRMs.

Therefore, when discussing the conclusions and outlooks from the research presented in this thesis, we must consider the potential impact the parameterisation scheme may have on the results presented. Throughout this thesis, I showed that the longwave feedbacks are a dominant factor in driving aggregation. Perhaps, from the results of Pope et al. (2022) this should be expected. It would be interesting to investigate the results presented here at different model resolutions and with an explicit convection scheme. There are many difficulties associated with this however, in particular, the computational expense of simulating a global domain for the time-scales these simulations require. However, I will next present some discussion on how an explicit convection scheme may impact the results from Chapters 2, 3, and 4.

In Chapter 2 I showed that the aerosol forcing drove a thermally-direct circulation which forced convection to aggregate. These results showed a lot of similarities to the CRM results from Shamekh et al. (2020a). In particular, both studies showed an importance of the radiative feedbacks in driving this aggregation, a lack of hysteresis when the forcing was removed, and an ability of the forcing to drive aggregation in the absence of radiative feedbacks. Thus I would expect the results of Chapter 2 to remain largely unchanged if computed with a CRM.

The investigation of the impact of an island on the aggregation of convection in Chapter 3 would possibly be the most interesting to explore with a higher resolution model. We found that the large-scale radiation-convection-circulation feedbacks were able to dampen the effect of the land surface cooling. This led to a land-centred circulation at all times, flooding the island and preventing dry soil from forming. In the work of Hohenegger and

Stevens (2018), there were found to be two opposing soil moisture-convection feedbacks. One was a positive aggregation feedback associated with increased convective instability over wet soils; the other was a negative aggregation feedback with dry soils inducing a low-level circulation reversal towards the non-convecting region. In our simulations, this circulation reversal never happened due to the lack of any dry soil. An investigation using a higher resolution model with explicit convection would allow us to investigate whether this is due to the resolution of the model used having an inability to resolve these feedbacks, or due to the processes and feedbacks which occur on the large-scale.

Finally, the results of the SST gradient investigation in Chapter 4 should be mostly robust in a model with explicit convection. This is due to the similarities shown between my results and those of Müller and Hohenegger (2020), who performed their analysis in a spherical CRM. Nevertheless, biases associated with convective parameterisation schemes have been shown to exhibit some important deficiencies. In particular, some GCMs simulate a double ITCZ instead of a single ITCZ (e.g. Mechoso et al. 1995; Lin 2007), and many GCMs capture equatorial Kelvin waves poorly (e.g. Straub et al. 2010). However, there are still CRMs which simulate a double ITCZ (e.g. Retsch et al. 2019) thus implying that presence of a single or double ITCZ is a result of more than just the convection parameterisation. Isolating the role self-aggregation plays on convective organisation at the equator would help to gain a better understanding of model biases in tropical convection. Thus, it remains important to continue to perform self-aggregation studies with both explicit and parameterised convection.

5.3 Avenues for future research

As introduced in Chapter 1, idealised models are an incredibly useful tool to enable us to probe more fundamental questions about the climate system (Schneider and Dickinson 1974; Hoskins 1984; Held 2005; Maher et al. 2019), and the work that has been produced

using RCE has greatly increased our understanding of how clouds, climate, and circulations interact. However, with using an idealised model comes limitations in how we can apply the results of a study to the real climate. Here, I will discuss some of the broader limitations of the approaches and methodologies used to fully contextualise the results in this thesis and present some opportunities for further research.

Aerosol-cloud interactions and observational fingerprints of self-aggregation

In Chapter 2 I used an idealised absorbing aerosol plume to force a thermally-direct circulation, which I showed had large impacts on aggregation. In our concluding remarks on that chapter, I highlighted that there are observed examples of plumes with a similar absorbing aerosol optical depth as used in our study (e.g. Eck et al. 2003; Vadrevu et al. 2015; Sharma et al. 2017; Filonchyk et al. 2020). Hence, there could be a link between high pollution or biomass burning events and convective aggregation. However, an additional complexity which must be taken into account is that my simulations were calculated using only the direct aerosol radiative effect, with no modelling of the interactions between aerosols and cloud droplets. The impact of aerosols on mesoscale convective systems (MCSs) is not well understood (Fan et al. 2016). It has been shown that increases in cloud condensation nuclei might impact MCS precipitation, intensity, and propagation through microphysical effects (e.g. Khain et al. 2005; Tao et al. 2007; Li et al. 2009; Seigel et al. 2013; Lebo and Morrison 2014), though this remains disputed, and the response to aerosols can differ with the type of MCS, the stage of the MCS within its lifecycle, and the response may be non-monotonic to aerosol abundance (e.g. Khain et al. 2005; Li et al. 2009; Seigel et al. 2013; Lebo and Morrison 2014; Fan et al. 2016; Kawecki et al. 2016; Chakraborty et al. 2018; Clavner et al. 2018; Fan et al. 2018). Dagan (2022) recently used small domain RCE simulations to investigate how aerosol-cloud interactions impacted the equilibrium climate sensitivity (ECS), finding an increase in the ECS with aerosol concentration due to an aerosol-driven, faster increase in precipitation efficiency, thus proving the usefulness of investigating aerosol-

cloud interactions in RCE. This precipitation efficiency increases faster under high aerosol concentrations due to a higher sensitivity of the liquid water mixing ratio to increasing CO_2 . Dagan (2022) conclude that their results might be of interest to self-aggregation studies as aggregated convection has also been shown to increase precipitation efficiency (Bao and Sherwood 2019).

In Chapter 2, I used a configuration of the aerosols MACv2-SP model which only implemented the direct aerosol-radiative effects of the plume. An interesting extension of this chapter could run two additional experiments whereby the cloud albedo effects of the aerosols are used to gain a better understanding of the impact of aerosols on the aggregation of convection. The first experiment could use the cloud-albedo effects in isolation, with the second experiment using both the direct radiative and cloud-albedo effects. Whilst this approach still does not account for potential aerosol lifetime effects on the convection, it would extend the analysis presented in this thesis to gain a more complete view of aerosol-aggregation interactions. The results of these three experiments together could help to understand firstly how MCSs might interact with aerosols, and secondly, help to inform on how we might be able to observe aggregation. The observational exercise could look for convective organisation surrounding strong aerosol emission plumes. If the conclusions of Chapter 2 hold true, they suggest that self-aggregation processes and feedbacks may amplify aggregation which is triggered by the aerosol plume. Thus, if we can create a dataset of observed organisation events around strong aerosols plumes such as from pollution, biomass burning, or volcanoes, then we can hunt for evidence of self-aggregation feedbacks at play in these observations.

Another complexity that would need to be considered when searching for observational fingerprints of self-aggregation around aerosol plumes is that our simulations were calculated on an aquaplanet, whilst most high aerosol plumes are produced over land. Of course, the work presented in Chapter 3 shows that aggregation may be preferential over

land, rather than ocean. There is some observational evidence that this may be true, with Machado and Rossow (1993) finding a preference for tropical mesoscale convective clusters to form over land. A third, key idealisation used in the modelling of Chapter 2 is the use of fixed aerosol plumes. Two possible repercussions of this are that real aerosol plumes often have a non-persistent source, and plume-forced aggregation will also drive plume-forced precipitation and thus the aerosols could be rained-out. Therefore, it is likely that the dynamics of a land surface (especially a more complex land surface than used in Chapter 3) accompanied with a temporary aerosol plume (unlike the constant one used in Chapter 2) are likely to have sufficient variability to disrupt the large-scale aggregation shown in this thesis, and so must be taken into account.

The monsoon

One significant phenomenon to which my work could be utilised for, but has not been fully discussed here is the monsoon. Whilst detailed discussions on this topic lie outside of the scope of this thesis, it is worth highlighting that a combination of the simulation designs presented in Chapters 2, 3 and 4 could be an incredibly useful test bed for investigating the monsoon. Recent work has suggested that regional monsoons are localised perturbations of a tropical convergence zone, which may sit at the equator (the ITCZ) or be pulled over a continent as a monsoon (e.g. Bordoni and Schneider 2008, 2010; Mukherjee et al. 2014; Faulk et al. 2017; Hill et al. 2019; Geen et al. 2020). Also, a large focus in the monsoon community is the role anthropogenic aerosols play in driving monsoon changes, currently and in the future (Ding et al. 2015). As the model design in this thesis removes many of the complexities of the real-world atmosphere, it allows us to study how convection fundamentally interacts with circulations, aerosols, and land. Therefore, I recommend a future study which combines our model design in Chapters 2, 3 and 4 with an idealised island, SST gradients, and aerosol plumes. It would then be easy to tweak parameters in order to create an ensemble of simulations with different SSTs, land properties, and aerosol optical properties. This work would

be similar to the Tropical Rain belts with an Annual cycle and a Continent Model Intercomparison Project (TRACMIP; Voigt et al. 2016) in which simulations with a zonally-symmetric, meridional SST gradient were performed which included a slab ocean, an idealised land continent, and rotation. The work I have suggested here strips TRACMIP back further, to a more idealised framework without interactive ocean surfaces, seasonal cycle, or rotation. This would allow us to investigate more fundamentally how the convection, land, and SST gradients are interacting. Comparing the results of this proposed study and TRACMIP would therefore enable us to have a more complete understanding of the ITCZ and monsoons.

