Letter to the Editor:

Before addressing the two reviews, we would like to point out that because of an oversight during cleaning older simulation data, we removed a part of the 3D model output, which is needed to reproduce Figs. 2 and 6 of this article. We therefore repeated the simulations discussed in this article using a new hardware configuration following an upgrade of our supercomputer center. The general conclusions and all main results of the article **are not affected** by this. Due to the chaotic nature of the studied phenomena there are a number of differences, including some substantial changes in precipitation amounts. For consistency, all numbers and figures have been updated for the revised version of the paper.

Response to Referee #1 (acp-2017-504)

We thank the referee for all the valuable comments that have improved the manuscript. Following his/her suggestions, we have streamlined our paper and focused on specific results, highlighting the benefits of this study. Please see below our point-by-point replies to the specific comments, with the referee's comments in black and our replies in blue.

Major comment: In the introduction, the authors give a very nice (and quite comprehensive) overview on the state the art in regional climate modeling with respect to summertime convection in the Alps. Essentially, CPM and CRM resolutions had been compared (e.g., Ban et al. 2015), the surrogate climate approach (SCA) has been used before (Kroener et al. 2017), the two microphysics schemes had been compared (Keller et al. 2016). What is new in the present study according to the authors (p16, l.11) is the use of the SCA for CRM. So, one would expect to learn a bit more on the advantages of the SCA in the first place (what is it that we can learn from it that we cannot obtain from the decade-long CRM simulations?) – and why? Second, one would expect the approach to be put into perspective: open questions according to the introduction are i) the limitation of precipitation extremes due to the Clausius-Clapeyron equation (p2, l.25), ii) the role of stratification [changes] for the precipitation in CRM (p3, l.2) and iii) the impact of the microphysics scheme on the cloud top [not so much the precipitation], (p3, l.11). So, which of these topics can be better addressed with the SCA than with decade-long simulations (and why)? What can we learn from a 11-days process study that cannot be obtained from the full decade-long simulations? At the end of the introduction, the authors then formulate three questions they want to address (p3, l.14). These questions, however, do not correspond (one-to-one) to those open questions – and to some degree do also not reflect what the authors summarize in their conclusions. I think therefore, the authors could make a much stronger case for their simulations if they would thoroughly work out what the potential of their simulations (approach) is (more than 'it has not been done') and by discussing their results in the light of earlier findings (and whether a disagreement could be resolved or explained) and their own questions in the beginning.

We agree with the referees that the paper was lacking a strong focus. Following the suggestions of the second referee we removed the comparisons of the one and two-moment microphysics scheme and further the analysis concerning the Clausius-Clapeyron scaling. With those major changes we could streamline the paper and put more emphasize on the selected findings. Overall this has led to a shorter paper, substantial decrease in figure count, and has contributed to a clearer structure and focus. We want to answer the following questions: How will the diurnal cycle of convection and the associated precipitation and clouds change in a warmer climate? How large is the impact of different temperature change profiles (HW versus VW)? How do the simulated changes depend on the modeling framework, in particular on the horizontal resolution (CPM versus CRM simulations)? To this end we focus on the comparisons between 2.2 and 12km resolution and the two climate change profiles. Accordingly we focused our introduction on these points and extended our conclusion section to reflect these changes.

Removing the two-moment microphysics has dropped the following panels: Fig. 2B,d,f; Right column of Fig. 3; Fig.4b; Fig.5b; Fig6b,d; Right column of Fig. 7; Fig. 8b,d; The microphysics column in table 1 and the right column of table 2 as well as all references to those figures and their discussion.

Removing the analysis of the Clausius-Clapeyron scaling has dropped the following elements: Fig. 5c,d; the method section 2.2 and table3 as well as all references to those figures and their discussion.

Addressing the first comment from the referee cited above, we extended the introduction to better explain the benefits of the SCA for this study:

See Page 2, Lines 24-28; Page 3, Lines 6-11

Addressing the second comment we focused the paper on the questions formulated at the end of the introduction, and to prevent confusion deleted the Clausius-Clapeyron paragraph as well as the discussion of two-moment microphysics from the introduction. Further we also extended the conclusion section to better reflect the questions we formulated in the introduction.

See Page 4, Lines 1-4, See conclusion section on Pages 13-14

Minor comments

Page 2, Line 27: I think the authors should expand a little on the advantages of the surrogate warming (and also maybe on the disadvantages). While in 1996 this approach was certainly mainly advantageous with respect to computing time, this has changed a little in recent times.

See reply to the first point of the major comment above. Further we included a paragraph in the discussion section addressing the disadvantage of the surrogate method. Page 14 Lines 22-24.

Page 6, Line 25 yielded a bimodal. . ..

Text corrected.

P7, l.14 Indeed, the 11-day period is quite limiting. Maybe the authors can expand a little on what processes they want to explore in more detail than possible with the decade-long CRM simulations. And especially, how this is related to the potential of the SCA.

We complemented the text by explaining the investigated process and the advantage of the surrogate approach. Page 3 Lines 6-11 and Page 6, Line 32 and Page 7, Lines 1-2

P7, l.28 we assume...: of course, because this is a paper about convection - but couldn’t this hypothesis be checked more thoroughly (using all the available data)?

We have reformulated this sentence, in the revised version (Page 7, Liens 13-14) we now state that the vertical redistribution of temperature “must largely be caused by convection and boundary layer processes”. We consider it unlikely that other processes (such as radiation) do also contribute. The full analysis would actually be quite cumbersome, as the parameterized and advective tendencies would need to be used (which mostly are not available with the current model output).

P9, I.22 here we also have observations - so it would be interesting to see the mean diurnal cycle of the observations, too (this could be realized by also in the model only considering the 'observed part' of the domain - assuming [but the authors can of course judge, based on the results], that the mean daily cycles in the model runs will not largely change if only a subdomain is used).

