SPECIAL PROJECT FINAL REPORT

All the following mandatory information needs to be provided.

Project Title:	Spatial and temporal dependencies extreme precipitation in a warming climate using large eddy simulation (SPACELES)
Computer Project Account:	SPNLLEND
Start Year - End Year :	2017 - 2018
Principal Investigator(s)	Geert Lenderink Kai Lochbihler
Affiliation/Address:	KNMI Utrechtseweg 297 De Bilt The Netherlands
Other Researchers (Name/Affiliation):	

The following should cover the entire project duration.

Summary of project objectives

(10 lines max)

In this project we will investigate with a Large Eddy Simulation (LES) changes in precipitation extremes in a warming climate. We specifically investigate the following questions: i) What are the controlling factors that govern cloud organization? What are the influences of wind shear, instability and moisture content? ii) How does precipitation intensity depend on warming? Does this response depend on the degree of organization of the convective clouds? and iii) How does the degree of organization of convective clouds respond to a warming scenario, and how does this impact changes in storm rainfall volume? In order to study these questions a rain-cell tracking algorithm will be applied to LES simulations of convective conditions for present-day climate and future climate conditions, applying a surrogate climate change scenario

Summary of problems encountered

(If you encountered any problems of a more technical nature, please describe them here.)

None……………………………………………………………………………………………

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Experience with the Special Project framework

(Please let us know about your experience with administrative aspects like the application procedure, progress reporting etc.)

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Summary of results

(This section should comprise up to 10 pages, reflecting the complexity and duration of the project, and can be replaced by a short summary plus an existing scientific report on the project.)

1. Scientific background

Convective precipitation extremes are increasingly causing severe damage due to local flooding, landslides and land erosion. However, convective processes occur at scales far finer than those resolved in climate models. For that reason mesoscale atmospheric models are currently being applied in order to assess changes in convective dynamics in a warming climate. These models – often referred to as convection permitting models – are typically run at a resolution of 2 km, thereby only resolving the largest motions of convective clouds. Here, we go one step further and apply a Large Eddy Simulation (LES) model which is specifically designed to explicitly resolve convective dynamics.

In the literature, convective rain is often found to show a super-CC behaviour; that is, intensities increase faster with (dew) point temperature than the Clausius-Clapeyron relation. Our hypothesis is that this super CC behaviour is caused by a local feedback in a convective cloud due to the influence of latent heating on the strength of the updrafts in the convective cloud. In a simple updraft model of a convective core, we could show that this mechanism indeed plays a role. However, the updraft model only contains a very basic description of the cloud dynamics, and does not contain a realistic representation of the interaction of convective clouds with the boundary layer due to cold pools originating from evaporating rain.

Turning to total volume of precipitation in a convective storm uncertainties may well be even larger. We conceptualized this in Figure 1 (figure by Lenderink from Westra et al. (2014)). There are two important controlling factors. First, the rate at which water vapour can be converted to rain. Here, the strength of the dynamics, with condensation in the updraft leading to the formation of cloud droplets and ice, and also the microphysics play a role. This determines the intensity of precipitation. As argued above there is reasonable support that intensity will increase in excess of the Clausius-Clapeyron relation. The other controlling factor is the moisture budget, with the amount of moisture following the Clausius-Clapeyron relation per cubic meter of air in a warmer climate. If the cloud accesses moisture from the same area the total volume of rain will also has to follow the CC relation. Given the super CC behaviour of the intensity it will have to shorten in time or become smaller in space (situation b in Figure 1).

Given the stronger dynamics of convective systems in a warmer climate, it may also be expected that convective systems become bigger in scale, accessing moisture from a larger area. In fact, observations in the Netherlands provide evidence that this is indeed the case, and also that is a large effect. This is found by estimating the size of precipitation events from the hourly station observations following the methodology in Loriaux et al. (2016), considering hourly precipitation measurement that are connected in time and space (with a radius of 50 or 70 km). For these events we find a substantial increase in cloud size at the high dew point temperature range.

If cloud clusters indeed increase in size with increasing temperatures, storm precipitation volumes could also increase in excess of the CC relation. This is substantially more than commonly assumed in climate change assessments. There is limited support for such a strong increase in storm precipitation volumes from short integration with a mesoscale model (Attema et al. 2014; Lenderink and Attema 2015; Lenderink et al. 2017) where it is found that also daily sums could increase beyond the CC scaling. In addition, recent results clearly indicate the role of large-scale atmospheric forcing in producing heavy and large-scale convective rain systems (Lenderink et al. 2017).