Interactive surfaces and length scale of aggregation

A simplification used in the simulations presented in this thesis is a fixed sea-surface temperature. Other studies have shown that the interactive SST typically delay or prevent aggregation (Tompkins 2001c; Hohenegger and Stevens 2016; Coppin and Bony 2017; Shamekh et al. 2020b; Tompkins and Semie 2021). However, I showed in Chapter 4 that our convective cluster was able to persist, even when the surface temperature anomalies reversed. From this, I hypothesise that convection is able to remain aggregated, if the cluster is sufficiently large, due to the positive virtual temperature anomalies produced by the lower-tropospheric longwave cloud radiative effect. Many of the forced convective clusters in our work are extremely large, far bigger than typical length scales of observed mesoscale convective systems (e.g. Houze 1989), though the clusters are on the same order as the MJO (e.g. Zhang 2005). It would be an interesting, and useful extension of this thesis to understand firstly how our results are affected by an interactive ocean surface, and secondly if there is a length scale at which the persistence of aggregation is independent of surface temperature. Further, the work presented in Chapter 4 also showed that, in the presence of a meridional SST gradient, homogenising the shortwave feedbacks had implications on both the time and length scales of aggregation. I showed this is likely through the interactions of shortwave radiative fluxes and the advection of FMSE. Thus, future investigation of

the time and length scales of aggregation could also explore this relationship.

The need for a full hierarchy

I have discussed throughout this thesis that there are a plethora of simplifications used in typical self-aggregation studies. As introduced in Chapter 1, various studies have begun to investigate what happens when these additional complexities are included in models. With rotation, studies have typically shown that self-aggregation can present as tropical cyclogenesis (e.g. Bretherton et al. 2005; Khairoutdinov and Emanuel 2013; Wing et al. 2016; Muller and Romps 2018; Carstens and Wing 2020), or as the MJO in near-global models (Arnold and Randall 2015; Khairoutdinov and Emanuel 2018). Other studies have investigated inhomogeneous surfaces (e.g. Tompkins 2001a; Hohenegger and Stevens 2016; Coppin and Bony 2018; Müller and Hohenegger 2020; Shamekh et al. 2020a,b; Leutwyler and Hohenegger 2021; Tompkins and Semie 2021), or the diurnal cycle (e.g. Haerter et al. 2020; Tompkins and Semie 2021; Jensen et al. 2022). I have argued in this thesis, that incrementally increasing the complexity of idealised models is a useful way to isolate how more realistic processes can impact the results. I have learned a lot from the studies which have done this, as exemplified in this thesis, however I propose that a full model hierarchy project should be undertaken. This could, for example, continue to incrementally increase the complexity of the model used, from a 'classic' RCE simulation, through to an AMIP-style simulation, ideally with the addition of interactive SSTs. This targeted hierarchy would allow for a consistent analysis technique throughout, and as such would enable an easy comparison of results. This project is likely to help significantly improve our understanding of the manifestation of idealised self-aggregation in the real-world.

List of Figures

1.1	Cloud genera, as defined by the World Meteorological Organization	5
1.2	Climate feedbacks from IPCC AR6.	8
1.3	The three stages in the lifecycle of a deep convective cloud.	10
1.4	NASA Worldview snapshot showing Earth's clouds	17
1.5	Self-aggregation in different cloud-resolving models.	22
1.6	Self-aggregation in different general circulation models.	23
2.1	Vertical and horizontal profiles of aerosol plume AOD used as the diabatic heating perturbation.	62
2.2	Column relative humidity snapshots for two different sea-surface temperatures, both with and without aerosol plume.	64
2.3	Time series of σ_{CRH}^2 , a metric for convective aggregation for simulations with and without aerosol plume.	65
2.4	3D-mean fields showing the circulation and radiative fluxes driven by the aerosol plume.	66
2.5	3D fields showing radial and tangential circulations around the aerosol plume.	67
2.6	Mean σ_{CRH}^2 to test how strength of aerosol plume impacts the degree of aggregation.	70
2.7	Timeseries of normalised terms in FMSE variance budget for simulations with and without aerosol plume.	72

2.8	Timeseries of terms in FMSE variance budget for simulations with and without aerosol plume, decomposed into contributions from wettest and driest columns.	73
2.9	Snapshots of column relative humidity for simulations with and without aerosol plume and with either longwave or shortwave radiative feedbacks turned off.	76
2.10	Timeseries of σ_{CRH}^2 for simulations with and without aerosol plume and with either longwave or shortwave radiative feedbacks turned off.	77
2.11	Difference between 3D-mean fields showing the circulation and radiative fluxes driven by aerosol plume with and without longwave radiative feedbacks.	79
3.1	OLR and CRH fields showing convection persistently aggregating over land .	95
3.2	σ_{CRH}^2 timeseries, and temperature, relative humidity, and cloud fraction 3D vertical profiles for all experiments	96
3.3	Soil moisture at each level timeseries	97
3.4	Hovmöller plots of various atmospheric fields over the first 40 days.	99
3.5	FMSE variance budget timeseries	101
3.6	3D-mean fields showing circulation and radiative fluxes driving land-centred circulation	104
3.7	Hovmöller circulation plots for grass vegetation sensitivity test	106
3.8	FMSE variance budget timeseries for grass vegetation sensitivity test	107
3.9	Hovmöller circulation plots for HomogLW experiment	110
3.10	3D-mean circulation and radiative flux plots for HomogLW experiment . . .	111
3.11	Hovmöller plots of island size sensitivity test	114
4.1	OLR snapshot and OLR, CRH, and precipitation Hovmöller plots for all simulations	129
4.2	OLR with dry patches outlined using new metric	130
4.3	Transient FMSE variance budget plots for NoHomog simulation	131
4.4	Histograms and aggregation metric for all simulations	133

4.5	Meridional slice composites through wet and dry patches of FMSE transient budget terms and components	136
4.6	vertical slices of the zonal circulation when simulation is more/less aggregated	138
4.7	vertical slices of the zonal circulation when simulation is more/less aggregated	139

List of Tables

2.1	List of experiments in Chapter 2	60
3.1	Surface properties used to initialise the JSBACH4 land model within the ICON GCM for the rainforest and grass experiments.	93
3.2	List of experiments in Chapter 3	94

Bibliography

- Abbot DS (2014). Resolved snowball earth clouds. *Journal of Climate*,
- Albern N, Voigt A, Buehler SA, and Grützun V (2018). Robust and nonrobust impacts of atmospheric cloud-radiative interactions on the tropical circulation and its response to surface warming. *Geophysical Research Letters*, 45(16):8577–8585.
- Allan RP, Soden BJ, John VO, Ingram W, and Good P (2010). Current changes in tropical precipitation. *Environmental Research Letters*, 5(2):025205.
- Arakawa A (2004). The cumulus parameterization problem: Past, present, and future. *Journal of climate*, 17(13):2493–2525.
- Arnold NP and Putman WM (2018). Nonrotating convective self-aggregation in a limited area AGCM. *Journal of advances in modeling earth systems*, 10(4):1029–1046.
- Arnold NP and Randall DA (2015). Global-scale convective aggregation: Implications for the Madden-Julian Oscillation. *Journal of Advances in Modeling Earth Systems*, 7(4):1499–1518.
- Back LE and Bretherton CS (2009). On the relationship between SST gradients, boundary layer winds, and convergence over the tropical oceans. *Journal of Climate*, 22(15):4182–4196.
- Bao J and Sherwood SC (2019). The role of convective self-aggregation in extreme instantaneous versus daily precipitation. *Journal of Advances in Modeling Earth Systems*, 11(1):19–33.
- Bao J, Sherwood SC, Alexander LV, and Evans J. (2017). Future increases in extreme precipitation exceed observed scaling rates. *Nature Climate Change*, 7(2):128–132.
- Becker T (2018). On the interaction of precipitating convection with its environment and the role of convective organization. PhD Thesis. Universität Hamburg.

- Becker T and Stevens B (2014). Climate and climate sensitivity to changing CO₂ on an idealized land planet. *Journal of Advances in Modeling Earth Systems*, 6(4):1205–1223.
- Becker T, Stevens B, and Hohenegger C (2017). Imprint of the convective parameterization and sea-surface temperature on large-scale convective self-aggregation. *Journal of Advances in Modeling Earth Systems*, 9(2):1488–1505.
- Becker T and Wing AA (2020). Understanding the extreme spread in climate sensitivity within the radiative-convective equilibrium model intercomparison project. *Journal of Advances in Modeling Earth Systems*, 12(10):e2020MS002165.
- Bell JP, Tompkins AM, Bouka-Biona C, and Sanda IS (2015). A process-based investigation into the impact of the Congo basin deforestation on surface climate. *Journal of Geophysical Research: Atmospheres*, 120(12):5721–5739.
- Beucler T, Abbott TH, Cronin TW, and Pritchard MS (2019). Comparing convective self-aggregation in idealized models to observed moist static energy variability near the equator. *Geophysical Research Letters*, 46(17-18):10589–10598.
- Beucler T and Cronin T (2019). A budget for the size of convective self-aggregation. *Quarterly Journal of the Royal Meteorological Society*, 145(720):947–966.
- Beucler T, Cronin T, and Emanuel K (2018). A linear response framework for radiative-convective instability. *Journal of Advances in Modeling Earth Systems*, 10(8):1924–1951.
- Beucler T and Cronin TW (2016). Moisture-radiative cooling instability. *Journal of Advances in Modeling Earth Systems*, 8(4):1620–1640.
- Beucler T, Leutwyler D, and Windmiller JM (2020). Quantifying convective aggregation using the tropical moist margin's length. *Journal of Advances in Modeling Earth Systems*, 12(10):e2020MS002092.
- Biasutti M, Russotto RD, Voigt A, and Blackmon-Luca CC (2021). The Effect of an Equatorial Continent on the Tropical Rain Belt. Part I: Annual Mean Changes in the ITCZ. *Journal of Climate*, 34(14):5813–5828.
- Bollasina MA, Ming Y, and Ramaswamy V (2011). Anthropogenic aerosols and the weakening of the South Asian summer monsoon. *science*, 334(6055):502–505.