The observations in Figure 3 are daily means. For a comparison of the diurnal cycle of precipitation, hourly data from some subdomains (e.g. Switzerland) could be used. However, since we show the comparison of the diurnal cycle with Swiss observations in Keller et al. 2016, we decided against including a detailed validation of the diurnal cycle of precipitation observations in the current paper. To make the reader aware of the validation in the previous paper, we make a specific comment (see Page 9, Lines 1-2).

P9, I.26 first of all: the responses to HW and VW are... . More important: I am not sure what the authors want to point out here. Under the 'response to HW and VW' I would intuitively understand the difference between the blue curves on the one hand, and the red/orange lines on the other hand. If we take the peak, the dashed lines in Fig. 4a are rather closer to each other (i.e., the red/orange closer to the blue) than the full lines. So, is it something else that the authors want to point out? Apparently, when reading on, the authors refer to mean, temporally averaged precipitation (as given in Tab. 2). In a paper that deals with convection, however, I would find it extremely noteworthy, that HW is only larger during the night (and the microphysics scheme doesn't change this). So, what I really find striking is the large difference between HW and VW during the night - irrespective of all other differences. Can the authors comment on this?

We reformulated the paragraph so that it can be understood more easily. Page 9 Lines 5-13. We were also surprised by the HW effect on precipitation during night. The destabilizing effect of HW seems to be more pronounced during night time. Currently we do not have a convincing explanation for this behaviour.

P9, I.28 'these' are the present simulations, right?

Yes. We replaced 'these' with 'our' for a better understanding.

P9, I.29 we attribute 'this' reduction': which now? the CPM, or the CRM? those of Ban et al. or the present? Please specify (Note that if the present simulations were referred to, an appropriate comment would have been that this could be more than a hypothesis - because the authors have all the simulation data so they could identify the circulation changes over the 11 days...).

We reformulated the whole paragraph. Page 9 Lines 5-13

P9, I.30 interestingly, in my paper collection this is Kroener et al 2017. (Clim Dyn (2017) 48:3425–3440, DOI 10.1007/s00382-016-3276-3).

Reference updated.

P11, I.2 what is the ‚convection setup'?

"convection setup" was referring to the horizontal resolution. We reformulated the paragraph.

P11, I.9 see above: most findings are 'similar to those of Ban et al'. → by elaborating a little bit more on why to use this surrogate climate approach (even if for only 11 days) this would help to better motivate the present study.

This paragraph was removed. We extended the introduction and method section to work out the benefits of the SCA approach. See answer to major comment.

P13, l.4 couldn't those 'discrimination lines be shown in the figure?

We also thought about that but (1) adding another two lines to figure 7 makes the plot even more busy, and (2) the axes in figure 7 are chosen such that the 440 and 680 hPa level can easily be seen.

Fig. 7 the smallest letters and numbers are definitely too small.

We increased the figure size

P14, l.6 'below 310 hPa' seems to be misleading (I intuitively first checked p<310 hPa...). Better would be 'for heights below 310 hPa'.

Suggestion followed.

P14, l.15 . . .indicates a similar timing. . .: Still it is interesting to note that precipitation peaks around 1500 UTC (Fig. 4) for the CRM simulations and 1200 UTC for the CPM simulations. Combining earlier statements in the paper (p2, l.14, and p9, l.19, i.e. the reference to the Langhans et al. paper where it had been shown that the precipitation maximum is better simulated in higher resolution, and therefore should occur closer to 1500 UTC), this would imply that - at least for the chosen 11-day period - precipitation peaks almost [1-2 hr difference] when cloudiness has its minimum (Fig. 8). This is why (among others) I have suggested to add observed precipitation to Fig. 4. Maybe it can also trigger some additional analysis concerning which type of clouds actually contribute to OLR and to what degree OLR is determined by clouds.

During our period of interest, the OLR minima at around 17~UTC, indicates a maximal extension of high, cold clouds and corresponds therefore well with the maximum of precipitation, which is expected a little bit earlier than the cloud maxima. We would attribute the OLR maxima (Fig. 7a) around noon for the CRM simulations, which is still 2 hours before peak precipitation, to the rising atmospheric and ground temperatures during the day. After 12 UTC, this effect is overcompensated by the increasing cloud cover, which decreases OLR. It is important to notice that the 12km simulations are not able to reproduce these maxima over day between 8-12 UTC but have maxima at midnight (Fig 7a). For an in-depth analyses of the cloud cover changes, see Keller et al. 2016.

We reformulated the whole paragraph: Page 12, Lines 16-19 and Page 13, Lines 1-9

Fig. 8, caption: '(a, b) outgoing longwave radiation at the top of the atmosphere (obs) and the model domain (mod), respectively (I presume).

Caption revised

P15, l. 4 'All the control simulations show a too early peak': isn't this a contradiction to the finding in OLR? If the peak is too early, then the cloud cover peak is too early (but the OLR peak is too late). Can the authors comment on that?

Indeed, the formulation was misleading. An increase of high clouds leads to lower values in OLR and higher values in RSR. The too early peak in RSR in the morning corresponds to the OLR minimum in the morning. Further, OLR is sensitive to different cloud heights, while RSR is less sensitive to that. We complemented the text with more details. Page 13 Lines 6-9

P16, l. 24-26 The results of the CPM. . ..: I think these three lines contradict themselves. First, they can only refer to the VW/HW discussion, and second, if the two largely coincide why then do we have significant differences?

We agree the text was not clearly formulated we changed large parts of the conclusions.

Response to Referee #2 (acp-2017-504)

We thank the referee for all the constructive comments that have improved the manuscript. We followed the suggestions of the referee and reduced the amount of presented results giving more focus on specific ones. Please see below our point-by-point replies to the comments, with the referee's comments in black and our replies in blue.

