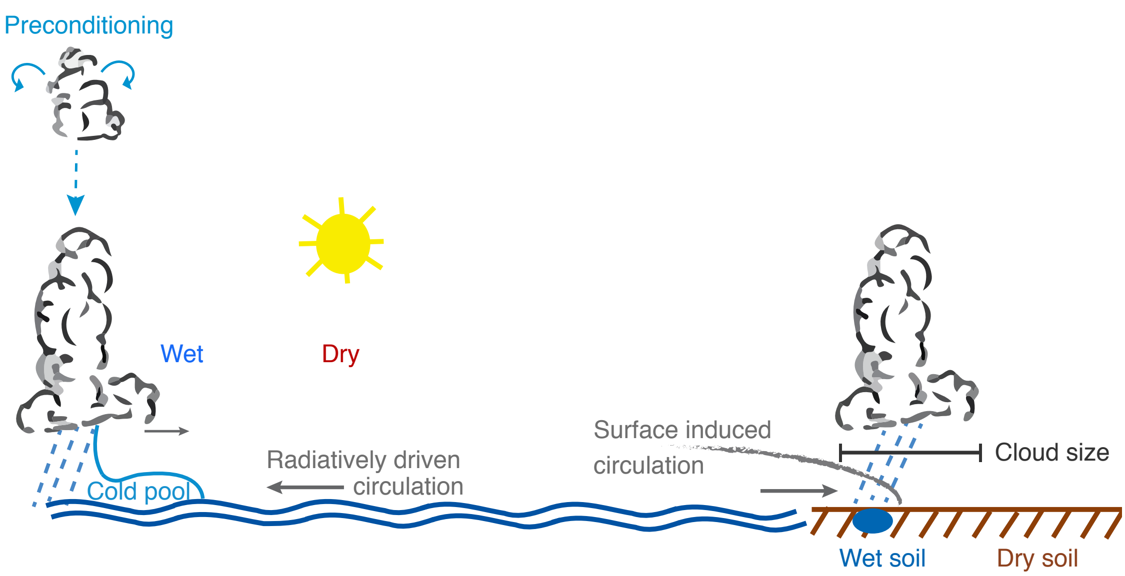
Precipitating Convection:

its daily transition, organization and interaction with the land surface



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Contents

Chapter 1

Introduction

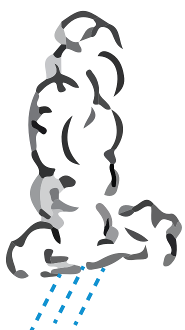

Figure 1.1: Precipitating convection, the topic of my research contributions.

Atmospheric convection plays a key role in the climate system. It transports heat, momentum, moisture and other particles from the surface into the higher layers of the atmosphere. By transporting and redistributing energy, it participates in the large-scale circulation of the atmosphere and helps set the temperature of the Earth's surface. In fact, one of the simplest conceptualizations of the climate system is one of radiative convective equilibrium (RCE), where the vertical temperature distribution is purely controlled by the interplay between radiation and convection (Manabe and Strickler, 1964). Radiation cools the atmosphere and warms the surface, destabilizing the atmospheric column and giving rise to convective motion. Convection redistributes the radiative energy vertically and is able to stabilize the atmospheric column against the destabilization by radiation. Convection maintains the atmosphere on a moist adiabat with a surface temperature of 300 K. Without convection, the surface temperature at equilibrium would amount to more than 330 K, much too warm compared to observations. The RCE conceptualization can explain many basic properties of the tropical climate (Popke, Stevens and Voigt, 2013). In the extratropics, transport by baroclinic eddies dominates, but convective instability remains important during summertime when it produces the largest share of precipitation.

Convection exhibits peculiar properties that make an understanding of its lifecycle and impacts not always straightforward. It is a multi-scale phenomenon that replicates the characteristics and lifecycles of its individual components across space and time scales (Mapes et al., 2006). The InterTropical Convergence Zone (ITCZ) represents the organization of convection on planetary scales. Zooming in, the ITCZ itself is made of convective clusters, such as squall lines or mesoscale convective systems. These convective clusters are made of individual cumulonimbi, of radius O(10) km, organized on scales of 100 km and more. At the beginning of their lifecycle, the cumulonimbi were shallow cumuli, ranging from a few meters to a few kilometers. Finally, these individual cumuli are just the visible signature of turbulent thermals that rise through the Planetary Boundary Layer (PBL). They are made of turbulent eddies, in the meter and sub-meter range. Explicitly resolving all these scales of motion, down to a few meters, on the full Earth and for climatic time scales, is impossible. As a comparison, General Circulation Models (GCMs), that are currently used for the 6th phase of the Coupled Model Intercomparison Project (CMIP), employ grid spacings of O(100) km, too coarse to explicitly represent most of the convective transport. Convection has to be parameterized. Convective parameterizations have been a source of persistent biases in GCMs, even in basic properties of the climate system such as position of the ITCZ or diurnal cycle of precipitation (Fiedler et al., 2020; Arakawa, 2004).

Convection also strongly interacts with itself, with the atmospheric environment and with the underlying surface. An often-mentioned example concerns the coupling of convection with circulations. Converging circulations in the atmosphere, as in the equatorial region with the Hadley cell, force upward motion that promotes the development of convection (Back and Bretherton, 2009). As the air rises, it condenses and releases heat. The anomalous deep heating in the convective column spins up its own circulation (Gill,

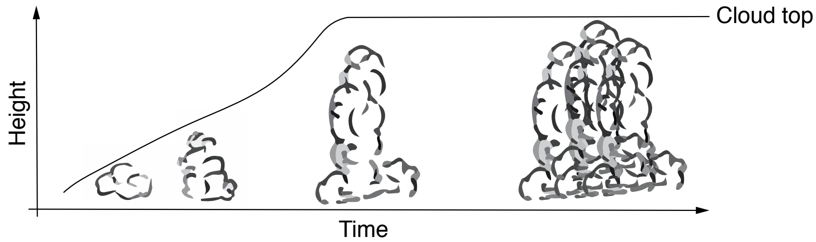

Figure 1.2: Schematic development of a deep convective cloud, up to its organization.

1980), making a determination of cause and effect rapidly difficult. Other well-known examples of ambiguous interactions include the fact that convection develops more easily in moist atmospheres (Derbyshire et al., 2004), but it itself moistens its near-by environment; or that it produces cold pools, cold pools that again helps triggering deep convection (Khairoutdinov and Randall, 2006).

In this review, I summarize my research contributions based on the papers explicitly mentioned along the text. The focus of my contributions has been on moist convection, particularly precipitating convection. I have viewed convection as a highly coupled problem and thus aimed at better understanding both the controls on and impacts of convection. Even if many individual forcings can affect the lifecycle of convection on their own, convection itself being one, not all of them can be relevant at the same time. Likewise, not all characteristics of convection, e.g. its timing or its degree of organization, may be important for the climate system.

Under this overall consideration, my research contributions first focused on the daily transition to deep convection (see Chapter 2). As sketched in Fig. 1.2, the simplest picture of the lifecycle of deep precipitating convection is one where shallow cumuli randomly develop in a moist and unstable atmosphere and deepen with time. My goal was to assess the relative importance of various controls on this transition, in particular through an understanding of their effects on the transition time and the cloud size distribution. The probability distribution function of cloud sizes had been characterized in many past studies, starting by the work of Lopez (1976), but, except for Khairoutdinov and Randall (2006) and Kuang and Bretherton (2006), none had explicitly looked at the transition to deep convection through the lens of the cloud size distribution. In a second step, I applied the gained process understanding for parameterization development with the hope of improving the representation of the timing of this transition and, in more general terms, of the diurnal cycle of convection. I also assessed the importance of this timing for climate. The poor representation of the diurnal cycle of convection in GCMs, a common pitfall ten years ago, motivated these research contributions.

Once convection has transitioned to deep convection, it often organizes and clumps into clusters (see Fig. 1.2). My second research contributions thus concerned the organization of convection (see Chapter 3). Over the past five years, the interest of the scientific community for an unexpected type of convective organization, called convective self-aggregation, has drastically increased. This self-aggregation of convection expresses the ability of randomly distributed deep convective clouds to spontaneously organize and aggregate into large-scale clusters, in purely homogeneous boundary conditions and in the absence of large-scale forcing (Tompkins and Craig, 1998; Bretherton, Blossey and Khairoutdinov, 2005). My work as well as work in my group has significantly contributed to this new research area. In a first step, I investigated the mechanisms underlying the self-aggregation of convection as well as its interactions with less idealized bottom boundary conditions: which conditions favor the self-aggregation of convection? Why? A motivation for and hypothesis underlying this work was that the ITCZ may actually be an expression of the self-aggregation of convection. Correspondingly, in a second step, I transferred the process understanding gained from idealized self-aggregation works to the real world, and probed the validity of the previously derived relationships between convective organization (self-aggregation) and its environment. This allowed me to investigate the importance of convective organization for climate. This latter question is now at the center of attention of many groups, following upon the recommendations of a workshop held on key unsolved questions on clouds, circulation and climate sensitivity (Bony et al., 2015), but was mainly uncharted territory five years ago.

The conceptual picture in Fig. 1.2 of convection randomly developing in the presence of a moist and unstable atmosphere, transitioning to deep convection and organizing on its own is likely more appropriate in the presence of homogeneous conditions, like over ocean. The presence of land complicates the picture. Land properties, through their control on the surface energy budget, can affect the PBL properties and hence the development and lifecycle of moist convection. This was already known in 1686, when Halley correctly explained the mechanisms underlying the monsoons (Halley, 1686), even before Hadley could explain the large-scale circulation of the atmosphere that now bears his name. Countless coarse-resolution climate studies, on the global and on the regional scale, have documented the impacts of land surface alterations on the climate (Mahmood et al., 2014) and highlighted the importance of the land surface for climate (Koster et al., 2004) and climate change (Seneviratne et al., 2006). But there are no guarantees that coarse-resolution models, which have to rely on parameterized processes, can adequately represent the coupling between the land surface and convection. This limitation of coarse-resolution models motivated my third line of research contributions, where I investigated the coupling between the land surface and convection in simulations with an explicit representation of convection (see Chapter 4). My aim was to understand whether the land surface or the convection ends up setting the final characteristics of the precipitation distribution, particularly for cases where the convection is known to interact with the land surface. For the land surface, I focused on two of its distinct characteristics: its limited water supply, meaning the effects of soil moisture on the amount and spatial distribution of precipitation; and its heterogeneity.

Even if my research contributions have focused on three distinct aspects of convection, its transition, its organization and its coupling to the land surface, two recurrent topics emerge from my work. The first one concerns the nagging question whether con-

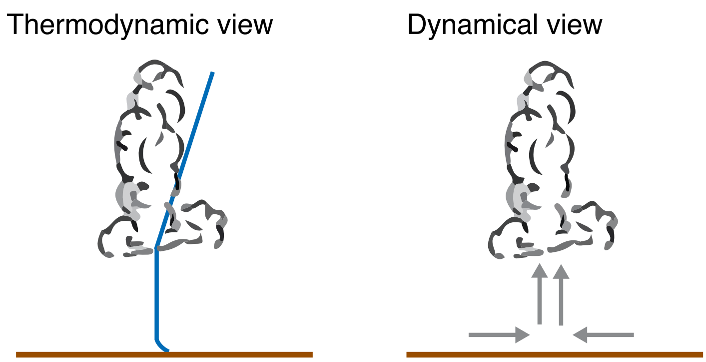

Figure 1.3: Thermodynamic versus dynamical control on convection.

vection is thermodynamically or dynamically forced (see Fig. 1.3). On the one hand, convective motions arise because of the presence of instability in the atmosphere. In that view, moist and unstable atmospheres favor the development of convection and the thermodynamic profile controls convection. It is a column view where no external forcing is required to trigger convection. On the other hand, forced upward vertical motion also leads to saturation and to the formation of convective clouds. Vertical motions arise in the presence of obstacles (topography) or circulations. The convection is here dynamically forced and the presence of horizontal heterogeneities, being in the atmosphere or at the surface, are key. Historically, the paradigm has shifted from thermodynamic control, at the time of the first RCE studies (Manabe and Strickler, 1964), to dynamical control when the first operational weather and climate models were developed (Tiedtke, 1989), and back to thermodynamic control around the mid 1990s (Emanuel and Raymond, 1993). My findings emphasize the role of circulations for setting the spatial distribution of precipitation, in particular circulations confined in the PBL.

The second recurrent topic of my work concerns the importance of convective scales and convective characteristics for the large-scale circulation of the atmosphere and for setting large-scale features of the climate system. As noted earlier, convection is a multi-scale phenomenon, but this is only of relevance if the small scales affect the large scale. My findings show that models with explicit and with parameterized convection can behave in a very distinct way, particularly in their responses to imposed perturbations and even when integrated under constrained and similar conditions. This calls for caution when using and interpreting the results of coarse-resolution GCMs that have to rely on convective parameterizations. However, the discrepancies may often be viewed as the expression of a poorly designed convective parameterization, rather than as the imprint of small-scale convective characteristics, not included in a convective parameterization, on the large scale. Simulations with explicit convection were for instance found to capture basic features of the climate system that convective parameterizations may struggle with at grid spacings much coarser than generally thought possible. The impacts of convective characteristics, such as the timing of the diurnal cycle or the mesoscale organization of convection, for setting basic and large-scale features of the climate system were not as readily observable as perhaps initially thought, letting the question as to their importance for climate open.

Studying deep convection requires atmospheric models integrated at high resolution, in the order of a few hundreds of meters, called *large-eddy resolving*, to a few kilometers, called *storm-resolving*, so that convection can be explicitly resolved. In contrast, *coarse-resolution* models employ grid spacings coarser than O(10 km) and a convective parameterization. A technical prerequisite of my work has thus been my use and development of high-resolution models, also on increasingly large domains. Already in my PhD, I used limited-area storm-resolving simulations with a grid spacing of 2.2 km to look at atmospheric predictability (Hohenegger, Lüthi and Schär, 2006; Hohenegger and Schär, 2007a,b; Hohenegger et al., 2008), at a time where such simulations were still in their infant years for operational weather forecasts. Later on, I conducted the first "climate" simulation on a mesoscale domain and on a monthly time scale (Hohenegger, Brockhaus and Schär , 2008) and, recently, I have been part of initiatives using month-long storm-resolving simulations on even larger domains, like the tropical Atlantic region (Klocke et al., 2017), up to the global scale (Stevens et al., 2019b; Hohenegger et al., 2020). Large domain, longer-term, storm-resolving simulations, which are becoming more and more feasible with the development in computer technologies, are exciting as they allow for the first time to look at the effects of the convective scales on the large-scale circulation of the atmosphere and on the climate.

Moreover, given the multi-scale nature of convection, another characteristic of my work has been the use of a multi-resolution approach. I have conducted large-eddy, storm-resolving and coarse-resolution simulations often on the same problem, to better understand the multi-scale nature of convection (see especially Hohenegger et al., 2009; Hohenegger, Schlemmer and Silvers, 2015; Hohenegger and Stevens, 2016; Retsch, Mauritsen, Hohenegger, 2019; Paccini, Hohenegger and Stevens, submitted). Even if I tackle the convection problem from the small scales towards the large scale, and favor the understanding from the process level, I applied this process understanding for parameterization development (Hohenegger and Bretherton, 2011) and supported model development activities related to the Max Planck Institute Earth System Model (Retsch, Hohenegger and Stevens, 2017; Crueger et al., 2018; Giorgetta et al., 2018; Mauritsen et al., 2019).

Chapter 2

The daily transition to deep convection

Figure 2.1: Processes involved in the daily transition to deep convection and investigated in this chapter.

On a summer day in the mid-latitude or over the tropical land areas, the development of convection shows a typical sequence of events that repeats itself from day to day (see e.g. Fig. 1.2). Shallow cumuli clouds, with vertical extent of a few kilometers, start populating the sky in the morning. With time, they grow deeper and become cumuli congestus clouds, i.e. "strongly sprouting cumuli with generally sharp outlines and often great vertical extent" (WMO, 1956, p. 40). If buoyant enough, congestus clouds reach the tropopause: they are then cumulonimbi recognizable by their characteristic anvil spreading at the tropopause. Deep convection leads to intense precipitation with a typical precipitation maximum in the late afternoon over land (Wallace, 1975; Yang and Smith, 2006). A similar transition occurs over ocean, but its timing is shifted with a main precipitation peak in the early morning hours (Gray and Jacobson, 1977; Randall, Harshvardhan and Dazlich, 1991).