- Bony S, Semie A, Kramer RJ, Soden B, Tompkins AM, and Emanuel KA (2020). Observed modulation of the tropical radiation budget by deep convective organization and lower-tropospheric stability. *AGU advances*, 1(3):e2019AV000155.
- Bony S, Stevens B, Coppin D, Becker T, Reed KA, Voigt A, and Medeiros B (2016). Thermodynamic control of anvil cloud amount. *Proceedings of the National Academy of Sciences*, 113(32):8927–8932.
- Bony S, Stevens B, Frierson DMW, Jakob C, Kageyama M, Pincus R, et al. (2015). Clouds, circulation and climate sensitivity. *Nature Geoscience*, 8(4):261–268.
- Bordoni S and Schneider T (2008). Monsoons as eddy-mediated regime transitions of the tropical overturning circulation. *Nature Geoscience*, 1(8):515–519.
- Bordoni S and Schneider T (2010). Regime transitions of steady and time-dependent Hadley circulations: Comparison of axisymmetric and eddy-permitting simulations. *Journal of the Atmospheric Sciences*, 67(5):1643–1654.
- Bretherton CS, Blossey PN, and K. M (2005). An energy-balance analysis of deep convective self-aggregation above uniform SST. *Journal of the Atmospheric Sciences*,
- Bruno RD, Da Rocha HR, De Freitas HC, Goulden ML, and Miller SD (2006). Soil moisture dynamics in an eastern Amazonian tropical forest. *Hydrological Processes: An International Journal*, 20(12):2477–2489.
- Byers HR and Braham RR (1948). Thunderstorm structure and circulation. *Journal of meteorology*, 5(3):71–86.
- Byrne MP and Schneider T (2016). Narrowing of the ITCZ in a warming climate: Physical mechanisms. *Geophysical Research Letters*, 43(21):11–350.
- Caballero R and Huber M (2010). Spontaneous transition to superrotation in warm climates simulated by CAM3. *Geophysical Research Letters*, 37(11).
- Carbone RE, Wilson JW, Keenan TD, and Hacker JM (2000). Tropical island convection in the absence of significant topography. Part I: Life cycle of diurnally forced convection. *Monthly weather review*, 128(10):3459–3480.

- Carstens JD and Wing AA (2020). Tropical cyclogenesis from self-aggregated convection in numerical simulations of rotating radiative-convective equilibrium. *Journal of Advances in Modeling Earth Systems*, 12(5):e2019MS002020.
- Chakraborty S, Fu R, Rosenfeld D, and Massie ST (2018). The influence of aerosols and meteorological conditions on the total rain volume of the mesoscale convective systems over tropical continents. *Geophysical Research Letters*, 45(23):13–099.
- Chou C, Chiang JCH, Lan CW, Chung CH, Liao YC, and Lee CJ (2013). Increase in the range between wet and dry season precipitation. *Nature Geoscience*, 6(4):263–267.
- Chou C, Neelin JD, Chen CA, and Tu JY (2009). Evaluating the “rich-get-richer” mechanism in tropical precipitation change under global warming. *Journal of climate*, 22(8):1982–2005.
- Clavner M, Cotton WR, Heever SC van den, Saleeby SM, and Pierce JR (2018). The response of a simulated mesoscale convective system to increased aerosol pollution: Part I: Precipitation intensity, distribution, and efficiency. *Atmospheric Research*, 199:193–208.
- Colin M, Sherwood S, Geoffroy O, Bony S, and Fuchs D (2019). Identifying the sources of convective memory in cloud-resolving simulations. *Journal of the Atmospheric Sciences*, 76(3):947–962.
- Coppin D and Bellon G (2019a). Physical mechanisms controlling the offshore propagation of convection in the tropics: 1. Flat island. *Journal of Advances in Modeling Earth Systems*, 11(9):3042–3056.
- Coppin D and Bellon G (2019b). Physical mechanisms controlling the offshore propagation of convection in the tropics: 2. Influence of topography. *Journal of Advances in Modeling Earth Systems*, 11(10):3251–3264.
- Coppin D and Bony S (2017). Internal variability in a coupled general circulation model in radiative-convective equilibrium. *Geophysical Research Letters*, 44(10):5142–5149.
- Coppin D and Bony S (2018). On the interplay between convective aggregation, surface temperature gradients, and climate sensitivity. *Journal of Advances in Modeling Earth Systems*, 10(12):3123–3138.
- Coppin D and Bony S (2015). Physical mechanisms controlling the initiation of convective self-aggregation in a General Circulation Model. *Journal of Advances in Modeling Earth Systems*, 7(4):2060–2078.

- Cotton WR, Bryan G, and Heever SC van den (2010). Storm and Cloud Dynamics–The Dynamics of Clouds and Precipitating Mesoscale Systems, International Geophysics, vol. 99. *Elsevier*, 10:S0074–6142.
- Craig GC (1996). Dimensional analysis of a convecting atmosphere in equilibrium with external forcing. *Quarterly Journal of the Royal Meteorological Society*, 122(536):1963–1967.
- Craig GC and Mack JM (2013). A coarsening model for self-organization of tropical convection. *Journal of Geophysical Research: Atmospheres*, 118(16):8761–8769.
- Cronin TW, Emanuel KA, and Molnar P (2015). Island precipitation enhancement and the diurnal cycle in radiative-convective equilibrium. *Quarterly Journal of the Royal Meteorological Society*, 141(689):1017–1034.
- Cronin TW and Wing AA (2017). Clouds, Circulation, and Climate Sensitivity in a Radiative-Convective Equilibrium Channel Model. *Journal of Advances in Modeling Earth Systems*, 9(8):2883–2905.
- Crook NA (2001). Understanding Hector: The dynamics of island thunderstorms. *Monthly weather review*, 129(6):1550–1563.
- Dagan G (2022). Equilibrium climate sensitivity increases with aerosol concentration due to changes in rain efficiency. *EGUsphere*, 1–20.
- Dagan G, Stier P, and Watson-Parris D (2019). Contrasting response of precipitation to aerosol perturbation in the tropics and extratropics explained by energy budget considerations. *Geophysical research letters*, 46(13):7828–7837.
- Davis CA (2015). The formation of moist vortices and tropical cyclones in idealized simulations. *Journal of the Atmospheric Sciences*, 72(9):3499–3516.
- De Rooy WC, Bechtold P, Fröhlich K, Hohenegger C, Jonker H, Mironov D, Pier SA, Teixeira J, and Yano JI (2013). Entrainment and detrainment in cumulus convection: An overview. *Quarterly Journal of the Royal Meteorological Society*, 139(670):1–19.
- Ding Y, Liu Y, Song Y, and Zhang J (2015). From MONEX to the global monsoon: A review of monsoon system research. *Advances in Atmospheric Sciences*, 32(1):10–31.
- Dingley B, Dagan G, and Stier P (2021). Forcing convection to aggregate using diabatic heating perturbations. *Journal of Advances in Modeling Earth Systems*, 13(10):e2021MS002579.

- Dingley B, Dagan G, Stier P, and Herbert RJ (2022). The impact of a land-sea contrast on convective aggregation in radiative-convective equilibrium. *in review*,
- Dixit V, Geoffroy O, and Sherwood SC (2018). Control of ITCZ width by low-level radiative heating from upper-level clouds in aquaplanet simulations. *Geophysical Research Letters*, 45(11):5788–5797.
- Djehdian LA, Chini CM, Marston L, Konar M, and Stillwell AS (2019). Exposure of urban food–energy–water (FEW) systems to water scarcity. *Sustainable Cities and Society*, 50:101621.
- Doswell CA (1985). *The operational meteorology of convective weather: storm scale analysis*. Tech. rep. Boulder, Colorado.
- Douville H et al. (2021). Water Cycle Changey. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Masson-Delmotte V et al. Cambridge university press, pp. 1055–1210.
- Dunlop S (2008). *A dictionary of weather*. OUP Oxford.
- Eck TF, Holben BN, Ward DE, Mukelabai MM, Dubovik O, Smirnov A, Schafer JS, Hsu NC, Piketh SJ, Queface A, et al. (2003). Variability of biomass burning aerosol optical characteristics in southern Africa during the SAFARI 2000 dry season campaign and a comparison of single scattering albedo estimates from radiometric measurements. *Journal of Geophysical Research: Atmospheres*, 108(D13).
- Emanuel KA (1994). *Atmospheric convection*. Oxford University Press on Demand.
- Emanuel KA (2013). Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. *Proceedings of the National Academy of Sciences*, 110(30):12219–12224.
- Emanuel KA, Wing AA, and Vincent EM (2014). Radiative-convective instability. *Journal of Advances in Modeling Earth Systems*, 6(1):75–90.
- Fan J, Rosenfeld D, Zhang Y, Giangrande SE, Li Z, Machado LAT, Martin ST, Yang Y, Wang J, Artaxo P, et al. (2018). Substantial convection and precipitation enhancements by ultrafine aerosol particles. *Science*, 359(6374):411–418.
- Fan J, Wang Y, Rosenfeld D, and Liu X (2016). Review of aerosol–cloud interactions: Mechanisms, significance, and challenges. *Journal of the Atmospheric Sciences*, 73(11):4221–4252.