Major comments

This is a potentially interesting study that deserves publication if the three major changes listed below are made:

We agree with the referees that the paper was lacking a strong focus. Following the suggestions of the second referee we removed the comparisons of the one and two-moment microphysics scheme and further the analysis concerning the Clausius-Clapeyron scaling. With those major changes we could streamline the paper and put more emphasize on the selected findings. Overall this has led to a shorter paper, substantial decrease in figure count, and has contributed to a clearer structure and focus. We want to answer the following questions: How will the diurnal cycle of convection and the associated precipitation and clouds change in a warmer climate? How large is the impact of different temperature change profiles (HW versus VW)? How do the simulated changes depend on the modeling framework, in particular on the horizontal resolution (CPM versus CRM simulations)? To this end we focus on the comparisons between 2.2 and 12km resolution and the two climate change profiles. Accordingly we focused our introduction on these points and extended our conclusion section to reflect these changes.

Removing the two-moment microphysics has dropped the following panels: Fig. 2B,d,f; Right column of Fig. 3; Fig.4b; Fig.5b; Fig6b,d; Right column of Fig. 7; Fig. 8b,d; The microphysics column in table 1 and the right column of table 2 as well as all references to those figures and their discussion.

Removing the analysis of the Clausius-Clapeyron scaling has dropped the following elements: Fig. 5c,d; the method section 2.2 and table3 as well as all references to those figures and their discussion.

1. The number of lines on each plot is too high to properly absorb the message you are trying to communicate. For instance, figure 6 has 12 lines on four plots for 48 lines. While I appreciate that you are trying to make a point that many of the lines are on top of each other, I have a hard time distinguishing the lines from each other and also the difference between one line or another and the key from one line to another. One suggestion is to delete the comparison to the one moment and two moment microphysics schemes from this paper. There is very little sensitivity and most of your points were made in the previous paper. I would focus on the difference between the 2.2 km and 12 km simulations and the current and surrogate climate.

We agree with the reviewer that figure 6 is very busy. We changed figure 6, separating cloud ice and cloud water, thereby reducing the amount of lines in this specific plot.

2. The paper treats all the results with nearly equal weight. I find it to more of a travelogue than a research paper. I think you have a message you want to convey to the reader and I would focus on that message from both the figures you show and the discussion in the text. As I mention above, I was most interested in the difference between the convective permitting and the convection parameterization simulations for both current and future climate. This message is lost in the travelogue style of presentation.

As stated above we agree with the reviewer that a stronger focus on specific results will improve the paper. As suggested above we remove the 1M vs. 2M comparison from the paper.

3. I would like to see more emphasis on the physical reason for the results.

For instance, why is the diurnal timing for convection changed going from convective permitting to convective parameterization simulations in figure 4?

This is an important research question but not the main focus of this paper. The result about the improved diurnal cycle with explicit convection is already broadly discussed in the introduction (P2, L9-18). Furthermore, we added another reference to a recent paper which addresses this question (Fosser et al. 2015, Clim. Dyn. Benefit of convection permitting climate model simulations in the representation of convective precipitation), see Page 9 Line 1. The reason for the later precipitation peak in convection-resolving simulations is at least partly understood. It is related to the representation of the life cycle of convective cells in explicit simulations, while parameterization schemes assume an ensemble of convective cells in equilibrium with the instability present in the vertical profile. The latter is particularly evident for convective adjustment schemes, which remove potential instability at every time step.

Why does the CPM simulation have less precipitation?

We do not consider these differences between CPM and CRM as being very significant, in fact we did not discuss them in the paper, although indeed CPM has slightly larger precipitation amounts. The main issue considered in the paper is the precipitation response to the two different forcing's considered (e.g. HW and VW), with HW producing a more pronounced precipitation increase. This result is not surprising, as VW addresses the case of increased vertical stratification, which will tend to suppress convection and reduce precipitation.

Is the amount it estimated close to observations?

In Fig. 11a of Keller et al. (2016), a comparison of the diurnal cycle of precipitation over Switzerland was shown for the three CTRL simulations as well as the observations. The panel shows that the diurnal cycle is better captured in the CRM simulations, and overall in reasonable agreement with observations, in particular when accounting for the observational uncertainties (discussed in Section 3.4 of Keller et al. 2016). As regards the comparison in Fig.3 of the current paper, there is again a reasonable qualitative agreement of the CTRL simulations.

Otherwise these are just model results and I haven't really learned anything other than there is a difference between the runs or not. There are only 11 days of simulation, so a focus on the physics rather than the climatology seems warranted and appropriate.

We agree that a focus on the physical interpretation makes sense. We think that the revisions have helped in bringing out the relevant points more clearly. Furthermore, there is a lot of discussion in the paper interpreting the differences between CTRL, HW and VW simulations.

Minor comments

Page 3, line 1. Please state the height in the atmosphere for which the north-south temperature gradient is impacted.

Corrected. It was 2m temperature.

Page 6. Line 29. Delete “steps at”.

Text corrected.

Page 6. I would like to see an image of the analysis domain in this paper.

The analysis domain is shown in Fig. 1a and explained in the first paragraph of Section 2.1. It is the domain of the CRM simulations.

Page 7, line 8. I would have liked to have seen a sequence of synoptic maps characterizing the 10 day period (if nearly constant, a composite map).

Such maps can be very informative, but to keep the paper focused we would rather not increase the figure count.

Page 9. Line 22.”with” should be replaced by “by”.

Text corrected.

Page 10. I would like to see difference plot for figure 3. It is very difficult to see what the differences in various runs actually are and what magnitude otherwise.

Figure 3 is meant to give a qualitative feeling for the amount and distribution of accumulated precipitation during the analyzed period. For an 11 day period the influence of internal variability is rather large and difference plots are very noisy and not as informative as the area-mean precipitation changes shown in Table 2, and the mean diurnal cycles shown in Fig. 4. We do not think that too much emphasis should be attached to spatial details, as only 11 days have been considered, and as summer convection is a fundamentally chaotic process.