So, the dynamics of storm clouds and the degree to which they organize in cloud clusters are playing a crucial role in this context. In order to capture this we have to rely on models that capture both the turbulent dynamics of clouds, but also the dynamics of the boundary layer, including cold pools. Therefore, we rely on a LES model run at a resolution of 200 m (or below). With the LES model we will do experiments using “observational based” forcing conditions for present-day climate conditions, and surrogate warming experiments (see e.g. Attema et al. 2014; Singleton and Toumi 2013; Loriaux et al. 2013)

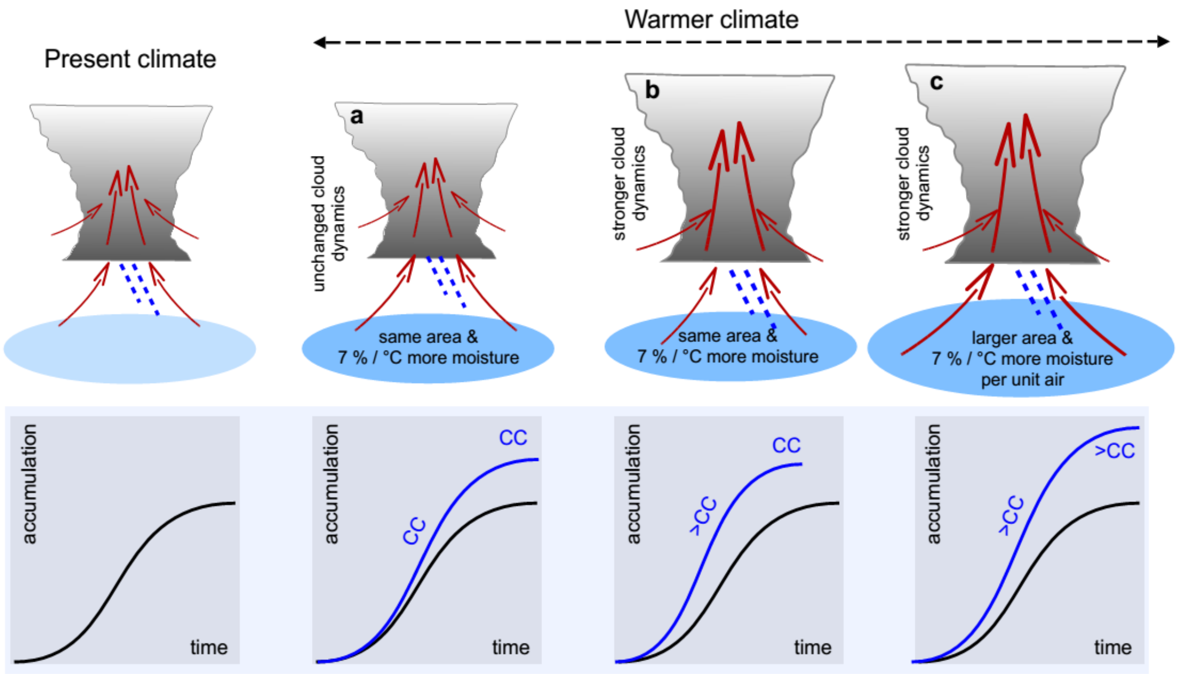

Figure 1. Conceptual picture of how rain-cell size, and intensity may respond to a warming climate.

2. Project results

The Dutch Atmospheric Large Eddy Simulation (DALES) model is a high resolution turbulent resolving community model that has been developed jointly by KNMI, Technical University Delft (TUD), Utrecht University and Wageningen University. For the dynamics a fifth order central difference scheme is used, while the sub-grid turbulence is parameterized by an eddy diffusivity approach using a Turbulent Kinetic Energy (TKE) closure. It contains a comprehensive physics package for cloud microphysics, radiation and soil processes (Heus et al. 2010). It runs well on massive parallel machines and has a perfect weak scaling behaviour (Schalkwijk et al. 2015b) and has been used semi-operational at the KNMI testbed for a period of more than a year (Schalkwijk et al. 2015a).

To study the above questions we have performed runs of one day long, simulating a convective day for the Netherlands based on atmospheric forcing derived from a combination of observations and a downscaling of ERA-interim (Loriaux et al. 2016). For these experiment we used a model domain of 1000x1000 grid points horizontally with approximately 200 vertical levels, equivalent to 200 x 200 km^2 and up to 18 km height. A model run cost 150-200 kSBU for one run at 200x200 km resolution.