The timing of the diurnal cycle of convective precipitation was a well-known pitfall of coarse-resolution atmospheric models ten years ago, common to all models (Dai, Giorgi and Trenberth, 1999; Guichard et al., 2004; Dai, 2006). Over land, it peaked around noon instead of late afternoon, and also over ocean, the peak occurred too early as compared to observations. Even if the representation of the diurnal cycle of convection has now improved in several models (Rio et al., 2009; Stratton and Stirling, 2012; Bechtold et al., 2014), it remains a weak spot of climate models (Fiedler et al., 2020). The poor representation of the convective diurnal cycle indicates that the processes important in setting the convective clock are either not included in a convective parameterization, are biased or are still not fully understood. The first improvement obtained in the representation of the convective diurnal cycle, as documented by the study of Rio et al. (2009), resulted from the inclusion of cold pools (see next paragraph) in a convective parameterization.

Various controls exist on the diurnal cycle of convection, controls that have been highlighted individually using large-eddy or storm-resolving simulations in the past (see Fig. 2.1). As the clouds transition to deep convection, the morphology and attributes of the convective clouds change. The clouds not only grow deep, they get wider (Kuang and Bretherton, 2006). As the buoyant plumes rise in the atmosphere, they mix with their environment and entrain cold and dry environmental air into the warm and moist updraft, reducing the buoyancy of the updraft. The rate of entrained air appears to decrease during the transition to deep convection (Del Genio and Wu, 2010; de Rooy et al., 2013). Moreover, detrained updraft air from shallower clouds during the mixing process moistens the environment, making it less hostile to the ascent of the next convective plume, a process called preconditioning (Waite and Khouider, 2010). Finally, the melting of solid hydrometeors and the evaporation of precipitation in the sub-cloud layer generate cold dense air that sinks through the atmosphere and spread at the surface as a density current, the cold pool. Artificially removing cold pools in model simulations hampers the triggering of deep convective clouds (Khairoutdinov and Randall, 2006). Enlarging clouds, reducing entrainment rates, moistening the environment and forming cold pools, are some of the processes that take place during the transition to deep convection.

Others, e.g. related to change in stability (Wu, Stevens and Arakawa, 2009), have been documented as well.

Even if a variety of transition mechanisms exists, only fast enough processes can be of relevance as the transition has to happen within a day. Moreover, the previously mentioned changes in cloud size, as the clouds transition, could provide an alternate and convenient way both to understand the transition and to include the relevant processes in a convective parameterization. I used these two ideas to look at the transition problem anew. More specifically, instead of looking at how mean properties, either of the clouds or of the environment, change during the transition, I investigated how transition mechanisms relate to the size of the biggest clouds and/or to the transition time. As transition mechanisms, I focused on preconditioning through congestus clouds, circulations induced by surface heterogeneity as well as cold pools, with the goal to determine the relevance of these mechanisms for the transition and their way of operating (Section 2.1). Logically, in a complementary step, I turned my attention to the representation of the diurnal cycle of convection in GCMs and on its importance for climate (Section 2.2). The contributions summarized below are the result of work by myself, part of a PhD thesis by Malte Rieck, a PhD student that I supervised, and work by a PostDoc (Linda Schlemmer) that I also supervised.

2.1 The transition time and the size of clouds

I used the above-mentioned idea of the transition time to assess the importance of moistening by previous clouds (preconditioning), a thermodynamic control on the transition to deep convection, versus moisture convergence (or equivalently forced ascent), a dynamical control on this transition (Hohenegger and Stevens, 2013a, remember Fig.1.3). In particular, I focused on the importance of the moistening by congestus clouds for the daily transition to deep convection. The existence of a significant congestus cloud population in the tropics, besides the well-known shallow and deep convective clouds, had only be formally discovered in 1999 by Johnson et al. (1999), letting open the question of their role. In 2010, Waite and Khouider (2010), using idealized simulations, showed that the detrainment of moisture from congestus clouds moistens the environment and helps the transition to deep convection. The study nevertheless employed homogeneous surface conditions and neglected large-scale forcing, which, on its own, is known to force the triggering of deep convection through forced moisture convergence and ascent (e.g. Back and Bretherton, 2009). To assess the efficiency of congestus moistening versus forced ascent, I derived transition times and moistening time scales combining observations, large-eddy simulations and simple theoretical estimates. Comparing a moist atmosphere populated with deep clouds to a dry atmosphere, as observed in the Atlantic ITCZ, congestus clouds would need 35 to 38 hours to moisten the atmosphere such as to make it conductive to deep convection. This is a theoretical time scale that can be computed taken into account how long the latent heat flux, whose moisture is transported vertically by convection and detrained by the congestus clouds, needs to moisten the atmosphere[1]. In contrast, the presence of even a very weak vertical velocity of 1 m s^{-1}, shortens this time scale to 18 h and to 4 h with a vertical velocity of 5 m s^{-1}, as a result of vertical moisture advection[2]. These bulk theoretical estimates are confirmed by idealized large-eddy simulations. Without imposed vertical velocity, congestus clouds take 10 h to transition, whereas this transition time reduces to 1 - 7 h depending on the strength of the imposed vertical velocity. Estimates of the transition time from satellite observations taken over the tropical Atlantic (see Fig. 2.2) are 4 h over ocean and 2 h over land. This is much faster than what can be achieved with congestus moistening alone, casting doubts upon the relevance of congestus moistening for the daily transition to deep convection. Further evidence speaking against the efficiency of preconditioning by congestus clouds are the fact that (i) most congestus clouds do not transition to deep convection actually; that (ii) the probability of transition does not increase with their lifetime and that (iii) the presence of cumuli congestus over a region does not enhance the likelihood for deep convection development.

At the time of publication, the idea of preconditioning, in particular by congestus clouds, had gained a lot of popularity, also to explain other aspects of deep convection, like the onset of the Madden-Julian Oscillation (Slingo et al., 2003). My results indicate that previous work might have overemphasized the importance of congestus moistening compared to dynamical forcing, whose efficiency to trigger convection is actually very well known in the context of nowcasting (Hohenegger and Stevens, 2013b). It is a first argument for the importance of dynamical, rather than thermodynamic controls on the lifecycle of convection. Studies by other groups using different datasets and methodologies (e.g. Kumar et al., 2013; Masunaga, 2013) came to similar conclusions concerning the transition to deep convection.

Over land, moisture convergence could be forced by thermally driven circulations triggered by surface heterogeneities (Segal et al., 1988, and see e.g. Fig. 4.1), posing again the question of their efficiency with respect to the transition time. In a follow-up study, Malte Rieck investigated the dependency of the transition time and of the cloud size on the presence of surface heterogeneity and on its length scale, using idealized large-eddy simulations (Rieck, Hohenegger and van Heerwaarden, 2014). The presence of surface heterogeneity not only forces the development of convection over the warmer patches (see Section 4.2 for more details on the underlying process), a well-known phenomenon, but also accelerates the transition time. The fastest transition had a transition time two-thirds that over a homogeneous surface, emphasizing again the efficiency of circulations in promoting the transition to deep convection. The presence of surface heterogeneity affects the cloud size distribution at a given time, but only the size of the largest clouds. The relationship between cloud size and length scale of the surface

[1] The moistening time scale by congestus is computed as $\frac{\Delta q_\mathrm{v}}{\frac{dq_\mathrm{v}}{dt}}$ with $\frac{dq_\mathrm{v}}{dt} = \frac{\mathrm{LH}}{L\rho(z_2 - z_1)}$, Δq_v required amount of moistening, q_v specific humidity, LH latent heat flux, L latent heat of vaporization, ρ density, t time and z height.

[2] Here $\frac{dq_\mathrm{v}}{dt} = \frac{1}{z_2 - z_1} \int_{z_1}^{z_2} -w \frac{dq_v(t_1, z)}{dz} dz$, with w vertical velocity.

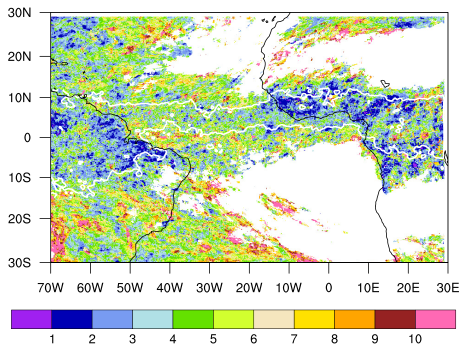

Figure 2.2: Map of observed transition times (h), from congestus to deep convection, derived from satellite data and averaged over May 2010. Points with less than five transitions are masked. The white line encloses the main region of deep convective activity. Figure taken from Hohenegger and Stevens (2013a).

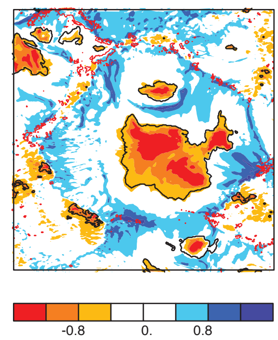

Figure 2.3: Humidity anomaly (g kg^{-1}) highlighting moist patches (blue). Black contours for cold pool outline, red contours for clouds. The shown subdomain is 100x100 km^2. Figure adapted from Schlemmer and Hohenegger (2016).

heterogeneity is non-linear. It can be understood from the combination of two different controls on the cloud size, each of them evolving at its own pace. On the one hand, clouds widen as a result of the destabilization of the atmosphere, a process independent of the heterogeneity length scale. On the other hand, clouds widen through the action of the thermally driven circulation, whose strength and thus vertical velocity depends on the underlying surface heterogeneity.

Even in the absence of surface heterogeneity or large-scale forcing, cold pools are another factor that aid the transition to deep convection. Although the existence of cold pools under deep convection has long been documented (Byers and Braham, 1949) and their importance for the organization of convection has long been known (e.g. Rotunno, Klemp and Weisman, 1988), the idea that cold pools are also important for the transition to deep convection is rather recent (Khairoutdinov and Randall, 2006; Böing et al., 2012). To better understand the connection between cold pools and transition, Linda Schlemmer investigated the relationship between cold pools and cloud size (Schlemmer and Hohenegger, 2014). She found that a relationship exists between the size of the large clouds, what we called moist patches, and cold pools. These moist patches are rings of enhanced moisture located at the edge of the cold pools (see Fig. 2.3). New clouds develop predominantly in these patches because of favorable thermodynamic and dynamical conditions. The number of clouds pro patches remains constant in time so that, as the patch widens, the cloud widens. The size of the patch itself relates to the cold pool size, thus linking cold pool size to cloud size. Based on these findings, Linda Schlemmer proposed a parameterization to include this effect in a convection scheme.

Given the importance of the moist patches for the transition to deep convection, Linda Schlemmer investigated in a follow-up study the origin of the moisture making up the moist patch. Does it come from the evaporation of precipitation, as suggested in RCE simulations conducted over ocean (Tompkins, 2001b), from the enhanced latent heat flux below the cold pool (Young, Perugini and Fairall, 1995), or from moisture convergence of environmental moisture by the cold pool wake? Conducting a moisture budget analysis of the moist patch (Schlemmer and Hohenegger, 2016), Linda Schlemmer found that moisture convergence dominates (86%), followed by surface fluxes (11%) and evaporation (4%). Furthermore, inserting tracers in the idealized large-eddy simulations revealed that surface moisture from the latent heat flux and evaporated rain water released within 2 h only makes 55% of the moisture accumulated in the moist patch, the remaining being old moisture pushed together by the cold pools, i.e. the result of moisture convergence.

Even though looking at three distinct aspects of the daily transition to deep convection, being congestus preconditioning, circulations triggered by surface heterogeneity and cold pools, the efficiency and importance of dynamical effects (moisture convergence) for this transition stand out. Furthermore, the size of the largest clouds could be related to the length scale of the surface heterogeneity or to the size of cold pools, providing a pathway to include these effects into a convective parameterization, as those effects are generally not included in a convective parameterization despite their obvious efficiency in promoting the transition (see next Section 2.2). The studies by Rieck, Hohenegger and van Heerwaarden (2014), Schlemmer and Hohenegger (2014) and Schlemmer and Hohenegger (2016) nevertheless only based on idealized large-eddy simulations. This is especially of concern for cold pools, whose formation is tight to phase changes of hydrometeors, phase changes that remain parameterized even in large-eddy simulations. Hence, as a follow-up and motivated by the findings of Schlemmer and Hohenegger (2014) and Schlemmer and Hohenegger (2016), I proposed to conduct a field campaign, called FESSTVaL, to be held in Lindenberg in 2021, with one goal to measure the characteristics of cold pools by deploying a high-resolution network of cheap self-built instruments ($\sim$ 100 of them) and weather stations ($\sim$ 20). This is a collaboration with the group of Prof. Felix Ament at the University of Hamburg, who is building the instruments. FESSTVaL will allow us to capture for the first time the horizontal structure of cold pools and their strength with fine enough resolution (O(1 km)), including the potential existence of moist patches.

2.2 The timing of the convective diurnal cycle in coarse-resolution simulations and its implications for climate

A motivation for looking at the transition mechanisms, as in the previous section, was that convective parameterizations failed to reproduce the diurnal cycle of convective precipitation. One of the systematic improvements of storm-resolving models against

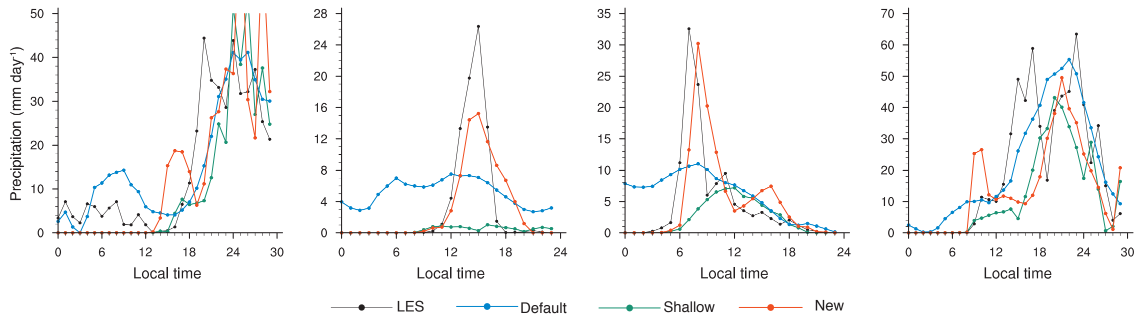

Figure 2.4: Diurnal cycle of precipitation for selected days of convection developing over mid-latitude land areas. Simulations are from the large-eddy model (black), the default SCM model version with traditional convective parameterization (blue), the SCM model version using only the shallow convection scheme as convective parameterization (green) and the SCM model version with the new convective parameterization (red). Figure adapted from Hohenegger and Bretherton (2011).

their coarser resolution counterpart is a more realistic timing of this diurnal cycle, even when applied on longer time scales, as first documented in Hohenegger, Brockhaus and Schär (2008). To improve the representation of the daily transition to deep convection, I tested a novel way to parameterize deep convection (Hohenegger and Bretherton, 2011). Historically, convective parameterizations have been first developed in GCMs to represent deep convection and then slightly adapted to include shallow convection. In reality, if anything, deep convection grows out of shallow convection. I tested the reverse approach, i.e. adapting a shallow convective parameterization that had been specifically developed to represent shallow convection, in my case by Bretherton, McCaa and Grenier (2004) and Park and Bretherton (2009), so that it can represent deep convection as well.