- Faulk S, Mitchell J, and Bordoni S (2017). Effects of rotation rate and seasonal forcing on the ITCZ extent in planetary atmospheres. *Journal of the Atmospheric Sciences*, 74(3):665–678.
- Fildier B, Parishani H, and Collins WD (2017). Simultaneous characterization of mesoscale and convective-scale tropical rainfall extremes and their dynamical and thermodynamic modes of change. *Journal of Advances in Modeling Earth Systems*, 9(5):2103–2119.
- Filonchyk M, Hurynovich V, Yan H, and Yang S (2020). Atmospheric pollution assessment near potential source of natural aerosols in the South Gobi Desert region, China. *GIScience & Remote Sensing*, 57(2):227–244.
- Filonchyk M, Yan H, Zhang Z, Yang S, Li W, and Li Y (2019). Combined use of satellite and surface observations to study aerosol optical depth in different regions of China. *Scientific reports*, 9(1):1–15.
- Findell KL and Eltahir EAB (2003). Atmospheric controls on soil moisture–boundary layer interactions. Part I: Framework development. *Journal of Hydrometeorology*, 4(3):552–569.
- Forster P et al. (2021). The Earth’s Energy Budget, Climate Feedbacks, and Climate Sensitivity. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Ed. by Masson-Delmotte V et al. Cambridge university press, pp. 923–1054.
- Fritsch JM, Kane RJ, and Chelius CR (1986). The contribution of mesoscale convective weather systems to the warm-season precipitation in the United States. *Journal of Applied Meteorology and Climatology*, 25(10):1333–1345.
- Geen R, Bordoni S, Battisti DS, and Hui K (2020). Monsoons, ITCZs, and the concept of the global monsoon. *Reviews of Geophysics*, 58(4):e2020RG000700.
- Gentine P, Holtslag AAM, D’Andrea F, and Ek M (2013). Surface and atmospheric controls on the onset of moist convection over land. *Journal of Hydrometeorology*, 14(5):1443–1462.
- Giorgetta MA et al. (2018). ICON-A, the Atmosphere Component of the ICON Earth System Model: I. Model Description. *Journal of Advances in Modeling Earth Systems*, 10(7):1613–1637.
- Grabowski WW (2001). Coupling cloud processes with the large-scale dynamics using the cloud-resolving convection parameterization (CRCP). *Journal of the Atmospheric Sciences*, 58(9):978–997.

- Grabowski WW and Moncrieff MW (2001). Large-scale organization of tropical convection in two-dimensional explicit numerical simulations. *Quarterly Journal of the Royal Meteorological Society*, 127(572):445–468.
- Grose MR, Narsey S, Delage FP, Dowdy AJ, Bador M, Boschat G, Chung C, Kajtar J., Rauniyar S, Freund MB, et al. (2020). Insights from CMIP6 for Australia's future climate. *Earth's Future*, 8(5):e2019EF001469.
- Guichard F and Couvreux F (2017). A short review of numerical cloud-resolving models. *Tellus A: Dynamic Meteorology and Oceanography*, 69(1):1373578.
- Haerter JO, Meyer B, and Nissen SB (2020). Diurnal self-aggregation. *npj Climate and Atmospheric Science*, 3(1):1–11.
- Hagemann S (2002). *An improved land surface parameter dataset for global and regional climate models*. Tech. rep. Hamburg, Germany: Max Planck Institute for Meteorology.
- Halley E (1686). An historical account of the trade winds, and monsoons, observable in the seas between and near the Tropicks, with an attempt to assign the physical cause of the said winds. *Philosophical Transactions of the Royal Society of London*, 16(183):153–168.
- Harrop BE and Hartmann DL (2016). The role of cloud radiative heating in determining the location of the ITCZ in aquaplanet simulations. *Journal of Climate*, 29(8):2741–2763.
- Harvey BJ, Cook P, Shaffrey LC, and Schiemann R (2020). The response of the northern hemisphere storm tracks and jet streams to climate change in the CMIP3, CMIP5, and CMIP6 climate models. *Journal of Geophysical Research: Atmospheres*, 125(23):e2020JD032701.
- Haywood J and Boucher O (2000). Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review. *Reviews of geophysics*, 38(4):513–543.
- Held IM (2005). The gap between simulation and understanding in climate modeling. *Bulletin of the American Meteorological Society*, 86(11):1609–1614.
- Held IM, Hemler RS, and Ramaswamy V (1993). Radiative-convective equilibrium with explicit two-dimensional moist convection. *Journal of the Atmospheric Sciences*, 50(23):3909–3927.
- Held IM and Hou AY (1980). Nonlinear axially symmetric circulations in a nearly inviscid atmosphere. *Journal of the Atmospheric Sciences*, 37(3):515–533.
- Held IM and Soden BJ (2006). Robust Responses of the Hydrological Cycle to Global Warming. *Journal of Climate*, 19(21):5686–5699.

- Held IM, Zhao M, and Wyman B (2007). Dynamic radiative–convective equilibria using GCM column physics. *Journal of the Atmospheric Sciences*, 64(1):228–238.
- Hennon CC, Papin PP, Zarzar CM, Michael JR, Caudill JA, Douglas CR, Groetsema WC, Lacy JH, Maye ZD, Reid JL, et al. (2013). Tropical cloud cluster climatology, variability, and genesis productivity. *Journal of climate*, 26(10):3046–3066.
- Hill SA, Bordoni S, and Mitchell JL (2019). Axisymmetric constraints on cross-equatorial Hadley cell extent. *Journal of the Atmospheric Sciences*, 76(6):1547–1564.
- Hohenegger C and Stevens B (2016). Coupled radiative convective equilibrium simulations with explicit and parameterized convection. *Journal of Advances in Modeling Earth Systems*, 8(3):1468–1482.
- Hohenegger C and Stevens B (2018). The role of the permanent wilting point in controlling the spatial distribution of precipitation. *Proceedings of the National Academy of Sciences*, 115(22):5692–5697.
- Holloway CE (2017). Convective aggregation in realistic convective-scale simulations. *Journal of Advances in Modeling Earth Systems*, 9(2):1450–1472.
- Holloway CE, Wing AA, Bony S, Muller C, Masunaga H, L’Ecuyer TS, Turner DD, and Zuidema P (2017). Observing convective aggregation. *Surveys in Geophysics*, 38(6):1199–1236.
- Holloway CE and Woolnough SJ (2016). The sensitivity of convective aggregation to diabatic processes in idealized radiative-convective equilibrium simulations. *Journal of Advances in Modeling Earth Systems*, 8(1):166–195.
- Hoskins BJ (1984). Dynamical processes in the atmosphere and the use of models. *Quarterly Journal of the Royal Meteorological Society*, 109(459):1–21.
- Houze RA (2014). *Cloud dynamics*. Academic press.
- Houze RA (1989). Observed structure of mesoscale convective systems and implications for large-scale heating. *Quarterly Journal of the Royal Meteorological Society*, 115(487):425–461.
- Houze RA (1977). Structure and dynamics of a tropical squall–line system. *Monthly Weather Review*, 105(12):1540–1567.
- Houze RA, Smull BF, and Dodge P (1990). Mesoscale organization of springtime rainstorms in Oklahoma. *Monthly Weather Review*, 118(3):613–654.

- Howard L (1803). I. On the modifications of clouds, and on the principles of their production, suspension, and destruction; being the substance of an essay read before the Askesian Society in the session 1802–3. *The Philosophical Magazine*, 17(65):5–11.
- Huang P, Xie SP, Hu K, Huang G, and Huang R (2013). Patterns of the seasonal response of tropical rainfall to global warming. *Nature Geoscience*, 6(5):357–361.
- Isaac GA (1986). Summer Cumulus Cloud Lifetime—Importance to Static Mode Seeding. *Precipitation Enhancement—A Scientific Challenge*. Springer, pp. 25–28.
- Jakob C, Singh MS, and Jungandreas L (2019). Radiative Convective Equilibrium and Organized Convection: An Observational Perspective. *Journal of Geophysical Research: Atmospheres*, 124(10):5418–5430.
- Jeevanjee N and Romps DM (2013). Convective self-aggregation, cold pools, and domain size. *Geophysical Research Letters*, 40(5):994–998.
- Jensen GG, Fiévet R, and Haerter JO (2022). The diurnal path to persistent convective self-aggregation. *Journal of Advances in Modeling Earth Systems*, e2021MS002923.
- Jin D, Oreopoulos L, Lee D, Tan J, and Kim K (2022). A New Organization Metric for Synoptic Scale Tropical Convective Aggregation. *Journal of Geophysical Research: Atmospheres*, 127(13):e2022JD036665.
- Jones C and Carvalho LMV (2006). Changes in the activity of the Madden–Julian oscillation during 1958–2004. *Journal of Climate*, 19(24):6353–6370.
- Jungclaus JH et al. (2022). The ICON Earth System Model Version 1.0. *Journal of Advances in Modeling Earth Systems*, 14(4):e2021MS002813.
- Kang SM, Shin Y, and Xie SP (2018). Extratropical forcing and tropical rainfall distribution: energetics framework and ocean Ekman advection. *Npj Climate and Atmospheric Science*, 1(1):1–10.
- Kaufman YJ, Tanré D, and Boucher O (2002). A satellite view of aerosols in the climate system. *Nature*, 419(6903):215–223.
- Kawecki S, Henebry GM, and Steiner AL (2016). Effects of urban plume aerosols on a mesoscale convective system. *Journal of the Atmospheric Sciences*, 73(12):4641–4660.
- Kent C, Chadwick R, and Rowell DP (2015). Understanding uncertainties in future projections of seasonal tropical precipitation. *Journal of Climate*, 28(11):4390–4413.