Page 9, line 29. Can you be more clear about the expected circulation changes?

We reformulated the whole paragraph and moved the circulation changes to the discussion section.

Page 9 Lines 5-13

Page 14, Lines 22-24

Page 11, line 9. Need to state what the differences are between the 12 km and 2 km runs and how they agree with Ban et al. (2015).

We removed this analysis from the paper see answer to major comment 2

Page 11, line 14. Need to state what the values of vertical velocity you are talking about.

We did not fully understand this comment. The distribution of vertical velocities is shown in Fig.5a.

Page 14. Lines 3-14. This is an interesting discussion of the causes for the differences in the VW and HW simulations. I would encourage a more detailed analysis as the discussion speculates more than determines what the real cause is. It might be useful to examine the evolution of clouds in detail for one or two days for both VW and HW to determine the cause. You only have 11 days, so an average does not necessarily give you a robust result.

The 11 days analyzed in this study are part of several month long free running simulations. Therefore internal variability makes it difficult to compare exactly one day of HW simulation against the same day in a VW simulation.

Page 16. Lines 15 and 16. Why is there an increase in heavy precipitation events for the CPM runs compared to the CRM runs? Do the CPM runs compare well to the CRM runs for non-heavy events?

We removed the scaling analysis from the paper, see answer to major comment 2. We removed this part of the conclusions.

Page 16, lines 24-26. I think this is the most interesting result of the paper and should be explored deeper. First of all, how does the VW change in vertical distribution physically effect the clouds? You only have 11 days of simulation, so you should be able to note some common evolution and physical changes. Second, why is the response of the CRM different than the CPM for HW and VW? This is a very interesting result that deserves more investigation.

The main difference between the CRM and CPM response to VW is the difference in upper-level clouds. This factor is now better stressed in the conclusions (see Pages 14, Liens 12-15). We think that the cloud cover changes in VW are related to reductions in convective activity. The fact that CPM is more strongly affected is difficult to interpret, as that model version is affected by a substantial overestimation of upper level clouds in CTRL.

Final comment

The conclusion section is much too short. There should be much deeper discussion of the results here that can help the reader understand the detailed simulation results presented in the previous section. What do you want the reader to take away from this study? I am current not sure, and that is a problem.

We agree with the comment of the reviewer. We extended and reformulated parts of our conclusion section, picking up the questions posed in the introduction.

See conclusion on Page 13-14.

The sensitivity of Alpine summer convection to surrogate climate change: An intercomparison between convection-parameterizing and convection-resolving models

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Abstract. Climate models project am heavy in precipitation events in response to greenhouse gas forcing. Important elements of such events are rain showers and thunderstorms, which are poorly represented in models with parameterized convection. In this study, simulations with 12 km horizontal grid spacing (convection-parameterizing model, CPM) and 2 km grid spacing (convection-resolving model, CRM) ~~, and with either a one-moment microphysics scheme (1M) or a two-moment microphysics scheme (2M)~~ are employed to investigate the change in the diurnal cycle of convection with warmer climate. For this purpose, simulations of 11 days in June 2007 with a pronounced diurnal cycle of convection are compared with surrogate simulations from the same period. The surrogate climate simulations mimic a future climate with increased temperatures, but unchanged relative humidity and similar synoptic-scale circulation. Two temperature scenarios are compared, one with homogeneous warming (HW) using a vertically uniform warming, the other with vertically-dependent warming (VW) that enables changes in ~~lapse rate~~lapse-rate.

The two sets of simulations with parameterized and explicit convection exhibit substantial differences, some of which are well known from the literature. These include differences in the timing and amplitude of the diurnal cycle of convection, and the frequency of precipitation with low intensities. ~~There are also significant differences in terms of the response to the surrogate warming. For CRM, an increase of hourly heavy precipitation events is found for both surrogate scenarios and microphysics schemes. The intensification is consistent with the Clausius-Clapeyron relation~~The response to climate change is much less studied. We can show that stratification changes have a strong influence on the changes in convection. Precipitation is strongly increasing for HW but decreasing for the VW simulations. For cloud type frequencies, virtually no changes are found for HW, but a substantial reduction in high clouds is found for VW. ~~Some of the CPM sensitivities differ significantly. Importantly, the increase of heavy precipitation events simulated by CPM is larger than suggested by the Clausius-Clapeyron relation. Moreover~~Further we can show that the climate change signal strongly depends upon the horizontal resolution. In particular, significant differences between CPM and CRM are found in terms of the radiative feedbacks, with CRM exhibiting a stronger negative feedback in the top of the atmosphere energy budget.

1 Introduction

The diurnal cycle of convective clouds and precipitation over Europe is mainly active during summer, when solar radiation is strongest. The available energy at the Earth's surface is partitioned into sensible and latent heat fluxes, which in turn are redistributed in the atmosphere by convective processes. If the resulting updrafts are strong enough and persistent, this leads to high cloud tops, which can be detected as cold temperatures in satellite measurements. In these, the diurnal cycle of summertime convection over Europe is found to be strongest over mountain areas, such as the Alps (Levizzani et al., 2010). A more conventional indicator for deep convection is surface precipitation. In line with the satellite measurements, pronounced seasonal maxima are found in summer along the Alpine ridge (e.g. Frei and Schär, 1998).