To do so, I included in a simple way some of the effects of the transition processes, namely: the widening of the clouds by cold pools; the additional lifting by cold pools; and the selective triggering of convection from the warmer and moister points of the domain. I employed idealized large-eddy simulations to parameterize such effects: the first one by relating entrainment rate, as a proxy for cloud size, to precipitation amount, as a proxy for cold pool activity; the second one, by relating the turbulent kinetic energy, used by the convective parameterization as closure, to precipitation and PBL depth; and the last one by including a term describing the variability in the PBL when computing the cloud base properties, this term being again linked to precipitation. Single Column Model (SCM) experiments revealed promising results, with a correct representation of shallow and deep convective cases and a correct timing of the precipitation diurnal cycle (see Fig. 2.4). Full GCM simulations nevertheless revealed the usual biases in terms of timing. As in contrast to SCMs, the large scale in GCMs is not constrained and 3D effects, like circulation, are important, I decided to take a step back and to give more attention to the question of the coupling of convection with circulation (see Chapters 3 and 4). Even though I haven't further developed my convective parameterization,

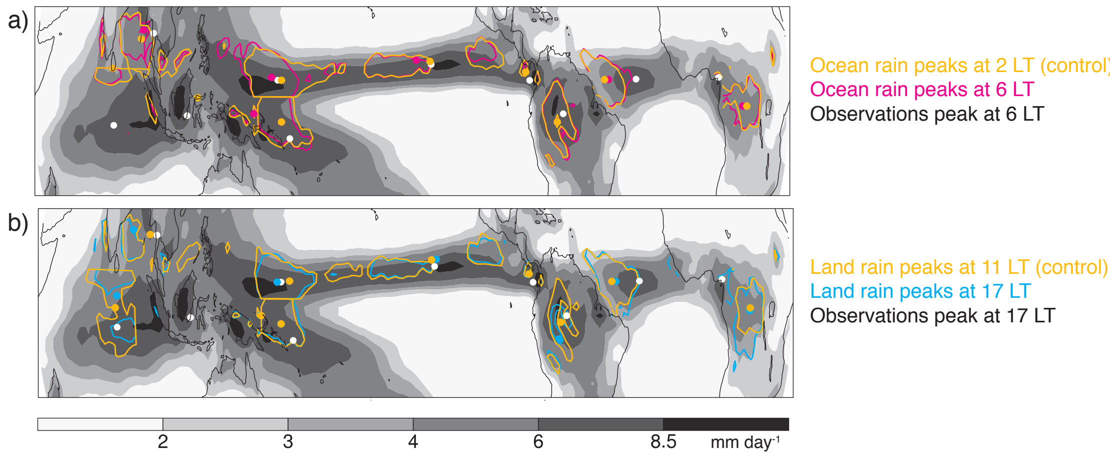

Figure 2.5: Observed mean precipitation (grey shading), simulated extent (colored lines) and location of weighted center of mass (colored dots for simulations, white for observations) of ITCZ objects for ten defined subregions (Atlantic, Africa, Indian Ocean, Asia, Maritime Continent, south Pacific, west Pacific, east Pacific, Central America, South America). ITCZ objects are defined by $RR > 0.7RR_{\max}$ with RR precipitation and $RR_{\max}$ maximum precipitation in a subdomain. In (a) the simulated precipitation diurnal cycle is modified over ocean only and in (b) over land only. Figure adapted from Hohenegger and Stevens (2013c).

other groups have tried to simulate deep convection by expanding a shallow convection scheme (D'Andrea et al., 2014; Park, 2014; Thayer-Calder et al., 2015; Suselj, Kurowski and Teixeira, 2019).

The timing of the diurnal cycle of convective precipitation is not the only bias in GCMs employing convective parameterizations. Well-known biases include a wrong partitioning of precipitation between land and ocean (Demory et al., 2014), the double ITCZ problem (Lin, 2007), or a wrong position of the Atlantic ITCZ (Siongco, Hohenegger and Stevens, 2014). The question arises, whether some of these biases are due to the wrong timing of the precipitation diurnal cycle or, in other terms, how important is actually the diurnal cycle of convection for representing large-scale features of the atmosphere. In that respect, the associated wrong diurnal cycle in cloudiness is of particular concern due to its interactions with the diurnal cycle of solar insolation. To investigate this, I artificially modified the convective parameterization of the ECHAM GCM to force a more correct representation of the diurnal cycle (Hohenegger and Stevens, 2013c). Shifting the diurnal cycle of convection turned out to have very little impact on the large-scale features of the precipitation distribution as measured by the position of the ITCZs (see Fig. 2.5). The only notable impact was found in the land-to-ocean precipitation ratio, where a more correct representation of the diurnal cycle induces an increase in precipitation amount over land, in better agreement with observations. The limited impact of the timing of the convective diurnal cycle may be the result of other, in GCMs poorly represented processes, that prevent a correct interaction of the diurnal cycle with the climate. This drawback can be partly bypassed using storm-resolving simulations. More recent studies using idealized limited-area storm-resolving simulations with and without diurnal cycle as well as comparisons between limited-area storm-resolving and coarse-resolution simulations have indeed revealed potential impacts of the diurnal cycle of convection, for instance for: the onset of the Madden-Julian Oscillation (Ruppert, 2016), the interaction between convection and land sea breezes (see Chapter 4 and Hohenegger, Schlemmer and Silvers, 2015), or the propagation of the African monsoon in today's climate (Marsham et al., 2013). The importance of the convective diurnal cycle for setting large-scale features of the precipitation distribution, such as position and width of ITCZs, using storm-resolving simulations remain though unexplored. With the application of storm-resolving climate models to the global scale and to longer simulation periods, recently demonstrated for eight models and a simulation period of 40 days in Stevens et al. (2019b), such an investigation is becoming possible.

This chapter summarized my research contributions concerning the daily transition to deep convection, its controls, representation in coarse-resolution models and impacts on climate. The idea of the transition time and of the cloud size was employed to investigate transition mechanisms, assess their efficiency and include corresponding missing effects in convective parameterizations. On the process side, my findings emphasize the efficiency of dynamical effects in controlling the daily transition to deep convection, questioning the picture of clouds randomly deepening on their own in a moist and unstable atmosphere. The size of the biggest clouds could be related to the length scale of surface heterogeneity, in the presence of a heterogeneous surface, or to cold pools. This latter relationship motivated the design of a field experiment targeted at sampling the characteristics of cold pools with unprecedented resolution. Even though a novel way to parameterize deep convection was tested, based on the gain process understanding and with the particular aim to better represent this transition, it didn't lead to the hoped improvements. In hindsight, focusing on the representation of this transition in a convective parameterization was maybe still too premature. First, other deficiencies, in particular interactions with circulations, are more stringent and mask improvement. And second, the importance of the timing of the precipitation diurnal cycle for setting large-scale features of the climatological precipitation distribution was not readily observable in the investigated coarse-resolution simulations. The importance of the timing of the diurnal cycle of convection for climate may thus be better investigated in future studies by conducting global storm-resolving simulations.

Chapter 3

The organization of convection

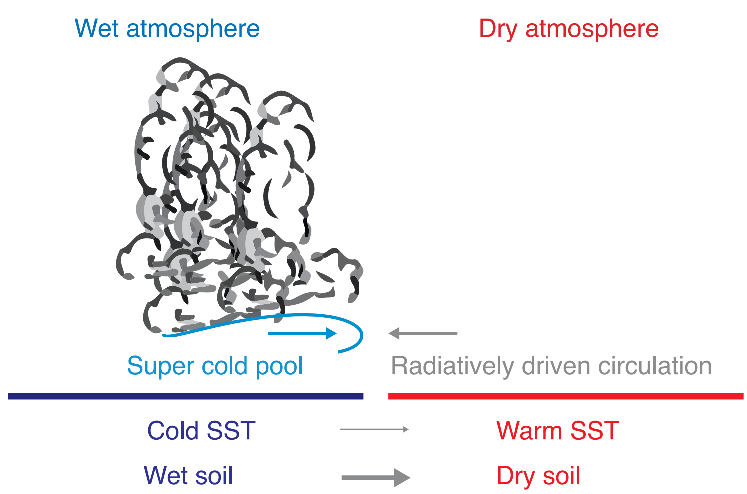

Figure 3.1: Interactions between the self-aggregation of convection and surface conditions. Relevant shallow circulations, confined in the planetary boundary layer, that determine the spatial distribution of convection, as disentangled in this chapter, are indicated.

The tendency of convection to organize is a well-known and striking ability of convection, clearly visible in satellite imagery. The ITCZ, monsoons, or the Madden-Julian Oscillation delineate large-scale regions of organized convective activity. At the mesoscale, individual convective clouds organize in squall lines, mesoscale convective systems, mesoscale convective complexes or hurricanes (Houze, 2004). Convection exhibits a pronounced tendency to clump together (Mapes, 1993). Even isolated convective clouds tend to distribute themselves in patterns that appear more organized than would be expected from a random distribution of these clouds over a given region (e.g. Plank, 1966). In a recent activity that I took part, scientists visually classified subtropical satellite images according to the spatial arrangement of their shallow convective clouds (Stevens et al., 2019a): from the 815 classified days, the "sugar", text-book like pattern, made of randomly distributed isolated trade wind cumuli, even turned out to be the least frequent of the four defined spatial patterns.

Numerous processes can lead to the organization of convection. Organization may be forced externally, by processes not directly related to the convection itself, or internally. Typical examples of externally forced convective organization are convection organized along a sea-breeze front or as a result of other sources of surface heterogeneity, a situation scrutinized in more detail in the next chapter (see Chapter 4). But even in the presence of a fully homogeneous atmosphere and homogenous boundary conditions, the convection can spontaneously start to organize. One example, already discussed in Chapter 2, is the organization of convection by cold pools. Cold pools break the random distribution of convective clouds by creating spatially confined favorable conditions for the development of convection, leading to an organization of the convective field (e.g. Fig. 2.3). Another example, studied in more detail in this chapter, is the self-aggregation of convection, as documented in idealized RCE studies (see e.g. Fig. 3.2). In the basic RCE set-up, an atmospheric model is integrated over a surface of fixed Sea Surface Temperature (SST), without rotation, without large-scale forcing, with uniform insolation and starting from a given, spatially homogeneous, atmospheric thermodynamic profile. Integrated in two and three dimensions, such simulations reveal that initially randomly distributed convective cells self-aggregate into one final convective cluster (Bretherton, Blossey and Khairoutdinov, 2005). Being externally or internally forced, and independently of the particular mechanism involved, the organization of the convective field requires the generation of heterogeneities that favor/hamper the development of convection in certain regions.

Even though the organization of convection is such a dominant feature, its importance for climate remained unclear and barely investigated five years ago. GCMs do not contain any representation of convective organization smaller than their grid spacing; still they are able to represent the large-scale organization of convection in the ITCZ and large-scale features of the climate system: Does this mean that the subgrid-scale organization of convection is unimportant? On the other hand, many aspects of the climate system, including the location of the ITCZs, remain biased (Fiedler et al., 2020): is the subgrid-scale organization of convection maybe important after all? In a workshop that I took part, dedicated to discuss grand challenges on clouds, circulation and climate sensitivity and held at the Ringberg castle in 2014, the question of the organization of convection and its importance for climate was chosen as one of the four challenges to be addressed in a concentrated effort by the scientific community (Bony et al., 2015).

Not only the Ringberg workshop contributed to the popularity of the topic of convective organization, but also the results of these RCE studies where the convection self-aggregates. The first three-dimensional storm-resolving RCE study appeared in 1998 (Tompkins and Craig, 1998), followed up by a handful of isolated studies specifically looking at the self-aggregation of convection in the next fifteen years (Tompkins, 2001a; Bretherton, Blossey and Khairoutdinov, 2005; Stephens, van den Heever and Pakula, 2008). Concurrent work by Muller and Held (2012), Jeevanjee and Romps (2013), Craig and Mack (2013), Wing and Emanuel (2014) and Emanuel, Wing and Vincent (2014) led to a renewed interest in the topic of the self-aggregation of convection (see Wing, 2019, for a comprehensive review on the self-aggregation of deep convection). Maybe because, despite the simplicity of the problem, these five studies disagreed on the underlying key mechanisms promoting self-aggregation (see Section 3.1), thus arousing the interests of the scientific community.

My research contributed to this rapidly growing field of studies investigating the self-aggregation of convection and the related question of the importance of organization for climate, particularly by extending the RCE conceptualization to a more dynamical representation of the surface at high resolution. One specific motivation for my involvement in this topic was the view that the RCE set-up provides another approach to understand the relative importance of thermodynamic versus dynamical controls on the spatial distribution of precipitation. Another motivation was the hypothesis that the ITCZ may be the best real-world analog for the self-aggregation of convection. In this sense, the RCE conceptualization offers a novel way to look at the ITCZ and provides hypotheses to assess the importance of organization for climate. Finally, the RCE set-up, given the homogeneity in its boundary conditions, also offers an opportunity to easily compare models across resolutions. Over the years, my group develops the special ability to conduct RCE simulations across configurations, from large-eddy resolving over storm-resolving to coarse resolution with parameterized convection, on a small domain, small planet and the full Earth.

Given these considerations, my research contributions first aimed to understand whether, fundamentally, convection wants to remain randomly distributed or organize, and which processes set this distribution. In that respect, I was particularly interested to understand the impact of the surface conditions. Almost all idealized storm-resolving studies on the self-aggregation of convection, even up to today, have focused on the situation of convection developing over a surface with fixed SST. In contrast to these studies, I investigated the self-aggregation of convection above SST gradients, coupled to a mixed layer ocean model and coupled to a land surface model. In a next step, I tested expectations derived from these RCE studies to the real world with the aim to quantify the importance of organization for climate. This also included an investigation of ways to represent organization in convective parameterizations. The work described below is the result of work by myself, a PhD student (Tobias Becker) that I co-supervised, a part of a PhD thesis by Sebastien Müller that I supervised, and work by three PostDocs (Julia Windmiller, supervised, Ann Kristin Naumann, co-supervised, Matthias Brueck, co-supervised).

3.1 The controls on the spatial distribution of convection

Many studies have now documented that, over a surface with fixed SST, the initially randomly distributed convective cells can spontaneously aggregate with time (see e.g. Fig. 3.2). On square domains, the convection self-aggregates into one final circular blob (e.g. Bretherton, Blossey and Khairoutdinov, 2005), on channel domains in a line (e.g. Wing and Cronin, 2016), and on a sphere of large radius into several blobs (e.g. Popke, Stevens and Voigt, 2013). Various mechanisms can lead to the self-aggregation of convection: up-gradient transport of moist static energy from non-convective to convective region (Bretherton, Blossey and Khairoutdinov, 2005), a coarsening process involving moisture (Craig and Mack, 2013), surface fluxes (Tompkins and Craig, 1998), a radiative instability (Emanuel, Wing and Vincent, 2014), radiative-convection feedback (Stephens, van den Heever and Pakula, 2008) or radiatively driven shallow circulations (Muller and Held, 2012). In contrast, cold pools tend to disaggregate the convection (Jeevanjee and Romps, 2013). Despite this diversity, aggregating mechanisms, in a way or in another, act to segregate the moisture field into very dry regions, unconducive for convection, and moist regions, where the convection remains confined.

As more and more groups conducted RCE simulations, it became clear that the occurrence of self-aggregation depends on the experimental set-up, e.g. grid spacing, domain size or chosen SST, and employed atmospheric model. This has been confirmed by the RCEMIP intercomparison project (Wing et al., 2018), an intercomparison exercise that my group contributed to by running large-eddy, storm-resolving and GCM simulations. Even when aspects of the model set-up, such as domain size, SST or grid spacing are prescribed across models, the final state of self-aggregation widely varies (Wing et al, 2020). Moreover, it appears that parameterizations and parameter choices inside a parameterization can decide on the fate of the self-aggregation process (Becker, Stevens and Hohenegger, 2017). Conducting RCE simulations with a GCM, Tobias Becker found that the degree of self-aggregation depends upon the entrainment rate specified in the convective parameterization. This was also noted in Nathan and Randall (2015) using a different model and for one tested SST. Large entrainment rates favor self-aggregation as they make convection sensitive to the ambient moisture and prevent deep convection to develop in dry regions. But the entrainment rate particularly matters in the presence of warmer SSTs, because the saturation deficit between updraft and environment increases with increasing SST.