- Khain A, Ovtchinnikov M, Pinsky M, Pokrovsky A, and Krugliak H (2000). Notes on the state-of-the-art numerical modeling of cloud microphysics. *Atmospheric Research*, 55(3-4):159–224.
- Khain A, Rosenfeld D, and Pokrovsky A (2005). Aerosol impact on the dynamics and microphysics of deep convective clouds. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 131(611):2639–2663.
- Khairoutdinov M, Randall D, and DeMott C (2005). Simulations of the atmospheric general circulation using a cloud-resolving model as a superparameterization of physical processes. *Journal of the Atmospheric Sciences*, 62(7):2136–2154.
- Khairoutdinov MF and Emanuel KA (2010). Aggregated convection and the regulation of tropical climate, Paper presented at 29th Conference on Hurricanes and Tropical Meteorology. Vol. 13. American Meteorological Society, Tucson, Arizona.
- Khairoutdinov MF and Emanuel KA (2018). Intraseasonal variability in a cloud-permitting near-global equatorial aquaplanet model. *Journal of the Atmospheric Sciences*, 75(12):4337–4355.
- Khairoutdinov MF and Emanuel KA (2013). Rotating radiative-convective equilibrium simulated by a cloud-resolving model. *Journal of Advances in Modeling Earth Systems*, 5(4):816–825.
- Kiely L, Spracklen DV, Wiedinmyer C, Conibear L, Reddington CL, Archer-Nicholls S, Lowe D, Arnold SR, Knote C, Khan MF, et al. (2019). New estimate of particulate emissions from Indonesian peat fires in 2015. *Atmospheric Chemistry and Physics*, 19(17):11105–11121.
- King MD, Platnick S, Menzel WP, Ackerman SA, and Hubanks PA (2013). Spatial and temporal distribution of clouds observed by MODIS onboard the Terra and Aqua satellites. *IEEE transactions on geoscience and remote sensing*, 51(7):3826–3852.
- Kingsmill DE (1995). Convection initiation associated with a sea-breeze front, a gust front, and their collision. *Monthly weather review*, 123(10):2913–2933.
- Klocke D, Pincus R, and Quaas J (2011). On constraining estimates of climate sensitivity with present-day observations through model weighting. *Journal of Climate*, 24(23):6092–6099.
- Knutson T, Camargo SJ, Chan JC, Emanuel K, Ho CH, Kossin J, Mohapatra M, Satoh M, Sugi M, Walsh K, et al. (2020). Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming. *Bulletin of the American Meteorological Society*, 101(3):E303–E322.

- Knutson T, Landsea C, and Emanuel K (2010). Tropical cyclones and climate change: A review. *Global perspectives on tropical cyclones: from science to mitigation*, 243–284.
- Köhler H (1936). The nucleus in and the growth of hygroscopic droplets. *Transactions of the Faraday Society*, 32:1152–1161.
- Koster RD, Dirmeyer PA, Guo Z, Bonan G, Chan E, Cox P, Gordon CT, Kanae S, Kowalczyk E, Lawrence D, et al. (2004). Regions of strong coupling between soil moisture and precipitation. *Science*, 305(5687):1138–1140.
- Laing AG and Fritsch JM (1997). The global population of mesoscale convective complexes. *Quarterly Journal of the Royal Meteorological Society*, 123(538):389–405.
- Lamarck JB (1802). Sur la forme des nuages. *Annuaire Météorologique pour l'an XIV de l'ère de la République Française*, No. 3:149–164.
- Lane TP and Reeder MJ (2001). Convectively generated gravity waves and their effect on the cloud environment. *Journal of the atmospheric sciences*, 58(16):2427–2440.
- Lau KM and Kim KM (2006). Observational relationships between aerosol and Asian monsoon rainfall, and circulation. *Geophysical research letters*, 33(21).
- Lau KM, Kim MK, and Kim KM (2006). Asian summer monsoon anomalies induced by aerosol direct forcing: the role of the Tibetan Plateau. *Climate dynamics*, 26(7):855–864.
- Lau WKM, Kim KM, Chern JD, Tao WK, and Leung LR (2020). Structural changes and variability of the ITCZ induced by radiation–cloud–convection–circulation interactions: inferences from the Goddard Multi-scale Modeling Framework (GMMF) experiments. *Climate Dynamics*, 54:211–229.
- Lebo ZJ and Morrison H (2014). Dynamical effects of aerosol perturbations on simulated idealized squall lines. *Monthly Weather Review*, 142(3):991–1009.
- Leutwyler D and Hohenegger C (2021). Weak cooling of the troposphere by tropical islands in simulations of the radiative-convective equilibrium. *Quarterly Journal of the Royal Meteorological Society*, 147(736):1788–1800.
- Li G, Wang Y, Lee KH, Diao Y, and Zhang R (2009). Impacts of aerosols on the development and precipitation of a mesoscale squall line. *Journal of Geophysical Research: Atmospheres*, 114(D17).
- Li Z, Lau WKM, Ramanathan V, Wu G, Ding Y, Manoj MG, Liu J, Qian Y, Li J, Zhou T, et al. (2016). Aerosol and monsoon climate interactions over Asia. *Reviews of Geophysics*, 54(4):866–929.

- Lin JL (2007). The double-ITCZ problem in IPCC AR4 coupled GCMs: Ocean–atmosphere feedback analysis. *Journal of Climate*, 20(18):4497–4525.
- Liu C and Allan RP (2013). Observed and simulated precipitation responses in wet and dry regions 1850–2100. *Environmental Research Letters*, 8(3):034002.
- Lohmann U and Roeckner E (1996). Design and performance of a new cloud microphysics scheme developed for the ECHAM general circulation model. *Climate Dynamics*, 12(8):557–572.
- Lohmann U, Lüönd F, and Mahrt F (2016). *An introduction to clouds: From the microscale to climate*. Cambridge University Press.
- Mace GG, Deng M, Soden B, and Zipser E (2006). Association of tropical cirrus in the 10–15-km layer with deep convective sources: An observational study combining millimeter radar data and satellite-derived trajectories. *Journal of the atmospheric sciences*, 63(2):480–503.
- Machado LA and Rossow WB (1993). Structural characteristics and radiative properties of tropical cloud clusters. *Monthly Weather Review*, 121(12):3234–3260.
- Madden RA and Julian PR (1972). Description of global-scale circulation cells in the tropics with a 40–50 day period. *Journal of Atmospheric Sciences*, 29(6):1109–1123.
- Madden RA and Julian PR (1971). Detection of a 40–50 day oscillation in the zonal wind in the tropical Pacific. *Journal of Atmospheric Sciences*, 28(5):702–708.
- Maddox RA (1980). Mesoscale convective complexes. *Bulletin of the American Meteorological Society*, 1374–1387.
- Maher P, Gerber EP, Medeiros B, Merlis TM, Sherwood S, Sheshadri A, Sobel AH, Vallis GK, Voigt A, and Zurita-Gotor P (2019). Model hierarchies for understanding atmospheric circulation. *Reviews of Geophysics*, 57(2):250–280.
- Manabe S and Wetherald RT (1967). Thermal Equilibrium of the Atmosphere with a Given Distribution of Relative Humidity. *Journal of Atmospheric Sciences*, 24:241–259.
- Manabe S and Strickler RF (1964). Thermal equilibrium of the atmosphere with a convective adjustment. *Journal of the Atmospheric Sciences*, 21(4):361–385.
- Mapes BE (2016). Gregarious convection and radiative feedbacks in idealized worlds. *Journal of Advances in Modeling Earth Systems*, 8(2):1029–1033.

- Mapes BE (2001). Water's two height scales: The moist adiabat and the radiative troposphere. *Quarterly Journal of the Royal Meteorological Society*, 127(577):2353–2366.
- Masunaga H, Holloway CE, Kanamori H, Bony S, and Stein THM (2021). Transient aggregation of convection: Observed behavior and underlying processes. *Journal of Climate*, 34(5):1685–1700.
- Masunaga H and Mapes BE (2020). A mechanism for the maintenance of sharp tropical margins. *Journal of the Atmospheric Sciences*, 77(4):1181–1197.
- Matsugishi S and Satoh M (2022). Sensitivity of the Horizontal Scale of Convective Self-aggregation to Sea Surface Temperature in Radiative Convective Equilibrium Experiments Using a Global Nonhydrostatic Model. *Journal of Advances in Modeling Earth Systems*, e2021MS002636.
- McAnelly RL and Cotton WR (1989). The precipitation life cycle of mesoscale convective complexes over the central United States. *Monthly Weather Review*, 117(4):784–808.
- Mechoso CR, Robertson AW, Barth N, Davey MK, Delecluse P, Gent PR, Ineson S, Kirtman B, Latif M, Le Treut H, et al. (1995). The seasonal cycle over the tropical Pacific in coupled ocean–atmosphere general circulation models. *Monthly Weather Review*, 123(9):2825–2838.
- Mekonnen MM and Hoekstra AY (2016). Four billion people facing severe water scarcity. *Science advances*, 2(2):e1500323.
- Miller STK, Keim BD, Talbot RW, and Mao H (2003). Sea breeze: Structure, forecasting, and impacts. *Reviews of geophysics*, 41(3).
- Morrison H, Lier-Walqui M van, Fridlind AM, Grabowski WW, Harrington JY, Hoose C, Korolev A, Kumjian MR, Milbrandt JA, Pawlowska H, et al. (2020). Confronting the challenge of modeling cloud and precipitation microphysics. *Journal of advances in modeling earth systems*, 12(8):e2019MS001689.
- Mukherjee A, Shankar D, Fernando V, Amol P, Aparna SG, Fernandes R, Michael GS, Khalap ST, Satelkar NP, Agarvadekar Y, et al. (2014). Observed seasonal and intraseasonal variability of the East India Coastal Current on the continental slope. *Journal of Earth System Science*, 123(6):1197–1232.
- Muller CJ and Bony S (2015). What favors convective aggregation and why? *Geophysical Research Letters*, 42(13):5626–5634.
- Muller CJ and Held I (2012). Detailed Investigation of the Self-Aggregation of Convection in Cloud-Resolving Simulations. *Journal of the Atmospheric Sciences*, 69(8):2551–2565.