The diurnal cycle of summertime convection has been investigated by conventional convection-parameterizing models (CPMs) and high-resolution convection-resolving models (CRMs). Both approaches have specific advantages. Long-term global climate projections need significantly more computer resources than weather forecasts of a few days. Thus, climate simulations are typically conducted using CPMs. The CPMs lack a good representation of the diurnal cycle of convection (Bechtold et al., 2004; Brockhaus et al., 2008; Hohenegger et al., 2008), which is improved in CRMs (Schlemmer et al., 2011; Langhans et al., 2013; Prein et al., 2013). In addition to the improvement in the diurnal cycle, improvements were also found in the frequencies of wet days and heavy precipitation events (Ban et al., 2014). In recent years, it has become possible to conduct decade-long CRM climate projections on regional (Kendon et al., 2014; Ban et al., 2015) and continental scales (Leutwyler et al., 2016, 2017). A review on climate simulations with CRMs can be found in Prein et al. (2015).

Projections of the summer climate over central Europe have found an increase in daily heavy precipitation events despite reductions in mean precipitation amounts (Christensen and Christensen, 2003; Frei et al., 2006; Rajczak et al., 2013). An intensity increase is also found for hourly heavy precipitation events, both by CPM and CRM simulations (Ban et al., 2015). Past research has indicated that changes in precipitation extremes are limited by the water vapor content in a warmer climate. This limitation follows the Clausius-Clapeyron relation (6–7 % K^{-1}) (e.g. Allen and Ingram, 2002). This argumentation is supported for daily events in a number of studies. ~~However, for hourly events some studies project an increase beyond this relation (Lenderink and Van Meijgaard, 2008; Kendon et al., 2014), while other studies confirm the Clausius-Caperyron scaling (Ban et al., 2015). Therefore, further investigations of the changes in precipitation extremes are needed.~~

One important limitation of ~~these~~ the mentioned climate change studies is the uncertainty introduced by circulation changes~~which can be quite substantial for regional scales even on 10 years (Deser et al., 2012). The expected changes in precipitation climate will be governed by a number of factors. To distinguish between thermodynamic and circulation contributions, surrogate experiments can be conducted~~. There are large differences between different GCMs (Woollings, 2010; Bony et al., 2015), and internal variations are substantial in particular in the near-term (Deser et al., 2012). Therefore it would be beneficial to separate between robust thermodynamic changes and uncertain circulation changes. This separation can be achieved by conducting surrogate experiments (Schär et al., 1996). In these regional climate model (RCM) experiments, the temperature distributions at the lateral boundaries are changed consistent with the expected large-scale warming, but relative humidity and circulation are held constant. Experiments of this type have revealed significant changes in mean precipitation and precipitation statistics when applying a vertically homogenous warming (HW) for mid-latitude conditions (Frei et al., 1998; Seneviratne et al., 2002; Im et al., 2010; Attema et al., 2014). However, climate change studies also show that there are pronounced stratification changes. More specifically, the upper troposphere is projected to warm at a faster rate than the surface (Santer et al., 2008; Collins et al., 2013). This implies that a vertically-dependent warming (VW) is closer to what is expected for the future. ~~?~~ Kröner et al. (2017) found that the associated stratification (or ~~lapse rate~~lapse-rate) effect explains one third of the projected changes in north-south ~~temperature gradient at~~ 2 m temperature gradient of the European summer climate. Furthermore, they showed that the stratification changes strongly modulate convective precipitation. ~~In the current study, we will use a related methodology and address stratification effects in the framework of CPM and CRM simulations.~~

For completeness it should be mentioned that a further surrogate approach exists, which is called pseudo-global warming (e.g. Rasmussen et al., 2011; Prein et al., 2016). There, the main difference to VW is that the temperature change is not only a function of height but also of the spatial coordinates. ~~To keep atmospheric dynamics in balance, this implies that also the climate change signal of other variables has to be calculated explicitly~~

In the current study, we will use the surrogate methodology and address thermodynamic and stratification effects in the framework of CPM and CRM simulations. The possibility to exclude circulation changes makes the surrogate approach very interesting for CRM simulations. They are often restricted to relatively short case studies because of the computational effort, hindering full climate change studies. The surrogate approach allows studying the same cases but in a warmer climate. Further we can study the dependence of the climate change signal on the horizontal resolution by combining CRM and CPM simulations.

In ~~Keller et al. (2016)~~this paper, an 11-day period in June 2007 with a pronounced diurnal cycle of convection is investigated~~by evaluating CPM and CRM simulations~~. It builds on a previous study (Keller et al., 2016) in which the same period was evaluated with satellite data. ~~One of the major outcomes of that paper is that using a two-moment microphysics scheme (2M) with ice sedimentation, instead of the standard one-moment microphysics scheme (1M) without ice sedimentation, reduces the high cloud cover bias, but without significantly affecting the precipitation response. The current paper builds on the previous study and expands it~~ Here we expand the previous work with surrogate simulations (HW and VW) for the same period. Apart from a small change in the setup (see Sect. 2.1), the control simulations are identical to the simulations in Keller et al. (2016), but restricting attention to simulations using one-moment microphysics scheme. We address the following three questions: How will the diurnal cycle of convection and the associated precipitation and clouds change in a warmer climate? How large is the impact of different temperature change profiles (HW versus VW)? How do the simulated changes depend on the modeling framework, in particular on the horizontal resolution (CPM versus CRM simulations) ~~and the cloud-microphysics parameterization (1M versus 2M schemes)~~?

The paper is structured as follows: In Sect. 2, the COSMO setup, the surrogate setup, the analysis methodology, and the observations used for evaluation are introduced. The results are presented and discussed in Sect. 3, and finally ~~,~~ the conclusions are presented in Sect. 4.