Two set of simulation have been performed, the first set was completed in 2017, whereas the second set was performed in 2018. The following two tables given an overview of all simulations performed. In total 32 simulation on the domain of 192x192 km have been performed with the length between 24 and 36 hours. Additionally, one simulation at the larger domain, and 16 on a smaller domain have been run.

	bare	With nudging	Larger domain (288x288km2)	Smaller domain (96x96km2)
M4K	1	1		4
M2K	1	1		
CTRL	1	1	1	4 (+4 with nudging)
P2K	1	1		
P4K	1	1		4

Table 1. Table with the experiments done in 2017. “bare” denotes the reference set of experiments. M4K to P4K refer to 4 degrees cooler to 4 degrees warmer climate conditions, compared to the control simulation (CTRL). A set of nudging experiments has been done, for which large scale conditions are nudged from in the second halve of the simulations. A few experiments also have been done on smaller and larger domains as well. The runs in this table use a prolonged daily cycle, consisting of 36 hour instead of 24 hour, which increases the statistical robustness of the results and allows more time to develop organized convective clouds.

	bare	RH	RH_low	Stab_M50	Stab_M100	Wfls30	Wfls60
M4K	1	1	1	1	1	1	1
M2K	2	1					
CTRL	3	[as bare]	[as bare]	[as bare]	[as bare]	1	1
P2K	1	1					
P4K	1	1	1	1	1	1	1

Table 2. Table with the set of experiments done in 2018. M4K to P4K have the same meaning as in Table 1. The runs use a different experimental setup, now using a realistic 24 hour diurnal cycle, but with more persist large-scale forcings at the end of the day. The sensitivity experiments are covarying relative humidity with temperature" and "RH_low" (only in low atmosphere), perturbations in temperature varying with height according to 50% of a moist adiabat "Stab_M50" and a full adiabat "Stab_M100". Note these runs share the control simulation with the "bare" set. The last two sets denote perturbations in the large-scale vertical velocity by 30% "Wfls30" and by 60% "Wfls60".