- Muller CJ and Romps DM (2018). Acceleration of tropical cyclogenesis by self-aggregation feedbacks. *Proceedings of the National Academy of Sciences*, 115(12):2930–2935.
- Muller CJ, Yang D, Craig G, Cronin T, Fildier B, Haerter JO, Hohenegger C, Mapes B, Randall D, Shamekh S, et al. (2022). Spontaneous Aggregation of Convective Storms. *Annual Review of Fluid Mechanics*, 54:133–157.
- Müller SK and Hohenegger C (2020). Self-aggregation of convection in spatially varying sea surface temperatures. *Journal of Advances in Modeling Earth Systems*, 12(1):e2019MS001698.
- Murakami H (2014). Tropical cyclones in reanalysis data sets. *Geophysical Research Letters*, 41(6):2133–2141.
- Murakami H, Mizuta R, and Shindo E (2012). Future changes in tropical cyclone activity projected by multi-physics and multi-SST ensemble experiments using the 60-km-mesh MRI-AGCM. *Climate dynamics*, 39(9):2569–2584.
- Murphy JM, Sexton DM, Barnett DN, Jones GS, Webb MJ, Collins M, and Stainforth DA (2004). Quantification of modelling uncertainties in a large ensemble of climate change simulations. *Nature*, 430(7001):768–772.
- Naumann AK, Stevens B, Hohenegger C, and Mellado JP (2017). A conceptual model of a shallow circulation induced by prescribed low-level radiative cooling. *Journal of the Atmospheric Sciences*, 74(10):3129–3144.
- Neale RB and Hoskins BJ (2000). A standard test for AGCMs including their physical parametrizations: I: The proposal. *Atmospheric Science Letters*, 1(2):101–107.
- Needham MR and Randall DA (2021). Riehl and Malkus Revisited: The Role of Cloud Radiative Effects. *Journal of Geophysical Research: Atmospheres*, 126(16):e2021JD035019.
- Neelin JD and Held IM (1987). Modeling tropical convergence based on the moist static energy budget. *Monthly Weather Review*, 115(1):3–12.
- Nepstad DC, Carvalho CR de, Davidson EA, Jipp PH, Lefebvre PA, Negreiros GH, Silva ED da, Stone TA, Trumbore SE, and Vieira S (1994). The role of deep roots in the hydrological and carbon cycles of Amazonian forests and pastures. *Nature*, 372(6507):666–669.
- Newell RE, Newell NE, Zhu Y, and Scott C (1992). Tropospheric rivers?—A pilot study. *Geophysical research letters*, 19(24):2401–2404.

- Nissen SB and Haerter JO (2021). Circling in on Convective Self-Aggregation. *Journal of Geophysical Research: Atmospheres*, 126(20):e2021JD035331.
- Nordeng TE (1994). Extended versions of the convective parametrization scheme at ECMWF and their impact on the mean and transient activity of the model in the tropics.
- Oouchi K, Yoshimura J, Yoshimura H, Mizuta R, Kusunoki S, and Noda A (2006). Tropical cyclone climatology in a global-warming climate as simulated in a 20 km-mesh global atmospheric model: Frequency and wind intensity analyses. *Journal of the Meteorological Society of Japan. Ser. II*, 84(2):259–276.
- Oueslati B, Bony S, Risi C, and Dufresne JL (2016). Interpreting the inter-model spread in regional precipitation projections in the tropics: role of surface evaporation and cloud radiative effects. *Climate dynamics*, 47(9):2801–2815.
- Patrizio CR and Randall DA (2019). Sensitivity of convective self-aggregation to domain size. *Journal of Advances in Modeling Earth Systems*, 11(7):1995–2019.
- Pendergrass AG (2020). Changing degree of convective organization as a mechanism for dynamic changes in extreme precipitation. *Current climate change reports*, 6(2):47–54.
- Pendergrass AG, Reed KA, and Medeiros B (2016). The link between extreme precipitation and convective organization in a warming climate: Global radiative-convective equilibrium simulations. *Geophysical Research Letters*, 43(21):11–445.
- Pincus R and Stevens B (2013). Paths to accuracy for radiation parameterizations in atmospheric models. *Journal of Advances in Modeling Earth Systems*, 5(2):225–233.
- Pope KN, Holloway CE, Jones TR, and Stein THM (2022). Radiation, Clouds, and Self-Aggregation in RCEMIP Simulations. *Authorea Preprint*,
- Pope KN, Holloway CE, Jones TR, and Stein THM (2021). Cloud-Radiation Interactions and Their Contributions to Convective Self-Aggregation. *Journal of Advances in Modeling Earth Systems*, 13(9):e2021MS002535.
- Popke D, Stevens B, and Voigt A (2013). Climate and climate change in a radiative-convective equilibrium version of ECHAM6. *Journal of Advances in Modeling Earth Systems*, 1–14.
- Popp M and Bony S (2019). Stronger zonal convective clustering associated with a wider tropical rain belt. *Nature communications*, 10(1):1–12.

- Ralph FM, Neiman PJ, Kiladis GN, Weickmann K, and Reynolds DW (2011). A Multiscale Observational Case Study of a Pacific Atmospheric River Exhibiting Tropical–Extratropical Connections and a Mesoscale Frontal Wave. *Monthly Weather Review*, 139(4):1169–1189.
- Ramanathan V, Chung C, Kim D, Bettge T, Buja L, Kiehl JT, Washington WM, Fu Q, Sikka DR, and Wild M (2005). Atmospheric brown clouds: Impacts on South Asian climate and hydrological cycle. *Proceedings of the National Academy of Sciences*, 102(15):5326–5333.
- Ramírez Reyes A and Yang D (2021). Spontaneous Cyclogenesis without Radiative and Surface-Flux Feedbacks. *Journal of the Atmospheric Sciences*, 78(12):4169–4184.
- Ramírez Reyes A and Yang D (2022). The Moisture-Entrainment-Convection Feedback Can Lead to Spontaneous Tropical Cyclone Genesis. *arXiv preprint arXiv:2208.11160*,
- Randall D, Khairoutdinov M, Arakawa AO, and Grabowski WW (2003). Breaking the cloud parameterization deadlock. *Bulletin of the American Meteorological Society*, 84(11):1547–1564.
- Raymond DJ (2001). A new model of the Madden–Julian oscillation. *Journal of the atmospheric sciences*, 58(18):2807–2819.
- Raymond DJ (2000). The Hadley circulation as a radiative–convective instability. *Journal of the atmospheric sciences*, 57(9):1286–1297.
- Reed KA, Medeiros B, Bacmeister JT, and Lauritzen PH (2015). Global Radiative–Convective Equilibrium in the Community Atmosphere Model, Version 5. *Journal of the Atmospheric Sciences*, 72(5):2183–2197.
- Reick CH, Gayler V, Goll D, Hagemann S, Heidkamp M, Nabel JEMS, Raddatz T, Roeckner E, Schnur R, and Wilkenskjaeld S (2021). *JSBACH 3-The land component of the MPI Earth System Model: documentation of version 3.2*. Tech. rep. Hamburg, Germany: Max Planck Institute for Meteorology.
- Reick CH, Raddatz T, Brovkin V, and Gayler V (2013). Representation of natural and anthropogenic land cover change in MPI-ESM. *Journal of Advances in Modeling Earth Systems*, 5(3):459–482.
- Retsch MH, Mauritsen T, and Hohenegger C (2019). Climate change feedbacks in aquaplanet experiments with explicit and parametrized convection for horizontal resolutions of 2,525 up to 5 km. *Journal of Advances in Modeling Earth Systems*, 11(7):2070–2088.
- Rhiel H and Malkus JS (1958). On the heat balance in the equatorial trough. *Geophysica*, 6:503–537.

- Robe FR and Emanuel KA (2001). The effect of vertical wind shear on radiative–convective equilibrium states. *Journal of the atmospheric sciences*, 58(11):1427–1445.
- Roeckner E, Stier P, Feichter J, Kloster S, Esch M, and Fischer-Bruns I (2006). Impact of carbonaceous aerosol emissions on regional climate change. *Climate dynamics*, 27(6):553–571.
- Rotunno R, Klemp JB, and Weisman ML (1988). A theory for strong, long-lived squall lines. *Journal of Atmospheric Sciences*, 45(3):463–485.
- Ruppert JH, Wing AA, Tang X, and Duran EL (2020). The critical role of cloud–infrared radiation feedback in tropical cyclone development. *Proceedings of the National Academy of Sciences*, 117(45):27884–27892.
- Sarangi C, Kanawade VP, Tripathi SN, Thomas A, and Ganguly D (2018). Aerosol-induced intensification of cooling effect of clouds during Indian summer monsoon. *Nature communications*, 9(1):1–9.
- Sarangi C, Tripathi SN, Kanawade VP, Koren I, and Pai DS (2017). Investigation of the aerosol–cloud–rainfall association over the Indian summer monsoon region. *Atmospheric Chemistry and Physics*, 17(8):5185–5204.
- Sassen K, Wang Z, and Liu D (2008). Global distribution of cirrus clouds from CloudSat/Cloud-Aerosol lidar and infrared pathfinder satellite observations (CALIPSO) measurements. *Journal of Geophysical Research: Atmospheres*, 113(D8).
- Satheesh SK and Moorthy KK (2005). Radiative effects of natural aerosols: A review. *Atmospheric Environment*, 39(11):2089–2110.
- Sato T, Miura H, Satoh M, Takayabu YN, and Wang Y (2009). Diurnal cycle of precipitation in the tropics simulated in a global cloud-resolving model. *Journal of Climate*, 22(18):4809–4826.
- Satoh M and Matsuda Y (2009). Statistics on high-cloud areas and their sensitivities to cloud microphysics using single-cloud experiments. *Journal of the atmospheric sciences*, 66(9):2659–2677.
- Satoh M, Matsuno T, Tomita H, Miura H, Nasuno T, and Iga S (2008). Nonhydrostatic icosahedral atmospheric model (NICAM) for global cloud resolving simulations. *Journal of Computational Physics*, 227(7):3486–3514.
- Schenk HJ and Jackson RB (2005). Mapping the global distribution of deep roots in relation to climate and soil characteristics. *Geoderma*, 126(1-2):129–140.
- Schneider SH and Dickinson RE (1974). Climate modeling. *Reviews of Geophysics*, 12(3):447–493.