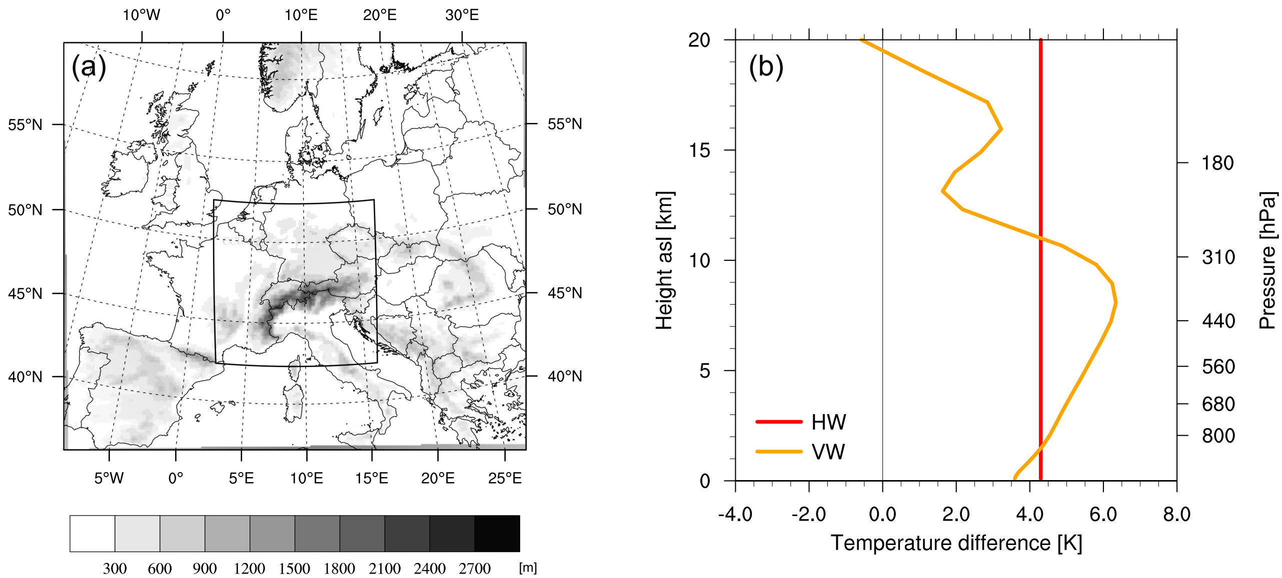

Figure 1. (a) Computational domains of the ~~CPM~~ convection-parameterizing simulations (CPM, full domain, 12 km resolution) and ~~the CRM~~ convection-resolving simulations (CRM, box in the center, 2 km resolution). Topography (m) is indicated in gray shading. The inner box also corresponds to the analysis domain. (b) Height profiles of the temperature differences for homogeneous warming (HW) and vertically-dependent warming (VW) relative to the control at the lateral boundaries of the CPM simulation domain, averaged over the investigated period (taken from ~~?~~Kröner et al. (2017)). Height is indicated in km on the ~~left~~ left-hand side, and pressure values at particular heights, averaged over the 11-day period, are indicated in hPa on the ~~right~~ right-hand side.

2 Methods and data

2.1 Model and surrogate setup

This study uses the COSMO model (Consortium for Small-Scale Modeling) in climate mode (referred to as COSMO-CLM) at kilometer-scale resolution (Baldauf et al., 2011). The setup is close to previous studies (e.g. Ban et al., 2014; Keller et al., 2016) and convection-resolving simulations in numerical weather prediction (NWP) mode at MeteoSwiss (e.g. Weusthoff et al., 2010). For this study, CPM simulations (at a grid spacing of 12 km) and CRM simulations (at a grid spacing of 2.2 km) are conducted, following the setup of Keller et al. (2016). The CPM simulations are conducted over Europe and initialized and driven by ERA interim, with the exception of initial soil moisture conditions, which are taken from a ten-year climate run of Ban et al. (2014). The CRM simulations are conducted over an extended Alpine area and are initialized and driven by the CPM simulations. All ~~CPM~~ simulations use a one-moment microphysics scheme (1M) (Reinhardt and Seifert, 2006)~~, while for the CRM simulations both the 1M or a two-moment microphysics scheme (2M) (Seifert and Beheng, 2006) are employed~~. The only significant difference to the setup of Keller et al. (2016) is that both CRM and CPM simulations use the same root depth. The root depth defines the lowest level from which plants can take water and use for transpiration (Doms et al., 2011). The

Table 1. Overview and specifications of the simulations analyzed in this paper.

Name	Spatial resolution	Convection scheme	Initial and boundary scheme	Initial date conditions	Domain (see Fig. 1a)
CTRL_12km	12 km	shallow and deep	ERA interim[a]	1 Oct 2006, 00 UTC	Europe
CTRL_2km	2.2 km	shallow	CTRL_12km	1 Apr 2007, 00 UTC	Alpine region
HW_12km	12 km	shallow and deep	ERA interim[a] + HW	1 Oct 2006, 00 UTC	Europe
HW_2km	2.2 km	shallow	HW_12km	1 Apr 2007, 00 UTC	Alpine region
VW_12km	12 km	shallow and deep	ERA interim[a] + VW	1 Oct 2006, 00 UTC	Europe
VW_2km	2.2 km	shallow	VW_12km	1 Apr 2007, 00 UTC	Alpine region

[a]Soil moisture for initial conditions is from a ten-year climate run of Ban et al. (2014).

analysis is performed over the CRM domain (Fig. 1a) for all simulations. ~~Further information about the setup used for the 2M can be found in Keller (2016, Sect. 2.1.1).~~

In addition to the control (CTRL) simulations mentioned above, six surrogate simulations are conducted. Within these surrogate simulations, two different ways of surrogate warming are applied: a homogeneous warming (HW) and a vertically-dependent warming (VW) (Fig. 1b). The specifications of all simulations are summarized in Table 1. Schär et al. (1996) showed that for a pressure-dependent but spatially independent temperature change $\Delta T(p)$, the same flow fields satisfy the hydrostatic set of governing equations. As the model levels of COSMO are not expressed in pressure coordinates, a height-dependent change $\Delta T(z)$ is specified for simplicity, but the resulting change in the mass balance is negligible.