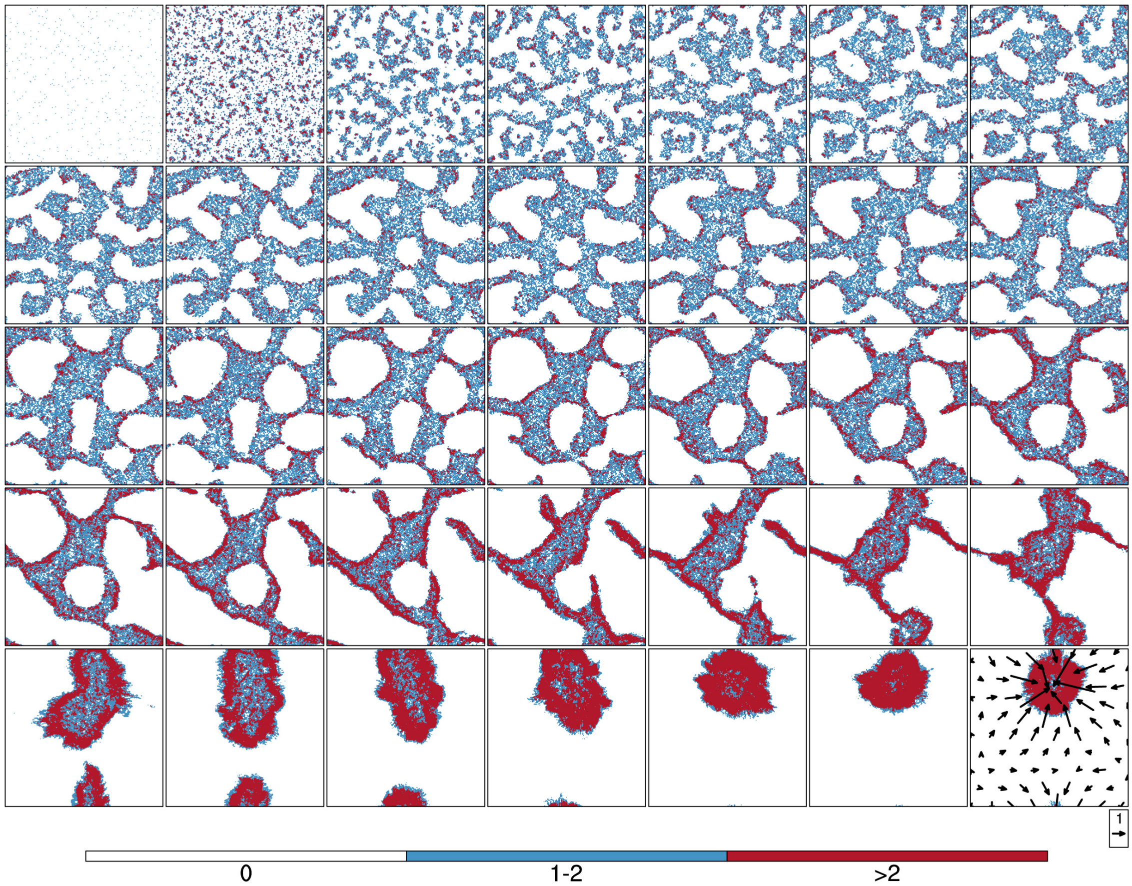

Figure 3.2: Frequency of convective occurrence. Each plot corresponds to one simulation day; the frequency at each grid point is computed as the number of times cloud water is present at 1 km (based on hourly instantaneous output). On the last plot, the daily mean of the horizontal wind from the lowest atmospheric layer is added. Figure taken from Hohenegger and Stevens (2016).

With fixed SST, the typical response in simulations with explicit convection is self-aggregation. This is not necessarily true when the SST is interactive, or over a land surface, as my work has shown for the first time. Over a slab ocean, the presence of interactive SST acts against the self-aggregation of convection, the more so, the shallower the slab and hence the larger the sensitivity of the SST to the surface energy budget (Hohenegger and Stevens, 2016). In my simulations, the convection did not self-aggregate for a slab ocean of depth smaller than 1 m. This behavior can be understood from a competition between aggregating and disaggregating mechanisms and their dependency upon the underlying SST. Convection self-aggregates if dry regions of the domain expand with time (see Fig. 3.2). A dry region expands if its export of moisture to the surrounding regions is larger than in-situ moistening by latent heat flux[1]. The mean SST, and hence the latent flux, increases more rapidly with time in simulations with a shallower slab given the smaller heat capacity. On top of that, the export of moisture is less efficient in such simulations due to the competition between two opposing circulations (see Fig. 3.1). The first circulation is driven by differences in radiative cooling between the dry and the wet regions. It is a shallow circulation confined in the PBL, which has been shown in previous RCE studies with fixed SST to be instrumental to the self-aggregation of convection (see especially Muller and Held, 2012), and which is directed from the dry to the wet region. The second circulation is triggered by SST gradients that develop with time. In particular, the cooling of the SST due to cloud shading by deep convection over the wet region spins up a thermally direct shallow circulation from the wet to the dry and warm region. The two circulations oppose themselves and result in a less efficient export of moisture from the dry to the wet region.

The generation of shallow circulations by distinct heterogeneity sources that end up competing and setting the final spatial distribution of convection is not restricted to the sole case of convection interacting with a slab ocean, but is a more universal finding pertinent to the interactions between convection and a nonhomogeneous/interactive surface. It could be found in the presence of imposed SST gradient (Müller and Hohenegger, 2020), or of a land surface with interactive soil moisture (Hohenegger and Stevens, 2018). In the first case, Sebastien Müller imposed meridionally varying SST profiles on a planet with a reduced radius. The imposed SST profiles were inspired from SST profiles employed in traditional aquaplanet experiments (Neale and Hoskins, 2000), with maximum SST at the equator and decreasing towards the poles. In contrast to aquaplanet experiments, though, the simulations kept a homogeneous insolation and neglected rotation. In the meridional direction (see Fig. 3.3), the SST gradient spins up a circulation whose intensity is proportional to the imposed SST gradient. This circulation leads to convergence at the equator and to the formation of a continuous convecting band along the equator. In the zonal direction, where the SST is homogeneous, self-aggregation can take place: a zonal flow develops, whose velocity is independent of the imposed SST gradient. This flow leads to a zonal contraction of the convergence line accompanied by a slight meridional expansion. Putting these two effects together, the stronger the SST gradient, the longer it takes for the self-aggregation to break the convergence line and the smaller the zonal contraction is. These results suggest that, in the real world, convergence line may be unstable to the self-aggregation of convection, an idea tested in Hohenegger and Jakob (2020) using reanalysis data (see next Section 3.2 for more detail on the results of this study).

In the second case, the case of a land surface, it is the development of soil mois-

[1] This can be seen formally by writing the moisture budget equation for the non-convective region: $\frac{\partial \overline{I_\mathrm{q}}}{\partial t} = \frac{\overline{LH}}{L} - \overline{C}$ and using the Leibniz rule of integration: $\frac{\mathrm{d}\overline{I_\mathrm{q}}}{\mathrm{d}t} = \overline{\frac{\partial I_\mathrm{q}}{\partial t}} + S_\mathrm{A}$ to write $\frac{\mathrm{d}\overline{I_\mathrm{q}}}{\mathrm{d}t} - \frac{\overline{LH}}{L} + \overline{C} = S_\mathrm{A}$ with I_q water vapor path (mass weighted), LH latent heat flux, L latent heat of vaporization, C column-integrated horizontal advective moisture divergence and S_A change in the size of the non-convective area.

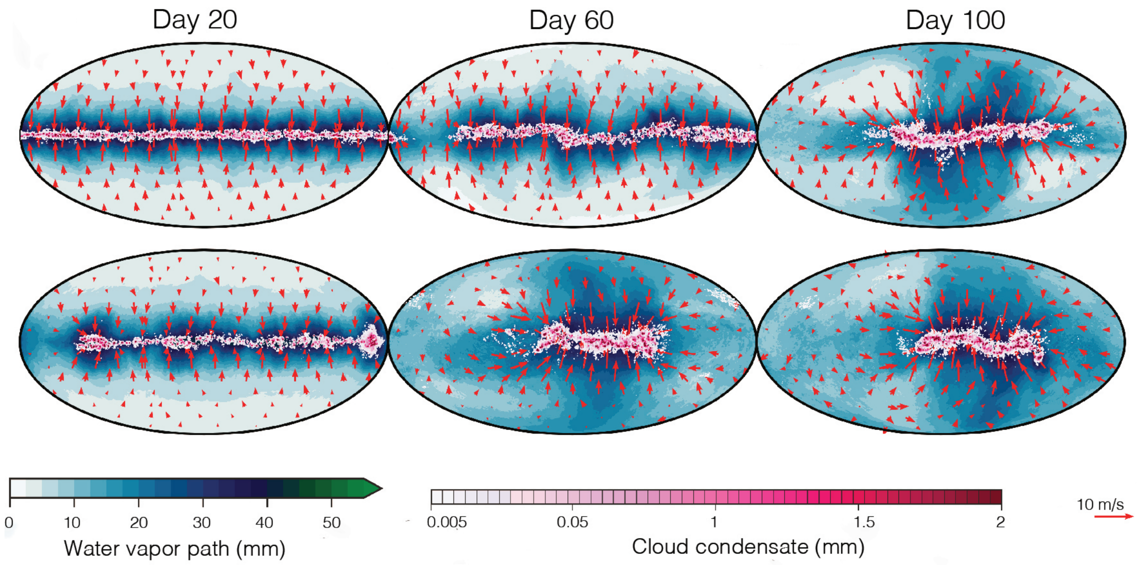

Figure 3.3: Vertically integrated cloud condensate (white to pink), water vapor path (shading) and surface flows on three different days for a simulation with a strong (upper row) and weak (lower row) SST gradient. Figure adapted from Müller and Hohenegger (2020).

ture gradient between wet and dry regions that triggers a shallow circulation (see Fig. 3.1) that competes with the underlying radiatively driven circulation, directed from the dry to the wet regions. As explained in more detail in the next chapter (Chapter 4), the soil moisture-induced circulation is stronger and leads to a homogenization of the precipitation distribution on longer time scales (Hohenegger and Stevens, 2018).

The previously mentioned three studies (Hohenegger and Stevens, 2016; Müller and Hohenegger, 2020; Hohenegger and Stevens, 2018) helped understand in a novel way the impact of the surface conditions on the spatial distribution of convection, using a simplified system where radiation, convection and the underlying surface interact with each other in an otherwise homogeneous environment. From this exercise, we learned that oceanic surfaces are more likely to keep the convection organized than land surfaces, the more so, the deeper the ocean surface layer. This is consistent with precipitation observations that show a narrower ITCZ over ocean than over land, a yet unexplained fact. Moreover, radiatively driven circulations can distort the spatial distribution of precipitation as set by SST gradients over tropical oceans (see also Naumann, Stevens and Hohenegger, 2019). A secondary shallow meridional circulation has been observed in the vicinity of the ITCZ (Zhang et al., 2008), and associated either to SST gradient (Nolan, Zhang and Chen, 2007), to latent heating from shallow convection in the subsiding regions (Wu, 2003) or to radiative cooling at the PBL top in subsiding regions (Nishant, Sherwood and Geoffroy, 2016).

When the convection self-aggregates, the size of the final convective cluster is significant, amounting for instance to a diameter of 200 km in a simulation domain of about 600 x 600 km^2. This motivates two further questions: is the convection randomly distributed inside the convective cluster or organized as well? And what determines the size of the cluster? Julia Windmiller investigated these two questions (Windmiller and Hohenegger, 2019). Even inside the final convective cluster, the convection is not randomly distributed but enhanced at its edges (see Fig. 3.2). Investigating potential thermodynamic and dynamical controls for the edge intensification (remember Fig. 1.3), Julia Windmiller found a dynamical control through enhanced moisture convergence at the edge. The moisture convergence again results from a balance between two shallow circulations (see Fig. 3.1): cold pools of individual convective cells that combine into what we called a super cold pool and act to expand the convective area; and the inflow, radiatively driven shallow circulation, that acts to compress the convective region. Estimating the velocity of the super cold pool using gravity current theory (see Eq. 3.1), and contrasting it to the value of the inflow velocity displayed by the simulations, indeed revealed similar velocities. Moreover, changes in the size of the convective cluster correlated with changes in the relative magnitude of the two circulations. This apparent edge intensification in RCE simulations is interesting as, in the real world, convection is also intensified at the edge of the ITCZ (Mapes et al., 2018). Motivated by these results, Julia Windmiller is currently investigating the importance of cold pools for setting the width of the ITCZ. This may represent another effect of cold pools on the precipitation distribution, beside their known role for the organization of convection (Rotunno, Klemp and Weisman, 1988), for the triggering of convective cells (Goff, 1976) and for the transition to deep convection (see previous Chapter 2).

Even if the self-aggregation of convection is associated with a confinement of convection into the moist and hence thermodynamically more favorable regions of a simulation domain, the presented results emphasize the importance of dynamical effects (circulations) in setting the spatial distribution of convection, rather than thermodynamic effects per se (moist/unstable, remember Fig. 1.3). In this sense, the results are in line with the results of Chapter 2 on the transition to deep convection. The results in this section are also noteworthy as the considered systems are very simple, starting from homogeneous conditions and thus disadvantaging dynamical effects that first require heterogeneity to develop before being able to act. The results not only emphasize the importance of circulations, but of shallow circulations. The isolated circulations driven by radiative heating anomalies, SST gradients or soil moisture gradients, as well as cold pools, are all shallow circulations that are the result of buoyancy anomalies in the PBL, with the cause of the buoyancy anomaly differing among them. In the simplest terms, their effect on the spatial distribution of convection can thus be understood using one common framework based on gravity current theory.

Gravity, or density, currents are dense fluid propagating into a lighter fluid (Benjamin, 1968). The gravity-current theory has been previously applied to cold pools (Charba, 1974) or shallow circulations driven by surface heterogeneity (Simpson, 1969). I employed it extensively throughout my research work to understand the self-aggregation of convection and the resulting spatial distribution of convection. The propagation speed

c of a gravity current is given by:

$$c = k\sqrt{\frac{gH\Delta\theta_{\mathrm{v}}}{\theta_{\mathrm{v}}^{0}}} \quad (3.1)$$

with k a constant, g gravity, θ_{v}^{0} virtual potential temperature of the light fluid, H depth of the circulation and $\Delta\theta_{\mathrm{v}}$ difference in θ_{v} between the two fluids. Equation 3.1 uses θ_{v} as a measure of density, but other variables (e.g. density or pressure) can be employed as well. Equation 3.1 indicates that the circulation associated with the strongest density difference will win in setting the spatial distribution of convection. It provides a simple framework to understand and predict the spatial distribution of convection, in agreement with the results of the conducted idealized studies.

One drawback of the gravity-current theory is that the constant k has to be specified and that it does not include friction. As an alternative theoretical framework to understand the self-aggregation of convection and, in particular, to understand the interactions between radiatively driven circulations, the PBL and shallow convection, Ann Kristin Naumann developed a conceptual one- and two-box models for the case of a dry (Naumann et al., 2017) and a wet (Naumann, Stevens and Hohenegger, 2019) PBL.

The process understanding gained from RCE work influenced the design of field campaigns, such as the NARVAL (Stevens et al., 2019c) and EUREC^{4}A (Bony et al., 2017) field campaigns. It especially puts dry regions, and not only moist regions, in the focus of attention to understand the development of convection, as, in the RCE conceptualization, it is often the dry region that ends up setting the spatial distribution of convection through its expansion. The obtained theoretical results also speak for more targeted measurements of shallow circulations, even over ocean, a difficult endeavor.

3.2 The importance of organization for climate

In the RCE world, the self-aggregation of convection is deemed important. Already one of the first RCE studies, Bretherton, Blossey and Khairoutdinov (2005), noted a strong drying of the mean atmosphere caused by the self-aggregation of convection. The water vapor path was around 20 mm in the dry region against 50 mm in the wet convective region. This strong drying has been confirmed in all subsequent RCE studies, independently of the employed model (Wing et al, 2020). In my storm-resolving simulation with a slab ocean (Hohenegger and Stevens, 2016), the occurrence of self-aggregation was not only important in determining the mean state of the climate, but, even more importantly, it affected its stability and possibly prevented a runaway greenhouse climate. The self-aggregation of convection generated the dry subtropics, allowing the climate to efficiently cool. Through this, the climate stabilized at an SST of 301.8 K, whereas preventing the self-aggregation of convection led to a continuous warming with an extrapolated equilibrium SST of 330.4 K.