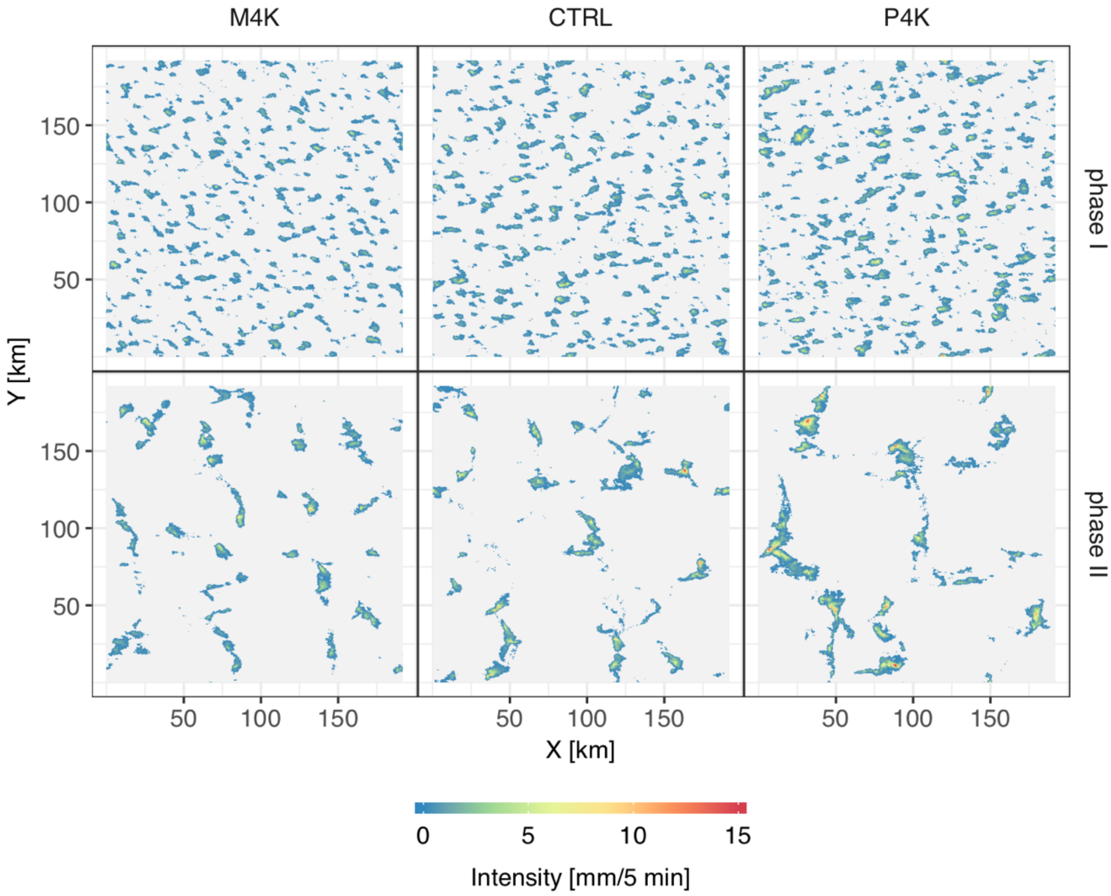

Figure 2. Snapshots of the precipitation intensity after approximately 12 hours (phase 1) and 17 hours (phase 2). In phase 1 mainly relatively small rain-cells occur, which rapidly develop into larger rain systems in phase 2. In particular in phase 2 the increase in size of the rain systems is clearly visible.

The analysis of the first data set (Table 1, bare runs) was completed in 2018 and lead to a publication in Journal of Geophysical Research: Atmospheres (accepted in May 2019). The data set consists of five simulations. Besides the control simulation (CTRL), four simulations with increased/decreased atmospheric temperature and moisture content were performed. To do so, temperature profiles were uniformly perturbed in steps from -4K, -2K, +2K and +4K with respect to the CTRL setup. Atmospheric moisture content was adjusted according to CC to keep RH at the same value as in CTRL.

The development of surface precipitation during the model day is similarly timed in all experiments and two several hours lasting phases of heavy rainfall activity were identified, which we further investigated. The first phase starts with the onset of precipitation and the second phase about five hours later. Figure 2 shows snapshots at the center of both phases for the -4K, CTRL and +4K experiments. It is clear that surface precipitation is generally higher under warmer conditions. A scaling analysis shows that rainfall extremes generally (on grid point level) increase with a rate ranging from 7.8%/K to almost 10%/K.

Besides that, it appears that individual rainfall events also become bigger with (i) increasing temperature and moisture content and (ii) during the transition from phase I to phase II. To quantify these findings, we used a clustering algorithm to identify individual rain cells and extracted their average intensity, total rainfall amount and size (square root of the area). The results show that while the average intensity of rain cells increases with temperature at a rate that is in the range of the CC relation their total rainfall amount increases at a much stronger rate – up to almost 20%/K.

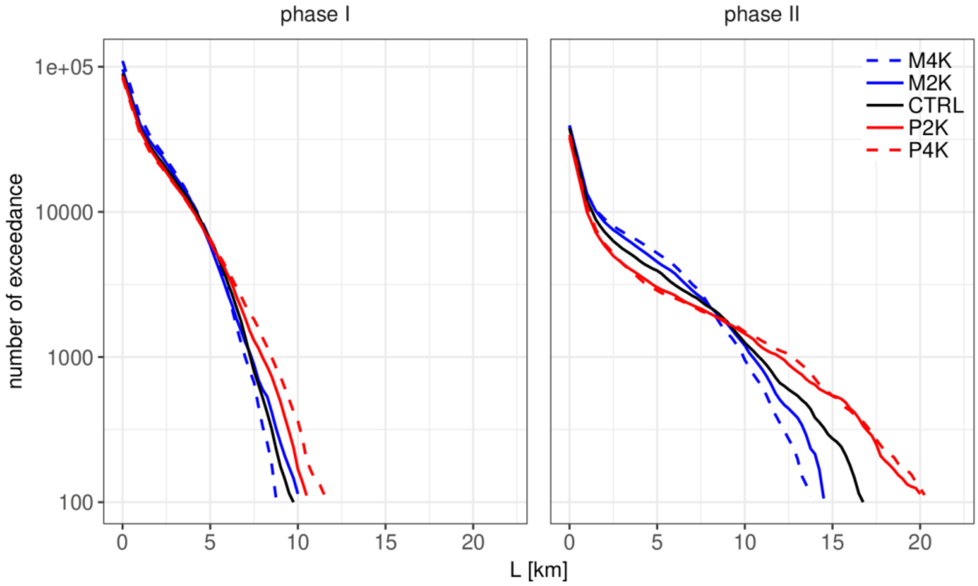

Figure 3. Distribution of rain cell size (linear length, root of the cell area) for phase 1 (shortly after the onset of precipitation) and phase 2 (the organized phase).