- Seigel RB, Van Den Heever SC, and Saleeby SM (2013). Mineral dust indirect effects and cloud radiative feedbacks of a simulated idealized nocturnal squall line. *Atmospheric Chemistry and Physics*, 13(8):4467–4485.
- Seneviratne SI, Corti T, Davin EL, Hirschi M, Jaeger EB, Lehner I, Orlowsky B, and Teuling AJ (2010). Investigating soil moisture–climate interactions in a changing climate: A review. *Earth-Science Reviews*, 99(3-4):125–161.
- Seneviratne SI, Lüthi D, Litschi M, and Schär C (2006). Land–atmosphere coupling and climate change in Europe. *Nature*, 443(7108):205–209.
- Sessions SL, Sentić S, and Herman MJ (2016). The role of radiation in organizing convection in weak temperature gradient simulations. *Journal of Advances in Modeling Earth Systems*, 8(1):244–271.
- Shamekh S, Muller CJ, Duvel JP, and d'Andrea F (2020a). How do ocean warm anomalies favor the aggregation of deep convective clouds? *Journal of the Atmospheric Sciences*, 77(11):3733–3745.
- Shamekh S, Muller CJ, Duvel JP, and d'Andrea F (2020b). Self-aggregation of convective clouds with interactive sea surface temperature. *Journal of Advances in Modeling Earth Systems*, 12(11):e2020MS002164.
- Sharma D, Srivastava AK, Ram K, Singh A, and Singh D (2017). Temporal variability in aerosol characteristics and its radiative properties over Patiala, northwestern part of India: Impact of agricultural biomass burning emissions. *Environmental Pollution*, 231:1030–1041.
- Shuttleworth WJ (1989). Micrometeorology of temperate and tropical forest. *Philosophical Transactions of the Royal Society of London. B, Biological Sciences*, 324(1223):299–334.
- Silvers LG and Robinson T (2021). Clouds and Radiation in a Mock-Walker Circulation. *Journal of Advances in Modeling Earth Systems*, 13(2):e2020MS002196.
- Silvers LG, Stevens B, Mauritsen T, and Giorgetta M (2016). Radiative convective equilibrium as a framework for studying the interaction between convection and its large-scale environment. *Journal of Advances in Modeling Earth Systems*, 8(3):1330–1344.
- Singh MS and O'Gorman PA (2013). Influence of entrainment on the thermal stratification in simulations of radiative-convective equilibrium. *Geophysical Research Letters*, 40(16):4398–4403.
- Skamarock WC, Klemp JB, Duda MG, Fowler LD, Park SH, and Ringler TD (2012). A multiscale nonhydrostatic atmospheric model using centroidal Voronoi tessellations and C-grid staggering. *Monthly Weather Review*, 140(9):3090–3105.

- Sobel A, Wang S, and Kim D (2014). Moist static energy budget of the MJO during DYNAMO. *Journal of the Atmospheric Sciences*, 71(11):4276–4291.
- Sobel AH and Bretherton CS (2000). Modeling tropical precipitation in a single column. *Journal of climate*, 13(24):4378–4392.
- Sobel AH, Nilsson J, and Polvani LM (2001). The Weak Temperature Gradient Approximation and Balanced Tropical Moisture Waves. *Journal of the Atmospheric Sciences*, 58(23):3650–3665.
- Stein THM, Holloway CE, Tobin I, and Bony S (2017). Observed relationships between cloud vertical structure and convective aggregation over tropical ocean. *Journal of Climate*, 30(6):2187–2207.
- Stephens GL, Van Den Heever S, and Pakula L (2008). Radiative–convective feedbacks in idealized states of radiative–convective equilibrium. *Journal of the Atmospheric Sciences*, 65(12):3899–3916.
- Stevens B, Fiedler S, Kinne S, Peters K, Rast S, Müsse J, Smith SJ, and Mauritsen T (2017). MACv2-SP: a parameterization of anthropogenic aerosol optical properties and an associated Twomey effect for use in CMIP6. *Geoscientific Model Development*, 10(1):433–452.
- Stevens B, Giorgetta M, Esch M, Mauritsen T, Crueger T, Rast S, Salzmann M, Schmidt H, Bader J, Block K, et al. (2013). Atmospheric component of the MPI-M Earth system model: ECHAM6. *Journal of Advances in Modeling Earth Systems*, 5(2):146–172.
- Stevens B, Satoh M, Auger L, Biercamp J, Bretherton CS, Chen X, Düben P, Judt F, Khairoutdinov M, Klocke D, et al. (2019). DYAMOND: the DYNAMics of the Atmospheric general circulation Modeled On Non-hydrostatic Domains. *Progress in Earth and Planetary Science*, 6(1):1–17.
- Straub KH, Haertel PT, and Kiladis GN (2010). An analysis of convectively coupled Kelvin waves in 20 WCRP CMIP3 global coupled climate models. *Journal of climate*, 23(11):3031–3056.
- Stubenrauch CJ, Rossow WB, Kinne S, Ackerman S, Cesana G, Chepfer H, Di Girolamo L, Getzewich B, Guignard A, Heidinger A, et al. (2013). Assessment of global cloud datasets from satellites: Project and database initiated by the GEWEX radiation panel. *Bulletin of the American Meteorological Society*, 94(7):1031–1049.
- Stull R (2006). 9 - The Atmospheric Boundary Layer. *Atmospheric Science (Second Edition)*. Ed. by Wallace JM and Hobbs PV. Second Edition. Elsevier Academic Press, pp. 375–417.

- Su H, Bretherton CS, and Chen SS (2000). Self-aggregation and large-scale control of tropical deep convection: A modeling study. *Journal of the atmospheric sciences*, 57(11):1797–1816.
- Sugi M, Murakami H, and Yoshimura J (2009). A reduction in global tropical cyclone frequency due to global warming. *Sola*, 5:164–167.
- Sugi M, Noda A, and Sato N (2002). Influence of the global warming on tropical cyclone climatology: An experiment with the JMA global model. *Journal of the Meteorological Society of Japan. Ser. II*, 80(2):249–272.
- Sundqvist H, Berge E, and Kristjánsson JE (1989). Condensation and Cloud Parameterization Studies with a Mesoscale Numerical Weather Prediction Model. *Monthly Weather Review*, 117(8):1641–1657.
- Talib J, Woolnough SJ, Klingaman NP, and Holloway CE (2018). The role of the cloud radiative effect in the sensitivity of the intertropical convergence zone to convective mixing. *Journal of Climate*, 31(17):6821–6838.
- Tan J, Jakob C, Rossow WB, and Tselioudis G (2015). Increases in tropical rainfall driven by changes in frequency of organized deep convection. *Nature*, 519(7544):451–454.
- Tao WK, Li X, Khain A, Matsui T, Lang S, and Simpson J (2007). Role of atmospheric aerosol concentration on deep convective precipitation: Cloud-resolving model simulations. *Journal of Geophysical Research: Atmospheres*, 112(D24).
- Teuling AJ, Seneviratne SI, Williams C, and Troch PA (2006). Observed timescales of evapotranspiration response to soil moisture. *Geophysical Research Letters*, 33(23).
- Tian B and Dong X (2020). The double-ITCZ bias in CMIP3, CMIP5, and CMIP6 models based on annual mean precipitation. *Geophysical Research Letters*, 47(8):e2020GL087232.
- Tiedtke M (1989). A Comprehensive Mass Flux Scheme for Cumulus Parameterization in Large-Scale Models. *Monthly Weather Review*, 117(8):1779–1800.
- Tobin I, Bony S, Holloway CE, Grandpeix JY, Sèze G, Coppin D, Woolnough SJ, and Roca R (2013). Does convective aggregation need to be represented in cumulus parameterizations? *Journal of Advances in Modeling Earth Systems*, 5(4):692–703.