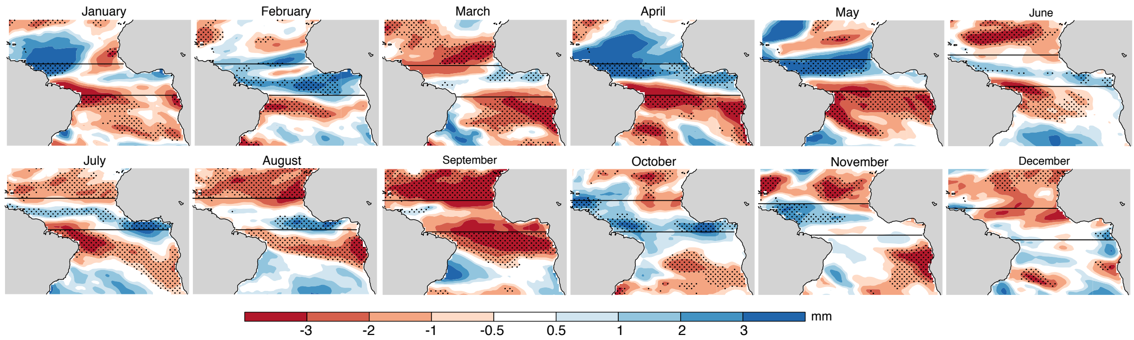

Figure 3.4: Monthly mean difference in water vapor path (shading, from ERA-interim) between the 5 years with the largest (most organized ITCZ) and the smallest (least organized ITCZ) number of long convergence lines per month. The black horizontal lines enclose the ITCZ region. Stippling indicates significance at the 90% level. Figure taken from Hohenegger and Jakob (2020).

These results give a first testable hypothesis on the effects of organization on climate. Tobin, Bony and Roca (2012), Stein et al. (2017) and Kadoya and Masunaga (2018) all searched for a relationship between organization and moisture in observations, within a same mesoscale region and for given large-scale conditions (same SST, vertical velocity and precipitation). They confirmed that mesoscale regions characterized by a higher degree of organization are drier than their less organized counterparts. In contrast, inspired by the results of my previous study (Hohenegger and Stevens, 2016), I investigated whether a relationship exists between the degree of organization of the ITCZ and the humidity in the subtropics, and this without any compositing on large-scale conditions to be able to diagnose the true relevance of organization in the midst of other factors (Hohenegger and Jakob, 2020). Such an investigation first required a quantification of the degree of organization. Various organization indexes have now been proposed, combining attributes such as number of convective cells, areas of cells, distances between cells, all within given analysis boxes (e.g. Tobin, Bony and Roca, 2012; Tompkins and Semie, 2017; White et al., 2018; Kadoya and Masunaga, 2018). Such indexes are however difficult to interpret, as also shown in two studies I took part (Pscheidt et al., 2019; Brueck, Hohenegger and Stevens, 2020). Moreover, they are only suitable for quantifying organization in mesoscale regions. Instead, I proposed to quantify the organization of a large-scale feature, such as the ITCZ, by making use of a dataset of convergence lines previously compiled by Weller et al. (2017). The underlying idea is that long convergence lines are the signature of a highly organized ITCZ structure, so that their number can serve as an organization index. Applying this metric to the Atlantic region revealed that years with a larger number of long lines are indeed associated with drier subtropics, particularly during summer (see Fig. 3.4), confirming the idealized results of my previous study (Hohenegger and Stevens, 2016). Even though I could not demonstrate any causality relationship, neither for a humidity anomaly preceding nor succeeding the organization signal, interannual variability in other atmospheric variables (gradient in SST, latent heat flux, precipitation, circulation, convergence strength) are inconsistent with the observed relationship. If a causality between the degree of ITCZ organization and subtropical humidity could be proven, it would be of key relevance for studies on climate and climate change given the role that subtropical humidity takes in stabilizing the climate and in determining the energy budget.

As an addendum, I also made use of the dataset of convergence lines and the proposed quantification of organization to test another prediction from my idealized work, i.e. the prediction from Müller and Hohenegger (2020) that the ITCZ is unstable to the self-aggregation of convection, the more so, the weaker the SST gradient is. Here I indeed found similarities between the annual cycle of the number of long lines and the strength of the SST gradient with a larger amount of long lines during periods of stronger SST gradient.

Another potentially important and not yet investigated effect of organization on climate concerns its potential effect on precipitation amount. In RCE simulations, aggregated convection is protected from its dry hostile environment by a moist shell, which prevents a strong reduction of its buoyancy with height (Becker et al., 2018). Aggregated convective scenes also exhibit a higher precipitation efficiency (Tobin, Bony and Roca, 2012; Stein et al., 2017). Both effects could favor stronger precipitation. Using the output of a realistically configured global storm-resolving simulations, Matthias Brueck investigated this relationship (Brueck, Hohenegger and Stevens, 2020). Surprisingly, no relationship could be found over the tropical region. If anything, more organized scenes seem to precipitate less. This means that the well-known fact that organized convective systems produce most of the tropical precipitation (Nesbitt, Cifelli and Rutledge, 2006) is not a result of their organization per se.

Other potential effects of organization on climate have been investigated by other groups, motivated by the results of RCE studies. Those especially concern relationships between cloud types and the degree of mesoscale organization (Stein et al., 2017) and between radiation and mesoscale organization (Tobin, Bony and Roca, 2012; Lebsock, L'Ecuyer and Pincus, 2017). Compositing strategies developed from RCE studies, making use of a decomposition of the moist static energy budget or of a decomposition of the atmosphere in moisture space have also been applied to tropical observations (Beucler et al., 2019; Schulz and Stevens, 2018) or realistic simulations (Holloway, 2017). Together with my own contributions, these studies show that understanding derived from the RCE conceptualization can be useful to uncover potential climatic impacts of organization in the real world.

That a link between organization and humidity exists seems at the moment the most certain effect of organization on climate, as it has been noted in more than one study and in different contexts. The effect of mesoscale organization is nevertheless not considered by any of the existing convective parameterizations. Tobias Becker thus investigated ways to include a mesoscale representation of convective organization in a convective parameterization. An idea commonly proposed to include organization is to reduce the entrainment rate of the convective plume in more organized situations (Mapes and Neale, 2011; Tobin et al., 2013). Comparing entrainment rates derived from RCE simulations with strongly aggregated and randomly distributed convection, Tobias Becker nevertheless disproved this idea (Becker et al., 2018). Strongly aggregated convection has a larger entrainment rate than unorganized convection, likely due to stronger turbulence around the updrafts. The reduction in updraft buoyancy with height still remains smaller, though, as aggregated updrafts are protected from their dry environment by a moist shell, and hence entrain moister air than randomly distributed convective updrafts. Similar results hold in realistically configured simulations (Becker and Hohenegger, submitted).

Including mesoscale organization in a convective parameterization may thus require introducing a parameterization for the moist shell surrounding the updraft, a more complicated undertaking than adapting the entrainment rate. But how big is really the penalty of not including mesoscale organization in a GCM? Can we link basic model biases to a misrepresentation of organization? I investigated this question, first by comparing the climate of storm-resolving and coarse-resolution simulation in the RCE framework, and second by comparing realistically configured simulations across resolutions.

I used the RCE framework, which easily allows a comparison of high- and low-resolution simulations given the spatial homogeneity of the prescribed boundary conditions, to compare how storm-resolving and coarse-resolution simulations with parameterized convection equilibrate their climate and respond to warming (Hohenegger and Stevens, 2016). As noted above, the storm-resolving simulation equilibrated thanks to the self-aggregation of convection. Interestingly, the self-aggregation of convection was not necessary in the coarse-resolution simulation. There, the regulation of the climate happened through strong shortwave cloud radiative effects, much stronger than at storm-resolving resolution. This led to a larger cloud cover (0.5 against 0.2), a moister atmosphere (33 against 27 mm) and a cooler SST (300.1 against 301.8 K) at coarse resolution. This distinction in the regulation mechanisms between the two simulations became more evident when considering the response to an imposed warming, mimicked by an abrupt increase in the solar insolation by 2%. The implied warming was 3.8 K in the storm-resolving simulation, with strongly aggregated convection, and only 1.6 K in the coarse-resolution simulation, due to its strong shortwave cloud radiative effects. These results indicate that, at least in the RCE framework, where the organization of convection can play a dominant role, storm-resolving and coarse-resolution simulations can behave very differently, also in their response to imposed perturbations. As such, these results undermine confidence in our ability to answer questions related to climate change using GCMs. The results also indicate that differences between storm-resolving and coarse-resolution simulations may be more visible in their sensitivity to imposed perturbations, as further shown in Chapter 4 concerning land surface perturbations.

The RCE conceptualization may well overemphasize the role of convective organization. As it is now possible to conduct month-long global simulation at storm-resolving resolution in a realistic set-up, I used this opportunity to investigate the relevance of

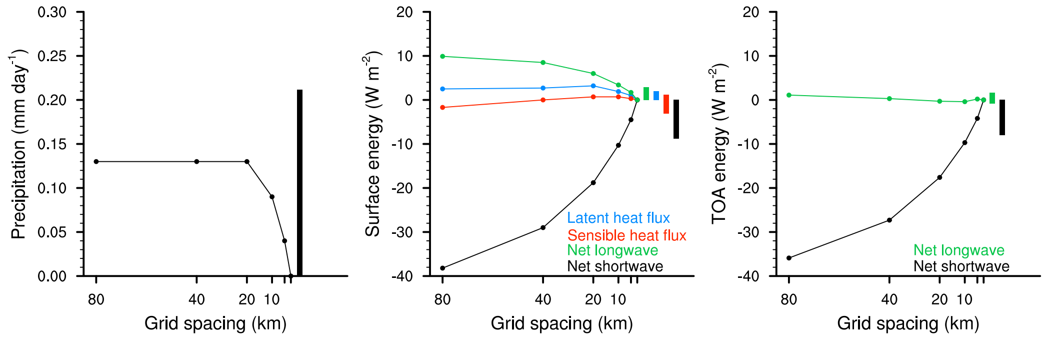

Figure 3.5: Global climate statistics as a function of grid spacing and as expressed as difference to the 2.5-km simulation. The vertical bars show one standard deviation computed from the ensemble of eight distinct storm-resolving models. Downward energy fluxes are positive except for sensible and latent heat flux. Figure taken from Hohenegger et al. (2020).

mesoscale organization for existing model biases. Directly comparing storm-resolving and coarse-resolution simulation with parameterized convection is misleading in this respect as differences may well arise from a poorly designed convective parameterization, rather than from its missing mesoscale organization. As an alternate approach, I compared the results of global simulations, integrated for 40 days, with grid spacings successively coarsened from 2.5 km to 5, 10, 20, 40 and 80 km (Hohenegger et al., 2020). All the simulations employ explicit convection, meaning that the 80-km simulation has no information on scales smaller than 80 km and also no representation of mesoscale organization. If mesoscale organization is important for climate, discrepancies should become apparent as the grid spacing is coarsened. The downside of this approach is that, if discrepancies are apparent, they may not be the sole result of the missing subgrid-scale organization. To assess the significance of the resolution-induced differences, I took advantage of a newly available and unique ensemble of storm-resolving simulations conducted by eight different modeling groups (Stevens et al., 2019b). As long as resolution-induced differences remain smaller than the ensemble spread, the resolution (and hence the implied unresolved scales) are viewed as unimportant for setting large-scale features of the climate system. Looking at large-scale features of the atmosphere, such as location of the ITCZ, precipitation amount, energy budget, resolution-induced differences are small, except in the net shortwave radiation due to a misrepresentation of trade wind cumuli (see Fig. 3.5). The resolution dependency is much smaller than initially thought and generally assumed, with e.g. weather forecasting models typically switching off convective parameterizations only below 3-4 km grid spacing. It is nevertheless consistent with the results of another independent study conducted on the regional scale that was published at the same time (Vergara-Temprado et al., 2020). In summary, the 5-km simulation, which can capture 26 out of the investigated 27 statistics, appears sufficient to represent basic features of the climate system. This is a good news for the prospects of conducting global climate simulations at storm-resolving scale. But even the 80-km simulation could still capture 9 of the investigated statistics, including the global mean precipitation amount, the latitudinal position and the width of the Atlantic ITCZ or the longitudinal position of the Pacific ITCZ. These results do question the importance of the small scales and of mesoscale organization, at least for setting large-scale features of the precipitation distribution. Current studies, where we have been investigating the sensitivity of the tropical Atlantic ITCZ to mode of SST variability (Paccini, Hohenegger and Stevens, submitted), or the propagation of the monsoon during the Holocene, both in storm-resolving and coarse-resolution simulation with parameterized convection, also revealed surprisingly small differences between the set-ups. Maybe small-scale features and mesoscale organization are, after all, not so important for setting large-scale features of the precipitation distribution, which, in this sense, would confirm the unexpected results of Brueck, Hohenegger and Stevens (2020). Or maybe uncertainties related to the microphysics, which has to be parameterized at storm-resolving resolution, remain too large and mask a reliable determination of organization effects in models.

This chapter summarized my research contributions towards understanding controls on the spatial distribution of convection and the effects of organization on climate, making use of the RCE conceptualization. Convection fundamentally strives to organize, and its resulting spatial distribution is set dynamically by shallow circulations, whose effects can be understood using gravity current theory. In a nutshell, the circulation associated with the strongest buoyancy anomaly wins. The consequence is that convection is more organized over ocean than over land, and strongly dynamical surfaces act to homogenize the precipitation distribution. Organization matters for climate as the large-scale degree of organization of the ITCZ correlates with the degree of dryness in the subtropics but, perhaps surprisingly, mesoscale organization does not matter for precipitation and the impacts of the small scales on the large-scale features of the precipitation distribution was not easily recognizable. Overall, RCE proved itself as a useful conceptualization to isolate potential effects of organization on climate, whereas the quantification of organization in the real world remains an unsatisfactorily solved issue as the many proposed organization indexes are hardly interpretable.

Chapter 4

The coupling of convection with the land surface

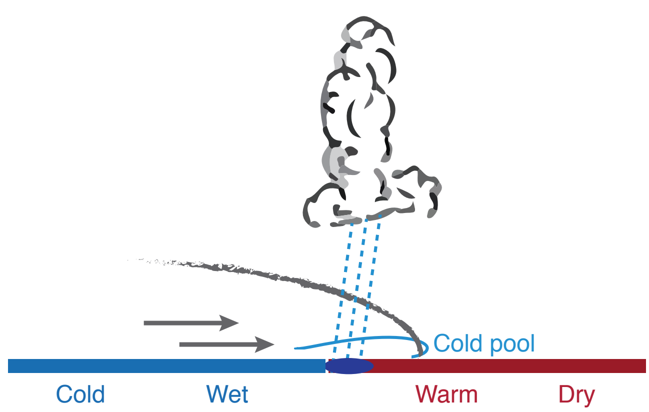

Figure 4.1: Convection triggered by a shallow circulation induced by land surface heterogeneity and interacting with it through the generation of precipitation and cold pools, as studied in this chapter.

Visual examples of the impacts of the land surface on convection include the earlier development of convective clouds over mountains, the redrawing of the coastline by convective clouds a few kilometers inland or, on larger scales, monsoon systems. The land surface has the potential to affect the triggering of convection, its spatial arrangement and the produced precipitation amounts. Once convection develops, it feeds back on the land surface. The coupled land-atmosphere system allows both for positive, e.g. in the case where an increase in soil moisture leads to an increase in precipitation, which in turn increases the soil moisture; and for negative feedbacks, e.g. in the case where an increase in soil moisture rather leads to a decrease in precipitation (Hohenegger and Schär, 2020). Positive feedbacks are of particular relevance for the climate system as they can amplify an existing perturbation, thus affecting the climate system on longer time scales. Given the potential role of the land surface in modulating climate variability (Seneviratne et al., 2006) and extremes (Fischer et al., 2007), numerous studies have assessed the importance of the land surface for the climate system. Such studies, conducted using coarse-resolution global or regional climate models with parameterized convection, have conveyed the view of a positively coupled land-atmosphere system, emphasizing the importance of the land surface and the needs for a realistic representation of the land surface in climate models. This has directly mirrored itself in the development of Earth System Models, where the inclusion of new processes (increasing complexity), particularly related to the land surface, has been favored over the use of higher resolution, needed to bypass some of the parameterization problems (Stevens and Bony, 2013).