This massive increase of total rain produced by an event is possible due to a concurrent increase of rain cell size. Figure 3 shows size distributions of rain cells for both phases. These results confirm the visual interpretation of the snapshots in Figure 2. In phase I the largest cells increase in size with increasing temperature. In phase II this increase is much stronger, and even more, the increase of the largest rain cells happens at the expense of smaller sized events. So, during transition from phase I to phase II the precipitation field is reshaped from many small events to fewer but bigger rain cells. The whole process is amplified by warmer and moister conditions.

Finally, to analyze how the intensity increase is connected to the growth of rainfall events we produced composites of extreme precipitating rain cells from phase I (Figure 4). Unfortunately, this analysis is not possible for phase II due to the asymmetric shape of rainfall events (see Figure 2).

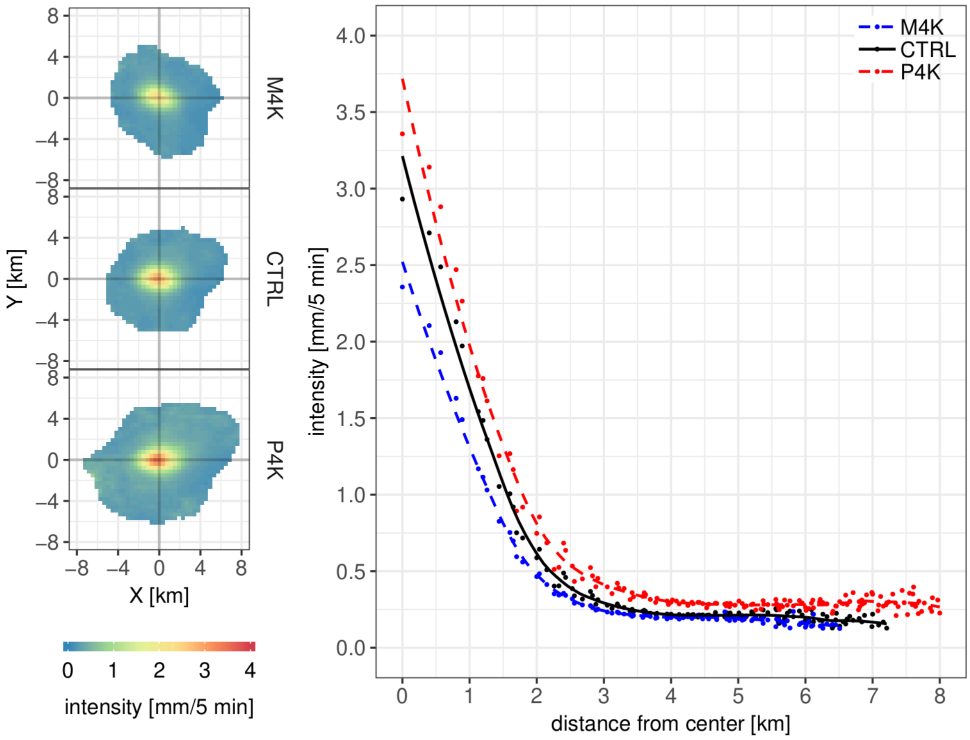

Figure 4. Composites of the most intense rain cells in three different model simulations, the reference runs (CTRL) and the 4 degrees cooler (M4K) and 4 degrees warmer simulation (P4K).

The composites clearly show that size and intensity of rain cells increase hand in hand (left side of Figure 4). Moreover, we observe that intensities increase over most of the rain cell area (right side of Figure 4). So, in our experiment the increase in intensity is not realized at the expense of the rain cell size, confirming the mechanism sketched in Figure 1c.

The first experimental setup (see Table 1) assumed no change in the atmospheric (dry) lapse rate, and no changes in relative humidity. In the context of climate change, this is rather crude approximation. It might be valid for some areas and season around the globe, however it is known that for most areas and seasons substantial changes occur in lapse rate and relative humidity. Usually, it is expected that the atmospheric stability increases (in terms of the dry processes) and the relative humidity decreases. In our second set of the experiment (see Table 2) executed in 2018 at ECMWF we investigated a number of these factors. One result with co-varying relative humidity is shown in Figure 5.