In applying the methodology, we follow ~~?~~Kröner et al. (2017): For calculating the temperature difference profiles ΔT of HW and $\Delta T(z)$ of VW, one of the core simulations of the CMIP5 project (Taylor et al., 2012) was used. The simulation follows the RCP 8.5 scenario (representative concentration pathways) (Moss et al., 2010). This scenario represents a relatively high greenhouse gas emissions pathway with an expected radiative forcing of 8.5 W m^{-2} at the end of the century (Riahi et al., 2011). This high emission scenario was chosen for this study to amplify potential differences between present and future climates. The simulation chosen for this study is from the Max Planck Institute (MPI). It was calculated with an earth system model (ESM), which couples an atmospheric model with an ocean model and a vegetation model. The atmospheric part of the model is the ECHAM6 model (Stevens et al., 2013), which includes a carbon cycle model, and has a "low" vertical resolution (LR, 47 layers). The full model is called MPI-ESM-LR (Giorgetta et al., 2013). The HW and VW profiles were calculated by ~~masking the EURO-CORDEX domain (Jacob et al., 2014) in the~~ averaging MPI-ESM-LR ~~simulation~~ (ensemble member r1i1p1) over the EURO-CORDEX domain (Jacob et al., 2014). This domain is slightly larger than the area of the 12 km simulations of this study. For the profiles, a mean annual cycle of the difference between the spatially averaged 30-year means of 1971 to 2000 and 2070 to 2099 was ~~taken~~considered. This annual cycle was smoothed ~~following~~ using the spectral smoothing method of Bosshard et al. (2011). The resulting ~~time-~~ time and height-dependent profile was taken for VW. For the profile of HW, the temperature values at 850 hPa were applied over the full height. The SST change signal is equal to the ΔT change signal of the lowest atmospheric level, which neglects a possible change in the land-sea temperature contrast.

For comparison to ~~the~~ observations, cloud top pressure (CTP) and cloud optical thickness (COT) are calculated after the methodology used in Keller et al. (2016). ~~Outgoing~~ The other variables analyzed, e.g. outgoing longwave radiation (OLR) and reflected solar radiation (RSR), are standard outputs of COSMO.

2.2 ~~Calculation of scaling rate~~

~~In Section 3.2, the scaling rate (SR) for different percentiles (p) is calculated as:~~

$$SR^s(p) = \frac{P^s(p) - P^c(p)}{P^c(p) \cdot \Delta T}$$

~~where P is hourly accumulated precipitation, s the surrogate warming simulation, c the corresponding control simulation, and ΔT the spatially and temporally averaged change in 2 m temperature between s and c.~~

~~The percentiles are calculated using both wet and dry events following Ban et al. (2015) and Schär et al. (2016). Before calculating the percentiles, data is pooled over the full analysis domain. This step differs from the method used in Ban et al. (2015). In their study, the calculation of the percentiles and the normalization by temperature was done for every grid point before averaging. With their method, the statistics are calculated for all grid points, independently of their spatial climatology, while with pooling the data of some region is treated as one sample. The method with pooling was chosen in this study, due to the small dataset (11-day period).~~

2.2 Observations

Precipitation data

For this study, the gridded precipitation dataset EURO4M-APGD (Isotta and Frei, 2013) is employed, which is based on rain-gauge measurements across the European Alps and adjacent areas (Isotta et al., 2014). EURO4M is a collaborative project of the European Union. The dataset has a daily temporal and 5 km spatial resolution. Known limitations of this product are an underestimation of high precipitation intensities and an overestimation of low precipitation intensities (Isotta et al., 2014).

Satellite data

Cloud properties of the Cloud_cci MODIS-Aqua dataset (Stengel et al., 2017) are used in our study, i.e. Level-3U data which contains unaveraged, pixel-based retrievals sampled on a regular longitude-latitude grid with a resolution of 0.02° covering Europe. The scientific content of these data is described in Stengel (in prep.). Cloud variables used in our study are cloud top pressure (CTP) and cloud optical thickness (COT). As the actual cloud detection value (cloudy or clear) comes with an uncertainty estimate on pixel level, we used the latter to only collect CTP and COT for pixels with a low uncertainty in cloud detection. We rejected all cloudy pixels for which the detection uncertainty exceeded 35 %. This value is somewhat arbitrary but mainly based on ~~analysing~~ analyzing the relative frequency of cloud detection uncertainty which yielded ~~in~~ a bimodal distribution when including all cloudy pixels, with 35 % being approximately the value separating the more certain from the more uncertain clouds. It needs to be noted that the omitted, more uncertain cloudy pixels are associated with mostly high CTPs, thus low-level clouds. This potentially biases the ~~used satellite data~~ satellite data used and needs to be kept in mind for the comparison ~~later on~~with model data. All satellite data outside the analysis domain (Fig. 1a) is omitted. Model equivalent CTP and COT values are selected from model ~~time steps~~ at 13 UTC to match the Aqua satellite overpass time of approximately 1:30 pm (local time).

The Geostationary Earth Radiation Budget (GERB) radiometer is onboard the Meteosat Second Generation (MSG) satellites. These satellites are geostationary, enabling a temporal resolution of 15 min. Outgoing longwave radiation (OLR) and reflected solar radiation (RSR) data are used in this study, which was produced at the Royal Meteorological Institute of Belgium (RMIB) (Dewitte et al., 2008) after the methodology of Harries et al. (2005), who state an error of < 1 % for both products. The spatial resolution of 9x9 km^2 at the sub-satellite point at the equator becomes approximately 12x18 km^2 over the Alps (cf. EUMETSAT, 2013).