The land surface communicates with the atmosphere via its controls on the surface energy budget. Changes in the land surface affect the magnitude of the sensible and latent heat fluxes, and changes in the surface fluxes impact the properties of the PBL and hence the development of convection. The control of the land surface properties on the surface fluxes is called the terrestrial leg, whereas the coupling between the surface fluxes and the atmosphere is called the atmospheric leg (Santanello et al., 2018). My research contributions focused on issues related to the atmospheric leg, implicitly assuming a correct representation of the terrestrial leg in atmospheric models. This assumption is certainly not true but can be justified to a first order by noting that the terrestrial leg is only important if a strong coupling between the surface fluxes and convection exists.

Although many studies have investigated land-atmosphere interactions, even basic interactions, such as the sign and the strength of the feedback between soil moisture and convective precipitation, remain debated. Land-atmosphere interactions are inherently ambiguous due to a combination of two factors. First, physically, distinct pathways exist that connect the land surface to the atmosphere, some of them sustaining a positive, other a negative feedback. Here it is again of utmost importance to distinguish between a thermodynamic, one-dimensional, and a dynamical, three-dimensional, view (i.e., Fig. 1.3). In the former case, changes in the surface fluxes vertically communicate to the PBL and to convection by affecting the stability of the atmosphere. In the latter case, horizontal gradient in surface fluxes generate thermally driven shallow circulations that force the development of convection. The response of convection to a change in surface fluxes under these two scenarios is different, an ambiguity that has led to many confusions in the published literature.

Second, diagnosing land-atmosphere interactions is not straightforward. In observations, land-atmosphere interactions are blurred by synoptic variability and filtering out the effects of synoptic variability remains highly uncertain (Guillod et al., 2014), not to mention the scarcity and uncertainty of measurements of surface fluxes or soil moisture. This is not an issue in model simulations, but, in coarse-resolution climate simulations, all the processes involved in land-atmosphere interactions happen on the subgrid scale and have to be parameterized. There is no guarantee that a parameterization faithfully reproduces such interactions (Dirmeyer, Koster and Guo, 2006).

The potential limitations of coarse-resolution models to study land-atmosphere interactions motivated my research contributions on land-atmosphere interactions. I aimed to understand whether the land surface, or the convection itself, ends up setting aspects of the precipitation distribution over land by taking advantage of models that do not have to rely on a convective parameterization. In that respect, I conducted the first realistically configured study on the soil moisture-precipitation feedback using storm-resolving simulations in a climatic context, and Malte Rieck, one of my PhD students, conducted one of the first large-eddy simulations coupled to an interactive land surface to study interactions between the land surface and deep convection. For the land surface, I focused on two of its distinct characteristics: its limited water supply (Section 4.1), meaning soil moisture; and its heterogeneity (Section 4.2). In the former case, I investigated the effects of soil moisture on the amount and spatial distribution of convection, whereas in the latter case, I concentrated on the effects of surface heterogeneity on the spatial distribution of convection. Past studies on land-atmosphere interactions, even at high resolution, have tended to stress the land component, I gave more attention to the role of convection itself. For instance, numerous studies have shown that land surface heterogeneity triggers the development of convection (see Fig. 4.1 and Section 4.2). But once convection develops, it feeds back on the initial land surface heterogeneity and may mask the control of the land surface, a feedback that has received far less attention. The work described below is the result of work conducted by myself, two PhD students (Malte Rieck and Guido Cioni) that I supervised and two PostDocs (Karsten Peters, David Leutwyler) that I also supervised.

4.1 Soil moisture and its effects on the amount and spatial distribution of precipitation

The speculation that soil moisture may affect the precipitation amounts was first expressed by S. Aughey in 1880 (see Holzman, 1937, p. 37), and has been debated many times since then. In a soil moisture-limited regime, an increase in soil moisture leads to an increase in latent heat flux, a change that is communicated vertically to the at-

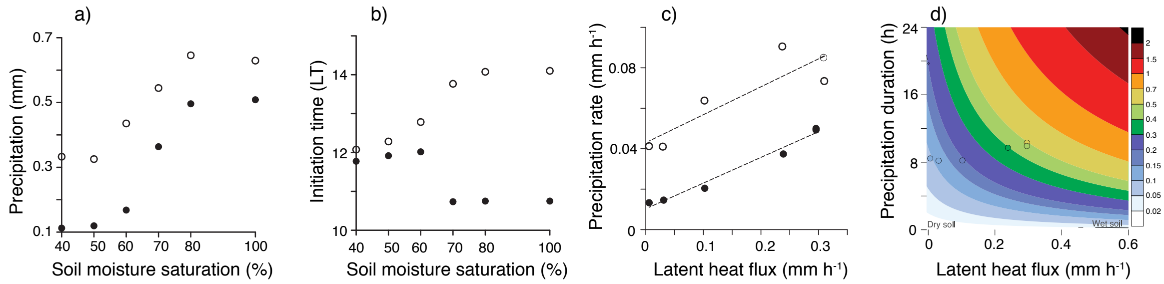

Figure 4.2: Variations of (a) total precipitation, (b) initiation time t_i and (c) mean precipitation rate $\overline{RR}$ as a function of soil moisture/latent heat flux for two sets of simulations starting from two distinct thermodynamic profiles (open and closed symbols). Panel (d) shows the resulting theoretical estimate of precipitation (shading, mm h^{-1}) for one of the thermodynamic profiles with colored circles for the simulation results. Figure adapted from Cioni and Hohenegger (2017).

mosphere. The oldest argument invokes a simple moisture recycling mechanism: an increase in evapotranspiration leads to more water in the atmosphere and hence more precipitation (Eltahir and Bras, 1996). The relevance of this simple moisture recycling mechanism is questionable as most of the water vapor falling out as precipitation over a given region is actually water vapor that has been advected into that region, not in situ water vapor from local evapotranspiration (Dirmeyer and Brubarker, 2007). Even though the water vapor input does not come from local moistening, changes in latent heat flux affect the thermodynamic profile of the atmosphere and, through this, the likelihood of convection to be triggered. Depending on the initial thermodynamic profile, an increase in latent heat flux can both favor or hamper the triggering of convection (Findell and Eltahir, 2003). This is so because convection can be triggered by moistening the PBL (high latent heat flux) and bringing the level of free convection down to the PBL top; or by warming the PBL (high sensible heat flux) and bringing the PBL top to the level of free convection. Which of these two processes is more efficient depends upon the initial thermodynamic profile.

Such thermodynamic arguments only say something about the likelihood of convection to be triggered, not about the resulting precipitation amount. Guido Cioni expanded this theoretical framework to the precipitating case based on the results of idealized large-eddy simulations of the daily cycle of convection over land (Cioni and Hohenegger, 2017). The idea was that the daily accumulated precipitation amount (Fig. 4.2a) can be approximated by the mean precipitation rate $\overline{RR}$ multiplied by the length of the precipitation phase $t_\mathrm{e} - t_\mathrm{i}$. The length of the precipitation phase can be longer both over wet or dry soils, depending on the initial thermodynamic profile. The latter affects the initiation time t_i, in agreement with the thermodynamic arguments presented by Findell and Eltahir (2003), see Fig. 4.2b. But the precipitation rate $\overline{RR}$, in this idealized system with no moisture advection, always scales with the latent heat flux and is thus always favored over wet soils (see Fig. 4.2c). Moreover, it turned out that this

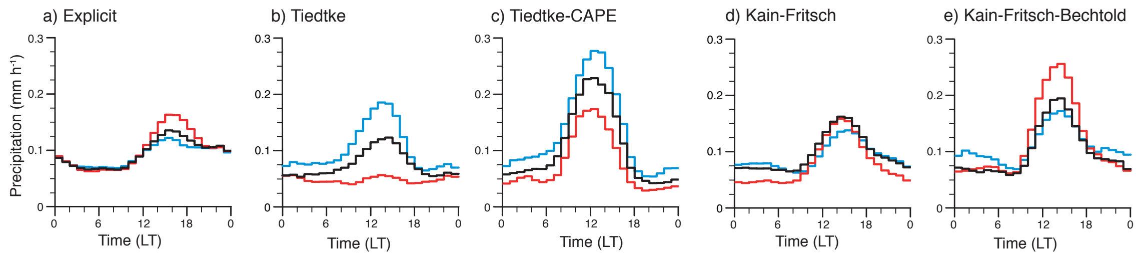

Figure 4.3: Monthly mean precipitation diurnal cycle in a control simulation (black) and in a simulation with an initially increased (blue) and decreased (red) soil moisture. Panel (a) for the storm-resolving simulation, panels (b)-(e) for the coarse-resolution simulations with different versions of the convective parameterization: (b) Tiedtke scheme, (c) Tiedtke scheme with CAPE closure, (d) Kain-Fritsch scheme and (e) Kain-Fritsch-Bechtold scheme. Figure taken from Hohenegger et al. (2009).

scaling of $\overline{RR}$ with the latent heat flux is too strong to be overcompensated by an earlier triggering of convection over dry soils and thus by a longer precipitation duration, as can be seen from the steepness of the curves in Fig 4.2d over dry soils. From this expanded theoretical framework, one thus expects that an increase in soil moisture leads to an increase in precipitation. A negative soil moisture-precipitation feedback is only expected in those cases where convection only develops over dry soils or if changes in soil moisture affect the advected water vapor, an effect not considered in this theoretical framework (see Section 4.2 for some discussion on the advection component).

Which type of thermodynamic profiles controls the development of convection during summertime over Europe: those that favor convection over wet, over dry and wet or only over dry soils? I conducted a month-long simulation integrated with a grid spacing of 2.2 km over a domain encompassing the Alpine region, and performed sensitivity experiments by initially modifying the soil moisture content over the full simulation domain to diagnose the strength and sign of the soil moisture-precipitation feedback (Hohenegger et al., 2009). This was a unique study: the control simulation, documented in Hohenegger, Brockhaus and Schär (2008), was the first storm-resolving simulation on a mesoscale domain integrated for more than a few days. The study itself was the first study to look at the soil moisture-precipitation feedback in a realistic set-up, in a climatic context, and using a model where the convection is explicitly resolved. And the results gave a picture fundamentally different from the one known based on coarse-resolution regional climate models that use a convective parameterization, where a positive soil moisture-precipitation feedback had been found (e.g. Schär et al., 1999). My simulations namely revealed a negative soil moisture-precipitation feedback over the Alpine region (see Fig. 4.3a). The simulated thermodynamic profiles were characterized by a strong capping inversion that inhibited the development of convection over wet soils due to missing PBL growth in the simulation with explicit convection. The apparent contradiction in feedback sign as compared to previous studies could be the result of peculiar thermodynamic conditions that prevailed during the simulated month, or indicate that the feedback sign is actually set by the model set-up. To clarify this last point, I repeated my experiments using a coarse-resolution regional climate model with a grid spacing of 40 km and parameterized convection. These simulations revealed a positive feedback (Fig. 4.3b). Moreover, using different versions of the convective parameterization, either positive, neutral or negative feedbacks could be obtained (Figs. 4.3c-e), depending whether the convective parameterization was able to see the capping inversion at the top of the PBL or not.

My study clearly indicates that the coupling between the land surface and convection is actually set by the representation of convection, a serious problem for investigations of land-atmosphere interactions with coarse-resolution models. This dependency was later confirmed by Taylor et al. (2013), who also obtained opposite feedback signs between explicit (negative sign) and parameterized (positive sign) convection when investigating the response of precipitation to soil moisture heterogeneity. However, my study does not necessarily imply that the soil moisture-precipitation feedback has to be negative. One potential pitfall is the use of a limited-area set-up that spuriously constrains the boundaries of the storm-resolving simulation by the driving coarse-resolution simulation. Investigating the soil moisture-precipitation feedback in a global model integrated at storm-resolving resolution might finally allow settling down the question of the sign of the soil moisture-precipitation feedback.

The studies of Cioni and Hohenegger (2017) and Hohenegger et al. (2009) investigated the control of soil moisture on the precipitation amount, not on the spatial distribution of precipitation. As a follow-up step, I aimed to understand whether soil moisture fundamentally acts to homogenize the precipitation distribution, or to keep the precipitation to the previously precipitating areas (Hohenegger and Stevens, 2018). Two scenarios are a priori possible. On the one hand, taking again a thermodynamic view and assuming a positive soil moisture-precipitation feedback, the increase in soil moisture under the precipitating region favors higher latent heat flux, higher moisture input in the atmosphere and stronger precipitation, thus keeping the precipitation to the precipitating region. On the other hand, and taking this time a dynamical view, soil moisture in the non-precipitating region decreases with time, limiting the latent heat flux and enhancing the sensible heat flux. Resulting gradients in sensible heat flux between non-precipitating and precipitating regions lead to temperature and pressure gradient that can trigger a thermally driven circulation from the cold precipitating to the dry and warm non-precipitating region. If strong enough, this circulation could bring the precipitation from the precipitating to the non-precipitating region, a homogenization effect by soil moisture on the spatial distribution of precipitation. As already briefly mentioned in Section 3.1, I applied for the first time the RCE conceptualization to a very simple representation of a land surface to investigate this question using an explicit 3-dimensional representation of convection. I found that soil moisture acts to homogenize the precipitation distribution (see Fig. 4.4). At the latest when the soil dries out, the soil moisture-induced circulation becomes stronger than the background circulation that maintained the convection to the precipitating region. This finding can be

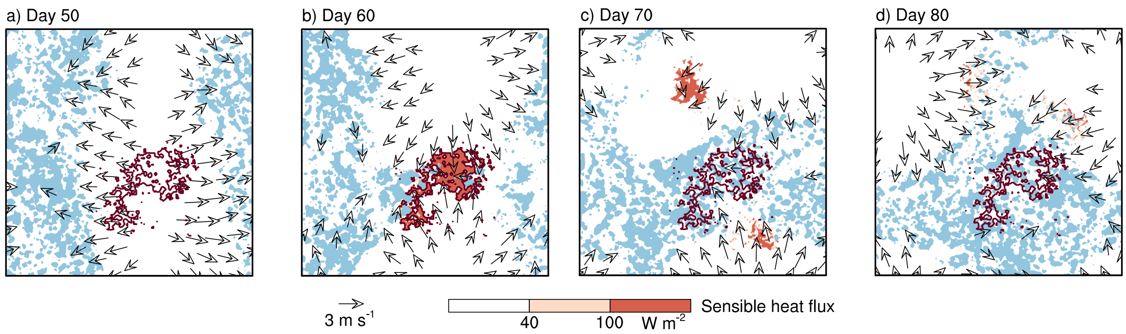

Figure 4.4: Spatial distribution of wind (arrows), sensible heat flux (red shading) and precipitating region (blue shading) for different days. The dark red contours enclose all the points where the soil moisture reaches its permanent wilting point on day 60. Winds weaker than 2 m s^{-1} are masked. Figure taken from Hohenegger and Stevens (2018).

explained theoretically by comparing the strength of the two circulations. The strength of the soil moisture-induced circulation is derived using Eq. 3.1 combined with a bulk model of the PBL and with the linearized version of the surface energy budget equation. This approach allows linking the strength of the soil moisture-induced circulation to soil moisture and hence to the drying needed to offset the background circulation[1].