- Tobin I, Bony S, and Roca R (2012). Observational Evidence for Relationships between the Degree of Aggregation of Deep Convection, Water Vapor, Surface Fluxes, and Radiation. *Journal of Climate*, 25(20):6885–6904.
- Tompkins AM (2001a). On the relationship between tropical convection and sea surface temperature. *Journal of climate*, 14(5):633–637.
- Tompkins AM (2001b). Organization of tropical convection in low vertical wind shears: The role of cold pools. *Journal of the atmospheric sciences*, 58(13):1650–1672.
- Tompkins AM (2001c). Organization of tropical convection in low vertical wind shears: The role of water vapor. *Journal of the atmospheric sciences*, 58(6):529–545.
- Tompkins AM and Craig GC (1998). Radiative–convective equilibrium in a three-dimensional cloud-ensemble model. *Quarterly Journal of the Royal Meteorological Society*, 124(550):2073–2097.
- Tompkins AM and Semie AG (2021). Impact of a mixed ocean layer and the diurnal cycle on convective aggregation. *Journal of Advances in Modeling Earth Systems*, 13(12):e2020MS002186.
- Tompkins AM and Semie AG (2017). Organization of tropical convection in low vertical wind shears: Role of updraft entrainment. *Journal of Advances in Modeling Earth Systems*, 9(2):1046–1068.
- Tselioudis G, Tromeur E, Rossow WB, and Zerefos CS (2010). Decadal changes in tropical convection suggest effects on stratospheric water vapor. *Geophysical Research Letters*, 37(14).
- Vadrevu KP, Lasko K, Giglio L, and Justice C (2015). Vegetation fires, absorbing aerosols and smoke plume characteristics in diverse biomass burning regions of Asia. *Environmental Research Letters*, 10(10):105003.
- Velasco I and Fritsch JM (1987). Mesoscale convective complexes in the Americas. *Journal of Geophysical Research: Atmospheres*, 92(D8):9591–9613.
- Voigt A, Biasutti M, Scheff J, Bader J, Bordoni S, Codron F, Dixon RD, Jonas J, Kang SM, Klingaman NP, et al. (2016). The tropical rain belts with an annual cycle and a continent model intercomparison project: TRACMIP. *Journal of Advances in Modeling Earth Systems*, 8(4):1868–1891.
- Voigt A, Bony S, Dufresne JL, and Stevens B (2014). The radiative impact of clouds on the shift of the intertropical convergence zone. *Geophysical Research Letters*, 41(12):4308–4315.

- Voigt A, Alber N, Ceppi P, Grise K, Li Y, and Medeiros B (2021). Clouds, radiation, and atmospheric circulation in the present-day climate and under climate change. *Wiley Interdisciplinary Reviews: Climate Change*, 12(2):e694.
- Wallace JM and Hobbs PV (1977). *Atmospheric science: an introductory survey*. Vol. 92. Academic press.
- Wang B (1994). Climatic regimes of tropical convection and rainfall. *Journal of Climate*, 1109–1118.
- Wang C, Kim D, Ekman AML, Barth MC, and Rasch PJ (2009). Impact of anthropogenic aerosols on Indian summer monsoon. *Geophysical Research Letters*, 36(21).
- Wang S and Sobel AH (2017). Factors controlling rain on small tropical islands: Diurnal cycle, large-scale wind speed, and topography. *Journal of the Atmospheric Sciences*, 74(11):3515–3532.
- Webster PJ (1987). The variable and interactive monsoon. *Monsoons*. Ed. by Fein JS and Stephens PL. Vol. 632. Wiley New York, pp. 269–330.
- Webster PJ, Magana VO, Palmer TN, Shukla J, Tomas RA, Yanai MU, and Yasunari T (1998). Monsoons: Processes, predictability, and the prospects for prediction. *Journal of Geophysical Research: Oceans*, 103(C7):14451–14510.
- Weisman ML and Klemp JB (1982). The dependence of numerically simulated convective storms on vertical wind shear and buoyancy. *Monthly Weather Review*, 110(6):504–520.
- White BA, Buchanan AM, Birch CE, Stier P, and Pearson KJ (2018). Quantifying the effects of horizontal grid length and parameterized convection on the degree of convective organization using a metric of the potential for convective interaction. *Journal of the Atmospheric Sciences*, 75(2):425–450.
- Wild M, Folini D, Hakuba MZ, Schär C, Seneviratne SI, Kato S, Rutan D, Ammann C, Wood EF, and König-Langlo G (2015). The energy balance over land and oceans: an assessment based on direct observations and CMIP5 climate models. *Climate Dynamics*, 44(11):3393–3429.
- Wild M, Hakuba MZ, Folini D, Dörig-Ott P, Schär C, Kato S, and Long CN (2019). The cloud-free global energy balance and inferred cloud radiative effects: an assessment based on direct observations and climate models. *Climate Dynamics*, 52(7):4787–4812.
- Williams AIL, Stier P, Dagan G, and Watson-Parris D (2022). Strong control of effective radiative forcing by the spatial pattern of absorbing aerosol. *Nature Climate Change*, 12(8):735–742.

- Windmiller JM and Craig GC (2019). Universality in the spatial evolution of self-aggregation of tropical convection. *Journal of the Atmospheric Sciences*, 76(6):1677–1696.
- Wing AA (2019). Self-Aggregation of Deep Convection and its Implication for Climate. *Current Climate Change Reports*, 5(1):1–11.
- Wing AA, Camargo SJ, and Sobel AH (2016). Role of radiative–convective feedbacks in spontaneous tropical cyclogenesis in idealized numerical simulations. *Journal of the Atmospheric Sciences*, 73(7):2633–2642.
- Wing AA and Cronin TW (2016). Self-aggregation of convection in long channel geometry. *Quarterly Journal of the Royal Meteorological Society*, 142(694):1–15.
- Wing AA and Emanuel KA (2012). Organization of Tropical Convection: Dependence of Self-Aggregation on SST in an Idealized Modeling Study, Paper presented at 30th Conference on Hurricanes and Tropical Meteorology. AMS.
- Wing AA and Emanuel KA (2014). Physical mechanisms controlling self-aggregation of convection in idealized numerical modeling simulations. *Journal of Advances in Modeling Earth Systems*, 6(1):59–74.
- Wing AA, Emanuel KA, Holloway CE, and Muller CJ (2017). Convective self-aggregation in numerical simulations: A review. *Shallow clouds, water vapor, circulation, and climate sensitivity*, 1–25.
- Wing AA, Reed KA, Satoh M, Stevens B, Bony S, and Ohno T (2018). Radiative–convective equilibrium model intercomparison project. *Geoscientific Model Development*, 11(2):793–813.
- Wing AA, Stauffer CL, Becker T, Reed KA, Ahn MS, Arnold NP, Bony S, Branson M, Bryan GH, Chaboureaud JP, et al. (2020). Clouds and Convective Self-Aggregation in a Multi-Model Ensemble of Radiative–Convective Equilibrium Simulations. *Journal of Advances in Modeling Earth Systems*, e2020MS002138.
- Wodzicki KR and Rapp AD (2022). More intense, organized deep convection with shrinking tropical ascent regions. *Geophysical Research Letters*, 49(15):e2022GL098615.
- Wood R (2014). Clouds and Fog: Stratus and Stratocumulus. *Encyclopedia of atmospheric sciences*. Ed. by North GR, Pyle J, and Zhang F. 2nd. Vol. 1. Elsevier, pp. 196–200.
- Yanase T, Nishizawa S, Miura H, Takemi T, and Tomita H (2020). New critical length for the onset of self-aggregation of moist convection. *Geophysical Research Letters*, 47(16):e2020GL088763.

- Yang B, Guo X, Gu JF, and Nie J (2022). Cloud-Radiation Feedback Prevents Tropical Cyclones From Reaching Higher Intensities. *Geophysical Research Letters*, 49(24):e2022GL100067.
- Yang D (2019). Convective heating leads to self-aggregation by generating available potential energy. *Geophysical Research Letters*, 46(17-18):10687–10696.
- Yang D (2021). A shallow-water model for convective self-aggregation. *Journal of the Atmospheric Sciences*, 78(2):571–582.
- Yang D (2018a). Boundary layer diabatic processes, the virtual effect, and convective self-aggregation. *Journal of Advances in Modeling Earth Systems*, 10(9):2163–2176.
- Yang D (2018b). Boundary layer height and buoyancy determine the horizontal scale of convective self-aggregation. *Journal of the Atmospheric Sciences*, 75(2):469–478.
- Yao L, Yang D, and Tan ZM (2022). A Vertically Resolved MSE Framework Highlights the Role of the Boundary Layer in Convective Self-Aggregation. *Journal of the Atmospheric Sciences*, 79(6):1615–1631.
- Yoshida K, Sugi M, Mizuta R, Murakami H, and Ishii M (2017). Future changes in tropical cyclone activity in high-resolution large-ensemble simulations. *Geophysical Research Letters*, 44(19):9910–9917.
- Zängl G, Reinert D, Rípodas P, and Baldauf M (2015). The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. *Quarterly Journal of the Royal Meteorological Society*, 141(687):563–579.
- Zhang B, Soden BJ, Vecchi GA, and Yang W (2021). Investigating the Causes and Impacts of Convective Aggregation in a High Resolution Atmospheric GCM. *Journal of Advances in Modeling Earth Systems*, 13(11):e2021MS002675.
- Zhang C (2005). Madden-Julian oscillation. *Reviews of Geophysics*, 43(2).
- Zhang C, Adames ÁF, Khouider B, Wang B, and Yang D (2020). Four theories of the Madden-Julian oscillation. *Reviews of Geophysics*, 58(3):e2019RG000685.
- Zhang C, Mapes BE, and Soden BJ (2003). Bimodality in tropical water vapour. *Quarterly Journal of the Royal Meteorological Society: A journal of the atmospheric sciences, applied meteorology and physical oceanography*, 129(594):2847–2866.

Zhu Y and Newell RE (1998). A proposed algorithm for moisture fluxes from atmospheric rivers.
Monthly weather review, 126(3):725–735.