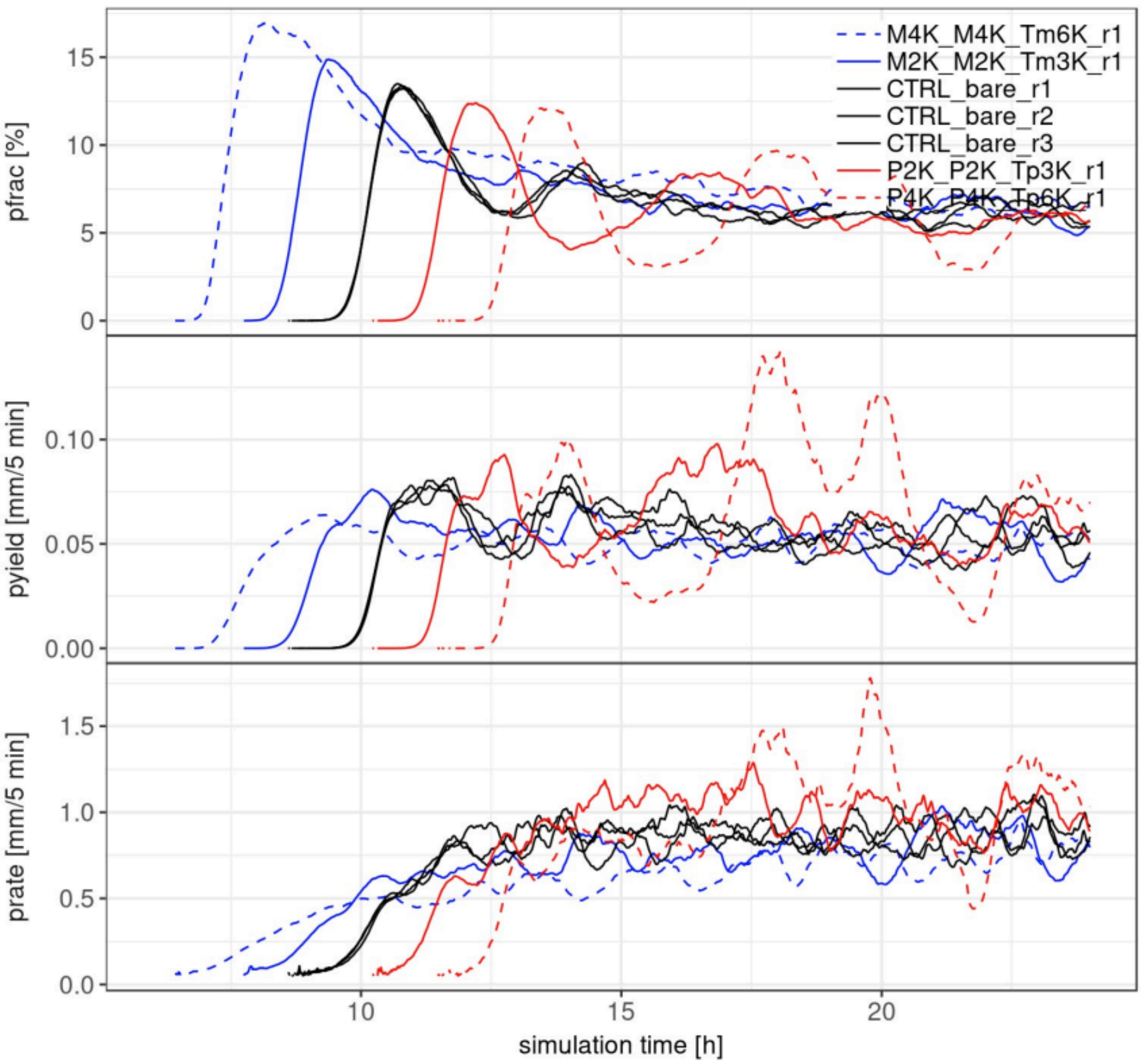

Figure 5. Time series of rain area fraction (upper), mean rain yield(middle) and rain rate conditional on the rain area (lower) panels for a an experiments with co-varying relative humidity (Table 2, second column).Colder runs (blue) have higher relative humidity and convection is initiated earlier, whereas warmer runs (red) have lower relative humidity.

The analysis of the second set of runs is still ongoing. A publication will follow end of 2019.

List of publications/reports from the project with complete references

Lochbihler, K, G. Lenderink and A.P. Siebesma (2019) Response of extreme precipitating cell structures to atmospheric warming. J. Geophys. Res. (atmosphere) In press.

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Future plans

Kai Lochbihler will continue to write another paper on the LES results, in particular focussing on second set in Table 2.