Even if being idealized, implications for the climate system can be derived from these results. First, I couldn't find any signature of a thermodynamic control of soil moisture on the spatial distribution of precipitation, speaking again for the importance of dynamical effects in controlling the distribution of convection, in line with the results of Chapters 2 and 3. Second, the ability of the soil to dry out emerged as a key property of the land surface. A recent study by David Leutwyler, where he investigated the impact of tropical islands on tropical tropospheric temperatures, emphasized this even more (Leutwyler and Hohenegger, submitted). Including the ability of the soil to dry led to a weak cooling of tropospheric temperatures by islands, in contrast to a previous study by Cronin and Emanuel (2015) who had found a warming when neglecting this effect. This indicates that a correct representation of the soil drying process in climate models may be of particular relevance for correctly simulating the climate system. Third, the results led to the counter-intuitive statement that the drying of the soil actually acts against the formation of deserts and terminates heat waves. This last aspect is at odds with previous studies that have emphasized the importance of soil drying in amplifying heat waves (Fischer et al., 2007), albeit in models using a parameterized representation of

[1] The propagation speed of the soil moisture-induced circulation is linked to soil moisture by replacing θ_v in Eq. 3.1 by its bulk expression for a convective boundary layer of height h deepening into a layer of uniform stratification Γ: $\theta_\mathrm{v} = \theta_\mathrm{v}^0 + \Gamma h$ and $h = \sqrt{\frac{2}{\Gamma}\frac{SH}{\rho c_\mathrm{p}}t}$. The sensible heat flux SH is computed from the linearized energy budget equation: $Q = SH\left[1 + \frac{L}{c_\mathrm{p}}\frac{r_\mathrm{a}}{r_\mathrm{a}+r_\mathrm{s}(\phi)}\frac{\partial q_\mathrm{s}}{\partial T}\right] + \rho L\frac{q_\mathrm{s}[1-RH]}{r_\mathrm{a}+r_\mathrm{s}(\phi)}$ with Q net radiation, q_s saturation specific humidity, T temperature, RH relative humidity, r_a aerodynamic resistance, r_s soil moisture resistance, ϕ soil moisture, L latent heat of vaporization, c_p specific heat capacity, ρ density and t time. The soil moisture enters these equations through its control on r_s.

convection and coarse resolution, where the involved interactions between convection and circulations, which could terminate such events, are unlikely to be correctly represented (Taylor et al., 2013; Hohenegger, Schlemmer and Silvers, 2015). Few hints that soil moisture, or in more general terms the land surface, acts to disorganize the convection in the real world exist: the ITCZ is wider over land than over ocean; the monsoon propagates farther inland over the African continent in drier years (Hohenegger and Stevens, 2018); and the Madden-Julian Oscillation is more likely to propagate over the Maritime Continent when the latter is wet and land-sea breezes are weak (Ling et al., 2019).

4.2 Surface heterogeneity and the feedback of convection

Besides the limited water supply of the land surface, the presence of heterogeneity in the surface properties is another distinctive characteristic of the land surface. Surface heterogeneities lead to gradients in sensible heat flux, in surface temperature and hence in pressure (Halley, 1686). The pressure gradient spins up a shallow circulation confined in the PBL, with its return current at the top of the PBL, and directed from the cold to the warm surface (see Fig. 4.1). The propagation of the circulation into the ambient air leads to upward motion at the front of the circulation, which facilitates the triggering of convection. As a result, convection is preferentially triggered at the breeze front and is organized along the breeze front (Byers and Rodebush, 1948; Hohenegger and Schär, 2020). Sources of surface heterogeneity that can trigger such circulations and affect the triggering of convection are various (Pielke, 2001): land-sea contrast, mountain-valley, soil moisture, vegetation type.

Numerous studies have investigated the triggering of convection by land surface-induced circulations, both in simulations and observations. That surface heterogeneity is important for the triggering of convection, particularly in semi-arid regions where high convective inhibition exists and a dynamical forcing is required to trigger convection (Taylor et al., 2011; Hohenegger, 2020), is now undisputed. But once convection develops, it can alter the characteristics of the underlying circulation in various ways (see Fig. 4.1): by generating its own circulation; through its impact on the surface temperature by cloud shading; or by replenishing soil moisture. The feedback of convection on the characteristics of a land surface-induced circulation has received surprisingly little attention. Investigating this feedback is nevertheless important as it further helps assessing the importance of the land surface for the lifecycle and distribution of convection.

From the three potential effects of convection mentioned above (convective circulation, cloud shading and soil moisture refilling), the last two appear unimportant, as shown in the PhD thesis of Malte Rieck (Rieck, 2015; Rieck, Hohenegger and Gentine, 2015). In particular, even after 15 days of daily convective development triggered by a

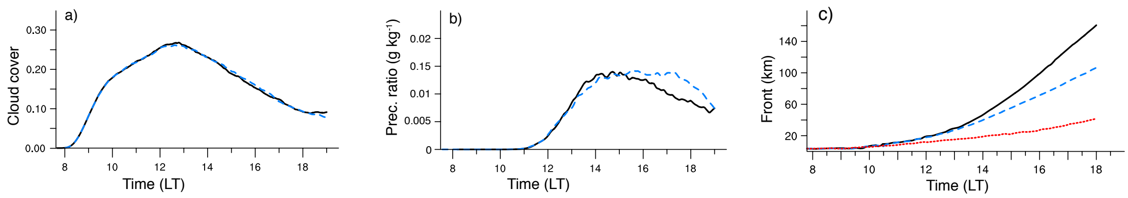

Figure 4.5: Time evolution of (a) cloud cover, (b) precipitation mixing ratio and (c) location of the breeze front in the control simulation (black), a dry simulation (no cloud and no precipitation formation, red) and a simulation where cold pool effects are removed (blue). Figure adapted from Rieck, Hohenegger and Gentine (2015).

vegetation breeze, the surface heterogeneity reappears in the horizontal pattern of the surface fluxes every morning. These simulation results could be understood theoretically. As observed in semi-arid regions, co-existing distinct vegetation types can produce latent heat flux differences in the order of 100 W m^{-2} (Hohenegger, 2020). Using the known relationship between latent heat flux and soil moisture, these 100 W m^{-2} can be transformed into a required soil moisture increase. The result is that 20 days of precipitation are required to offset the 100 W m^{-2}[2]. As in reality some of the precipitation is lost to runoff, a homogenization of the surface heterogeneity by precipitation appears unlikely.

In contrast, the impact of the own convective circulation on the land-surface induced circulation is very important in determining the characteristics of the circulation once convection has developed at the breeze front. Malte Rieck conducted sensitivity experiments using large-eddy simulations to disentangle the contribution from the land surface heterogeneity and from the convection itself on the final characteristics of the circulation, focusing on its propagation speed (Rieck, Hohenegger and Gentine, 2015). The circulation, originally triggered by the surface heterogeneity, first accelerates when clouds develop (compare the timing of the black curve in Figs. 4.5a and c or the black and red curves in Fig. 4.5c). This results from a modification of the pressure gradient across the breeze front by the clouds which suck PBL air from behind the front[3]. The circulation accelerates a second time soon after precipitation starts falling, as can be seen by comparing the timing of the black curve in Figs. 4.5b and c or the black and blue curves in Fig. 4.5c. This acceleration is the result of cold pools. Cold pools are associated with a virtual potential temperature anomaly of 2 K, much stronger than the initial gradient due to the surface heterogeneity (0.5 K), what allow them to take over the propagation (see Eq. 3.1). This is the same type of argument as already presented in the previous chapter, in Section 3.1, to understand the spatial distribution of precipitation under the RCE framework. The results thus indicate that, although the surface

[2] The latent heat flux is linked to soil moisture via the Penman-Monteith equation and the soil moisture resistance function given in the model. Values of other variables needed to solve the equation (e.g., net radiation, atmospheric resistance, precipitation, soil layer thickness) are taken from the simulation.

[3] Using mass conservation within the sub-cloud layer, the velocity due to this dynamical effect can be approximated by: $k\frac{\rho_{\mathrm{cold}}}{\rho_{\mathrm{warm}}}\frac{M_{\mathrm{c}}}{h_{\mathrm{c}}}$ with ρ_{warm} (ρ_{cold}) density of the warm (cold) fluid, M_{c} cloud-base mass flux, h_{c} cloud-base height and k proportionality constant.

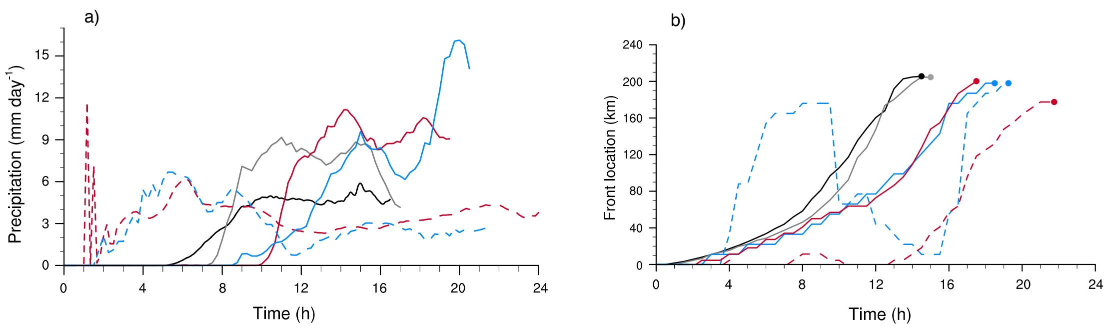

Figure 4.6: Time evolution of (a) precipitation and (b) breeze front location in a large-eddy simulation (black, UCLA-LES model, grid spacing 500 m), a storm-resolving simulation (grey, COSMO model, grid spacing 2.2 km) and two coarse-resolution simulations (blue, COSMO model, grid spacing 11 km and red, ICON model, grid spacing 8 km). Solid (Dashed) lines with explicit (parameterized) convection. Figure adapted from Hohenegger, Schlemmer and Silvers (2015).

heterogeneity is important to trigger convection, once convection develops, convection masks the control of the land surface on the circulation characteristics and the land surface becomes unimportant. This has two important consequences.

First, it suggests that biases in the representation of convection, due to poorly resolved or parameterized convective processes, mirror on the characteristics of a surface induced circulation, even in the presence of a perfect land surface. I investigated this hypothesis by performing idealized simulations using prescribed heterogeneous surface fluxes and distinct representations of convection, as sampled by the use of large-eddy, storm-resolving and coarse-resolution models (Hohenegger, Schlemmer and Silvers, 2015). Coarsening the grid spacing in simulations with explicit convection yields a later development of convection and a later acceleration of the breeze front (see solid lines in Fig. 4.6), as expected from and confirming the theoretical findings of Rieck, Hohenegger and Gentine (2015). Switching on a convective parameterization yields a too early onset of convection, so early that it totally distorts the propagation of the circulation (dashed lines in Fig. 4.6). This last result again questions the suitability of coarse-resolution regional and global models for investigations of land-atmosphere interactions. It speaks for a correct timing of the convective diurnal cycle, at least over heterogeneous regions (e.g. islands) and seems consistent with the noted impact of the timing of the convective diurnal cycle on the land-to-ocean precipitation ratio in Hohenegger and Stevens (2013c) (see Section 2.2). It also explains the results of Taylor et al. (2013) who had found a different feedback sign between explicit and parameterized convection focusing on the interactions between convection and heterogeneous soil moisture conditions. Finally, similar results for the case of convection interacting with a sea breeze have been reported by Birch et al. (2015) based upon realistically configured simulations over the Maritime Continent.

Second, the fact that convection ends up controlling the characteristics of a land-surface induced circulation simplifies the response of precipitation to soil moisture perturbations over a heterogeneous surface. As noted at the beginning of this chapter, soil moisture has two distinct ways to affect precipitation: thermodynamically (via changes in stability through local moistening by latent heat flux) and dynamically (moisture advection by surface induced circulation). In the presence of a heterogeneous surface made of two distinct patches of soil moisture, changes in soil moisture affect both controls. It would thus be useful to theoretically understand, which one of the controls is more important and how they play out together. On top of that, convection itself modifies the soil moisture content and the characteristics of the surface induced circulation, as noted above. Past studies (e.g. Chen and Avissar, 1994) have documented the response of precipitation to variations in soil moisture over an idealized heterogeneous surface using storm-resolving simulations. Building on such work, Guido Cioni aimed to derive a theoretical expression for $\frac{\partial P_\mathrm{d}}{\partial \phi_\mathrm{d}}$, i.e. the change in precipitation of the dry patch P_d with the soil moisture content of the dry patch ϕ_d, to be able to formally isolate the various controls on this expression (Cioni and Hohenegger, 2018). The derivative is:

$$\frac{\partial P_\mathrm{d}}{\partial \phi_\mathrm{d}} = C\tau Q(-\eta_\mathrm{A}\tau U + \eta_\mathrm{E}) \begin{cases} 0 & \text{for } \phi_\mathrm{d} < \phi_\mathrm{pwp} \\ \frac{1}{\phi_\mathrm{fc}-\phi_\mathrm{pwp}} & \text{for } \phi_\mathrm{pwp} \leq \phi_\mathrm{d} \leq \phi_\mathrm{fc} \\ 1 & \text{for } \phi_\mathrm{d} > \phi_\mathrm{fc} \end{cases} \tag{4.1}$$

with C constant, τ time scale, Q net radiation, ϕ_fc field capacity, ϕ_pwp permanent wilting point, η_A advection efficiency, η_E evaporation efficiency and U propagation speed of the circulation. The first term denotes the contribution to precipitation from moisture advection by the soil moisture-induced circulation, the second term the contribution from the local moistening by latent heat flux, and the two terms are weighted by their efficiency. For the idealized simulations conducted in Cioni and Hohenegger (2018), η_A is larger than η_E, but this may differ under other conditions. Key to note is that soil moisture does not show up in Eq. 4.1. The atmospheric conditions control the variation in precipitation with soil moisture, scaled by the available water capacity ($\phi_\mathrm{fc} - \phi_\mathrm{pwp}$). This is so because the simplest expression of the latent heat flux is a linear function of soil moisture (Budyko, 1961; Manabe, 1969). The moisture advection is also only a linear function of soil moisture[4] because the propagation velocity of the circulation U is set by the convection and not by the soil moisture heterogeneity once convection develops, as predicted by Rieck, Hohenegger and Gentine (2015) and further confirmed here. That the derivative does not depend upon the soil moisture content itself removes one source of uncertainty when determining the sensitivity of precipitation to soil moisture in model simulations, in the sense that models widely vary in their simulated soil moisture content, variations that apparently will not project upon the sensitivity of precipitation to soil moisture under that particular case scenario.

[4] The moisture advection depends upon U and upon the specific humidity difference between the two patches. The latter relates to the difference in latent heat flux between the two patches and hence to the difference in soil moisture between the two patches.

Hence, for the case of convection triggered by surface heterogeneity (see Fig. 4.1), convection ends up setting the characteristics of the resulting circulation. As concluded in Chapter 3 when investigating the self-aggregation of convection, the stronger circulation wins. As a last case scenario of convection interacting with the land surface, the reverse case was considered: the case where a convective system, which already existed and propagated through the action of its cold pool, encountered a change in surface properties (Peters and Hohenegger, 2017). To that aim, Karsten Peters employed idealized squall line simulations and varied the underlying surface temperature once the squall was already propagating. The initial expectation was that the increase in surface flux over the warmer surface would warm the cold pool and lead to a slowing down of the propagation. This did not happen because the cold pool is continuously refilled by cold tropospheric air. What did happen though is that the warmer surface leads to an earlier acceleration of the squall line propagation. This is related to a phenomenon called discrete propagation (Fovell, Mullendore and Kim, 2006). Secondary convection develops ahead of the squall line, the more so, the warmer the surface, and leads to a jump in the squall line propagation. Using the theoretical framework developed by Tawifk and Dirmeyer (2014) to a priori quantify the requested warming to trigger convection ahead of the squall line, Karsten Peters estimated that typical variations in surface temperature could yield up to a 3-h difference in the timing of the squall line. Otherwise, the squall line characteristics remained unaffected by the changes in surface temperature.

This chapter summarized my research contributions on land-atmosphere interactions with an overall aim to determine whether the land surface or convection ends up setting aspects of the precipitation distribution over land. My motivation was that coarse-resolution models with parameterized convection, generally used to investigate such interactions in a climatic context, may have led to an overemphasis of the importance of the land surface due to misrepresented convective processes. Certainly, the land surface does affect convection: the drying of the soil was found to be of special relevance as it serves to homogenize the precipitation distribution and to cool the tropical troposphere; surface heterogeneities trigger convection, a well-known fact; and if more water is put into a system, at least at equilibrium, more precipitation will fall. But in return, convection itself ends up largely controlling land-atmosphere interactions: its representation determines the sign of the soil moisture-precipitation feedback, and, even in the case of convection triggered by surface heterogeneity, the generation of cold pools ends up masking the effects of the land surface and the atmospheric conditions scaled by the water availability determine the strength of the variations of precipitation with soil moisture. Overall my findings speak for a weaker and potentially even negative feedback between soil moisture and precipitation, in contrast to the generally assumed strong positive feedback. Given these results and the limitations of the employed limited area set-up, my findings strongly speak for conducting global storm-resolving simulations on climatic time scales to investigate such questions.

Chapter 5

Conclusions

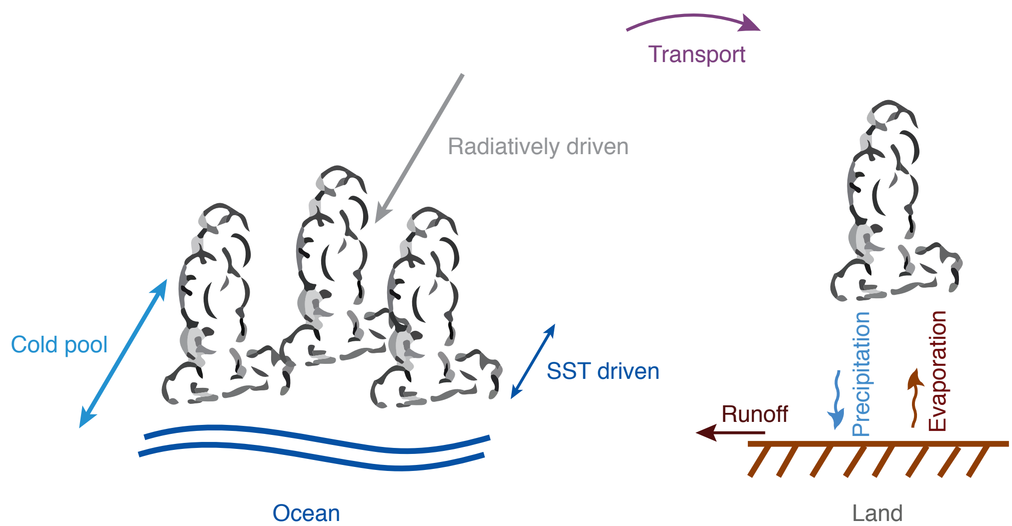

Figure 5.1: Potential interactions between convection and the underlying surface, in particular via the generation of shallow circulations: whether and how these interactions concur to set basic properties of the climatological precipitation distribution, such as ITCZ width (left) or partitioning of precipitation between land and ocean (right) remains unanswered. The strength of the coupling between ocean / land and convection is virtually unknown, a topic for future research.

5.1 Summary

If convection were not to exist, our planet may be a harsh place to live. As already recognized fifty-six years ago by Manabe and Strickler (1964), the surface temperature of our planet in a pure state of radiative equilibrium would amount to more than 330 K, far more than the observed 300 K of the tropics. Yet, many basic questions related to moist convection, its controls or the climatic impacts of its characteristics, such as its mesoscale organization, remain unanswered or unsettled. The fact that convection bridges from the small to the planetary scale and that it is so intrinsically linked to its environment makes an understanding of its lifecycle and an isolation of its climatic impacts a challenge.

As summarized in this review, I have focused my research contributions on precipitating convection, paying special attention to the transition from shallow to deep convection, to the organization of convection, and to the interactions between convection and the underlying land surface. For each of these topics, my goal was to understand the controls on as well as the resulting climatic impacts of the investigated feature. The choice of these three specific topics reflects three underlying ideas, that were still largely untested ten years ago: (i) the hypothesis that the transition time and the size of the biggest clouds might teach us something about the transition to deep convection, providing at the same time a convenient way to include transition mechanisms in a convective parameterization; (ii) the idea that the RCE conceptualization, where convection spontaneously self-aggregates, might help us understand under which circumstances convection organizes, providing new hypotheses to look at convective organization in the real world and to test its potential impacts on climate; and (iii) the hypothesis that the coupling between convection and the land surface is first set by the convection itself, implying a need to reinvestigate land-atmosphere interactions and their effects on climate using storm-resolving simulations. My research contributions led to new scientific knowledge on these three topics, and the key scientific results are summarized below:

1. Dynamical effects are much more efficient at promoting the daily transition to deep convection than thermodynamic ones. The previously formulated and popular idea of preconditioning, whereby the moistening by previous clouds promotes the daily recurring transition to deep convection, is too slow to explain observed transition times. Instead, large-eddy simulations and theoretical arguments speak for a dynamical control on this transition, with moisture convergence and subsequent upward motion providing the required moistening. This is true both over land and ocean.

2. In contrast to this preconditioning idea, cold pools efficiently promote the daily transition to deep convection by generating moist patches around them, whose sizes are proportional to the cloud sizes. These moist patches result predominantly from old moisture, already present in the PBL, that the cold pools push together. The uncovered relationship between cold pool size, moist patch size and cloud

size offers a way to parameterize the effects of cold pools on the transition to deep convection in a convective parameterization, an effect that is generally not accounted for in state-of-the-art convective parameterizations.

3. A novel way to parameterize deep convection, starting from a shallow convection scheme and including in a very simplified way some of the changes accompanying the transition to deep convection, such as the enlarging of the cloud size by cold pools, was developed and tested. Single column model experiments revealed promising results, with a correct timing of the precipitation diurnal cycle, a pitfall of convective parameterizations ten years ago, but full three-dimensional simulations did not confirm the results.

4. The spatial distribution of convection is not one where convection stays randomly distributed. Convection fundamentally strives to organize, even in the presence of homogeneous boundary conditions, as in idealized RCE studies. But it has to battle against the underlying surface that aims to disorganize it, the more so, the more dynamical the surface is. The resulting spatial distribution of convection is fully set dynamically through the interactions between convection and shallow circulations that reside in the PBL and are triggered by heterogeneities. These heterogeneities can be the result of convection (cold pools and radiative heating anomalies that develop between convective and non-convective regions), or of surface anomalies in the presence of a dynamical surface (gradients in SST or in soil moisture). Despite their distinct origins, these shallow circulations behave like density currents and their impacts on the spatial distribution of convection can be understood within a unified framework of gravity current theory (see Eq. 3.1): the shallow circulation associated with the largest density anomaly wins and sets the spatial distribution of precipitation. The results of these idealized studies provide new insights concerning the processes that may control the spatial distribution of convection in the real world, in particular processes that set the width and length of ITCZs, something we lack an explanation for (see Fig. 5.1 left). They imply that convection is actually more organized over ocean than over land, providing a potential explanation for the yet unexplained wider width of the ITCZ over land than over ocean. Their literal interpretation also implies that the width of oceanic ITCZs is set by a competition between cold pools and radiatively driven circulations, as long as interactions with the underlying ocean remain unimportant. Furthermore, they indicate that radiatively driven circulations can distort the spatial distribution of precipitation, which is generally expected to be primarily set by SST gradients. Lastly, they imply that the ITCZ is zonally more extended in the presence of stronger meridional SST gradients, a hypothesis that seems consistent with findings from reanalysis data.

5. Does this convective organization matter for climate? The response is ambivalent. On the one hand, the degree of organization of the ITCZ, whether convection is organized in an elongated band or in many small and disconnected clusters, was

for the first time shown to correlate with subtropical humidity. This was demonstrated using reanalysis data and a novel way to characterize organization. If a causal relationship could be proven, this would be of utmost importance for studies on climate and climate change. Furthermore, other groups have shown that a relationship exists between mesoscale convective organization and humidity within the same mesoscale region. On the other hand, mesoscale convective organization seems irrelevant for setting large-scale features of the precipitation distribution, against initial expectations. Quantifying the relationship between the degree of mesoscale organization and precipitation using global storm-resolving simulations, no relationship between the two could be found. This indicates that the well-known fact that most of the tropical precipitation is produced by mesoscale organized systems has nothing to do with their organization per se. Moreover, large-scale features of the precipitation distribution, such as location and width of the ITCZ, were robust to changes in grid spacing and, thus implicitly, to a misrepresentation of mesoscale convective organization as the grid spacing was coarsened. Such a weak sensitivity to grid spacing definitely questions the importance of small-scale convective characteristics for setting large-scale features of the distribution of precipitation. On the positive side, though, it follows that global simulations with explicit convection are actually possible at grid spacings much coarser than generally thought, a promising prospect given the computational costs of such simulations.

6. More organized convection does not exhibit smaller entrainment rates, as generally assumed, but is protected by a moist shell that minders the loss in buoyancy when environmental air is entrained. The results were found first using the RCE conceptualization and confirmed in realistically configured simulations.

7. The limited availability of moisture from the underlying land surface, in contrast to the ocean, is of key relevance to understand the effects of the land surface on convection and sets the land apart. This ability ensures a homogeneous distribution of precipitation over longer time scales and leads to a cooling, instead of a warming, of mid-tropospheric tropical temperatures by islands. That the drying out of the soil homogenizes the precipitation distribution is counter-intuitive as it means that this drying out actually terminates heat waves and acts against the formation of deserts. The results are nevertheless consistent with observations of the propagation of the monsoon over Africa and of the Madden-Julian Oscillation over the Maritime Continent. They suggest a less important role of soil moisture for climate variability as perhaps expected from the results of GCMs with parameterized convection, where the mechanisms at play cannot be represented explicitly.

8. Surface heterogeneity triggers convection through the generation of surface induced circulations, a well-known fact, but once convection develops, convection induces stronger perturbations in the PBL, in particular through the generation of

cold pools, that mask the initial surface heterogeneity. As a consequence, biases in the representation of convection directly project upon the characteristics of a surface induced circulation. As another consequence, the atmospheric conditions scaled by the available water capacity, and not soil moisture, control the strength of the variations of precipitation with soil moisture over a heterogeneous surface made of different patches of soil moisture (see Eq. 4.1).

9. The sign of the soil moisture-precipitation feedback in model simulations appears determined by convection and thus by its representation: it differs between simulations with explicit (negative) and parameterized (generally positive) convection and can actually be changed from positive to neutral to negative by changing the design of the convective parameterization. These findings question the results of numerous past studies that have been conducted with coarse-resolution climate models with parameterized convection, studies that have pleaded for a generally strong positive feedback between the land surface and the atmosphere. This has implications not only for the mean climate, but also for climate change and extremes given the assumed role of land surface processes in such situations.

Overall, my investigations contributed to the general discussion, whether convection is thermodynamically or dynamically controlled. Even if the thermodynamic perspective is often put forward to explain the lifecycle and spatial distribution of convection, dynamical arguments were needed to explain most of my findings. My investigations also contributed to answering the question of the importance of small-scale convective characteristics for setting large-scale features of the climate system. Differences between storm-resolving simulations and coarse-resolution simulations with parameterized convection do exist, in particular when considering land-atmosphere interactions. But these differences may be the result of a poorly designed convective parameterization rather than the imprint of small-scale convective characteristics not included in a convective parameterization (such as mesoscale convective organization).

On the methodological side, three aspects summarize my approach:

- The addressed research questions required the use of high-resolution simulations where convection is explicitly resolved. I took advantage of the increases in computer resources to make an extensive use of large-eddy simulations and storm-resolving simulations of the newest generation. I ran the first month-long simulation at storm-resolving resolution on a mesoscale domain; we were one of the first groups to couple a full land surface scheme to a large-eddy simulation model to study interactions between the land surface and deep convection; and we are now able to conduct storm-resolving simulations on very large domains, up to the global scale. Currently, I'm leading the contributions of the atmosphere department of MPI-M to our high-resolution development branch and I'm involved in the development of a global storm-resolving coupled model to be able to also study interactions between the oceanic surface and convection.

- The addressed research questions required the use of a dynamical representation of the surface. I thus applied the RCE conceptualization to study climatic problems related to interactions between convection and the underlying surface in a simplified, easier to understand, set-up. Even though studies on RCE have flourished over the past few years, almost all of them still focus on the case of a surface with fixed SST. I considered for the first time at storm-resolving resolution the case of SST gradients, islands with interactive soil moisture and a purely land planet with interactive soil moisture.

- The addressed research questions required the use of a multi-resolution approach, from the small to the larger scales, mirroring the nature of convection. This expressed itself by my concurrent use of large-eddy, storm-resolving and coarse-resolution simulations. At first, this required the use of three different models (UCLA-LES, COSMO and ECHAM), designed to be applied at different scales. Over the last few years, my research has benefitted from the versatility of ICON, the new weather and climate model developed jointly by MPI-M and the German Weather Service, that can be employed across scales.

5.2 Outlook

Specific ideas for future research, derived from the findings presented in this review, were already mentioned along the text where appropriate in Chapters 2, 3, 4 and Section 5.1. They can be summarized under the following overarching question that will frame my future research contributions:

What properties of the climatological distribution of precipitation are set by the underlying surface?

Up to now, I already investigated aspects of the interactions between convection and the underlying surface, but mostly focusing on the land problem and on phenomena occurring on the mesoscale and on a daily time scale, like the daily transition to deep convection, or the daily interactions between convection and shallow circulations induced by surface heterogeneities. Lying ahead is the question of the importance of these small-scale interactions between an underlying dynamical surface, being the land or the ocean, and convection for setting large-scale properties of the climatological precipitation distribution, such as position and width of ITCZs or the mean rain amount over land/ocean (see Fig. 5.1). A few considerations motivate addressing this question:

- *Missing theoretical understanding*: Some basic features of the precipitation distribution await clarification. One intriguing feature is the fact that, over the tropics, it rains as much over land than over ocean. This is not expected per se since we know that convective characteristics, such as time of peak rainfall or strength of convection, are definitely affected by the underlying surface. Moreover, the atmosphere over the ocean can tap into an infinite supply of water, which is not the case over land.

- *New conceptual framework*: the conceptualization of RCE is not new, but its application to climatic questions related to the presence of a dynamical surface has remained very limited. As shown in this review, this conceptualization can provide new insights on the potential effects of the land surface on the precipitation distribution.

- *New hypotheses*: Shallow circulations, triggered either by the surface or the atmosphere, were shown to control the spatial distribution of precipitation on the mesoscale in idealized simulations. This is one way the surface makes itself visible to the atmosphere. The role of such shallow circulations for setting large-scale features of the climatological precipitation distribution nevertheless remains largely unexplored. Do radiatively driven, cold pools and/or SST driven circulations control the position and width of ITCZs? Moreover, are they able to affect the partitioning of precipitation between land and ocean on the scale of the tropics? Or do they just spatially redistribute the precipitation amounts on the mesoscale, precipitation amounts that are set on the larger scale by thermodynamic constraints?

- *New Earth System Models*: State-of-the-art Earth System Models employ grid spacings that do not allow an explicit representation of convection. This means that the strength of the coupling between the surface and precipitation is basically set by the design of the convective parameterization. Over ocean, given the lack of coupled storm-resolving simulations, the strength of this coupling is virtually unknown. Over land, the strength of this coupling has been studied in limited-area storm-resolving simulations, with the pitfall of having to rely on lateral boundary conditions provided by a coarse-resolution model, what may well bias the resulting coupling. We are now on the verge of being able to conduct 30-y global coupled simulations at storm-resolving scale. This will allow us for the first time to assess the coupling strength and, over ocean, to quantify the importance of the coupling between interactive SSTs and convection for setting up position and width of ITCZs, for instance. This technical development also opens new perspectives for questions related to the biosphere. Vegetation responds strongly to the precipitation pattern. Allowing the vegetation to respond to the precipitation pattern, in a simulation with explicit convection, where most of the details of the land surface can be captured, is something that has never been done yet. It could for instance make vegetation more resilient to climate change and affect greening trends.

- *New measurement paradigms*: Instead of measuring very accurately and very comprehensively at a few points on Earth, the use of citizen-science based measurement activities, based on cheap, numerous and less accurate sensors, combined with intelligent postprocessing techniques, might offer new opportunities to look at land-atmosphere interactions and convection. This idea motivated the design of the FESSTVaL measurement campaign, where properties of cold pools will be monitored using a dense network of 100 temperature and pressure sensors deployed in a radius of O(10 km) around Lindenberg (Germany). Such techniques lend themselves naturally to the question of surface impacts on the atmosphere given that surface effects manifest themselves quite directly in temperature and, in the presence of shallow circulations, pressure.

Appendix A

List of abbreviations

CMIP	Coupled Model Intercomparison Project
COSMO	COnsortium for Small-scale MOdeling
ECHAM	Name of a GCM
EUREC^{4}A	ElUcidating the RolE of Clouds-Circulation Coupling in ClimAte
FESSTVaL	Field Experiment on Submesoscale Spatio-Temporal Variability in Lindenberg
GCM	General Circulation Model
ICON	ICOsahedral Non-hydrostatic model
ITCZ	InterTropical Convergence Zone
NARVAL	Next-generation Aircraft Remote-sensing for VALidation studies
PBL	Planetary Boundary Layer
RCE	Radiative Convective Equilibrium
SCM	Single Column Model
SST	Sea Surface Temperature
UCLA-LES	University of California Los Angeles Large-Eddy Simulation model

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