3 Results

Our study period is ~~from~~ June 3 to 13~~June~~, 2007, which was characterized by a pronounced diurnal cycle of convection over the Alps and surrounding areas with a maximum of precipitation and high cloud cover in the afternoon (Keller et al., 2016). This synoptic situation makes the time period ideal to study the diurnal cycle of convection under relatively undisturbed conditions. The changes in this diurnal cycle due to surrogate climate change are investigated in this section. First, differences between the introduced temperature profiles at the lateral boundaries (Fig. 1b) and the resulting profiles inside the domain are studied. Second, the impact of the surrogate warming on precipitation and clouds is investigated for the two horizontal resolutions.

We are aware that an 11-day period is very short from a climatological perspective. ~~But we consider this as a process-oriented study. Here, important parameters such~~ However, as the large-scale flow ~~are constrained , therefore~~ is constrained the internal variability becomes smaller than in classical climate studies and shorter periods can be investigated. The advantage of the surrogate approach in this case is that ~~while classical climate studies average over changes in processes and synoptic conditions with the warmer climate,~~ we can investigate ~~here~~ changes in the diurnal cycle of convection under the same synoptic condition, while conventional climate studies require averages over extended periods with different synoptic conditions to ensure an appropriate sampling.

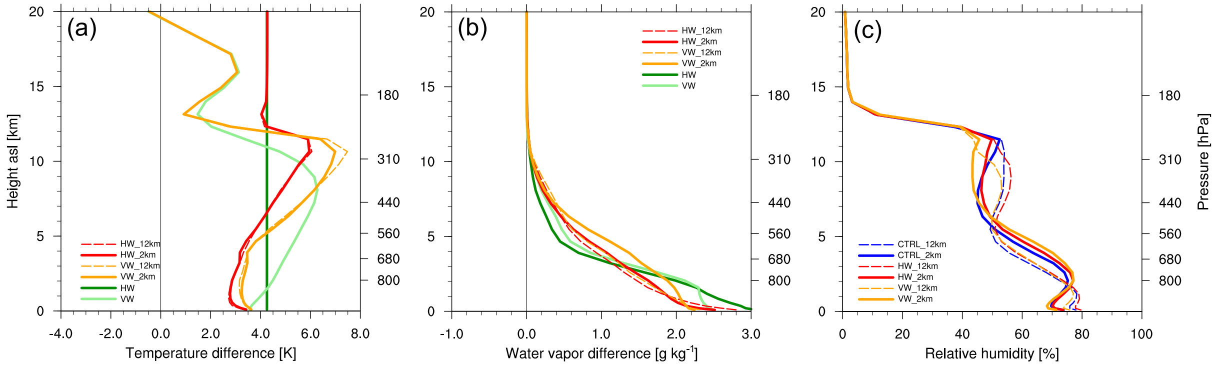

Figure 2. Vertical profiles, averaged spatially inside the analysis domain and over all hours from 3 to 13 June 2007~~of~~ , with respect to the control simulations. (a~~,b~~) ~~temperature difference inside the analysis domain~~ Temperature differences of HW (red) and VW (orange) simulations~~with respect to the control simulations~~, and at the lateral boundaries of the CPM simulations ~~domain~~ (green~~, same as Fig. 1b~~), (~~c,d~~b) same but for specific humidity~~difference inside the analysis domain of HW and VW simulations with respect to the control simulations~~, and ~~at the lateral boundaries of the CPM simulations domain, and~~ (~~e,f~~c) same but for relative humidity ~~of~~ for all ~~nine~~ six simulations (control in blue). Dashed lines indicate ~~12km1M~~ 12 km runs ~~(left column),~~ and solid lines ~~2km1M~~ 2 km runs ~~(both columns), and dotted lines 2km2M runs (right column)~~. Height is indicated in km on the left side and in hPa on the right side of every graph.

3.1 Vertical temperature and humidity profiles

~~Figs~~Fig. 2a ~~and b show~~ shows the differences of HW and VW with respect to control (CTRL) of the spatially and temporally averaged temperature profiles inside the analysis domain ~~from hourly data~~ during the 11-day period. Differences are taken ~~between the 12km1M runs (Fig. 2a), the 2km1M runs (Figs. 2a, b), and the 2km2M runs (Fig. 2b).~~ for the 12 km and 2 km runs . The differences imposed at the CPM-boundaries are indicated in dark green (HW) and light green (VW). Overall, the profiles of ~~all three HW runs and of all three VW runsare comparable, with the smallest differences due to different microphysics schemes~~the two HW and the two VW runs, respectively, resemble each other. This indicates similar surrogate conditions for ~~all HW and all VW simulations~~the two HW and VW simulations, respectively. Below 4.5 km, the profiles of HW and VW are quite similar, despite the large differences in the initial profiles. From 4.5 to 11 km, the ~~difference~~ differences between HW and VW ~~increases~~increase, and for all VW profiles an enhanced warming with height is found. Above 11 km, the profiles approximate the lateral boundary profiles (green) with height, since temperature is relaxed to the driving model toward the upper boundary. In comparison to the lateral boundary profiles, a cooling is found below 6.5 km for HW and below 8.5 km for VW. Above these heights and below 12 km, the atmosphere becomes warmer than the originally introduced warming. ~~We assume that the redistribution of temperatures in the model domain compared to the boundaries is~~ The vertical redistribution of temperature, in comparison to the prescribed boundaries, must largely be caused by convection ~~. The transformation of the initial HW-profile (dark green) to profiles (red) that are similar to the initial VW-profile (light green) indicates that the VW experiment is closer to the model equilibrium than HW for this period.~~ and boundary layer processes.

Vertical profiles of specific humidity differences ~~in the analysis domain and at the lateral CPM-boundaries~~ are shown in ~~Figs~~Fig. 2~~c and d~~b. These differences are positive, as expected. Similar to temperature, a decrease is found compared to the initial profiles (green) below a certain height, and an increase above this height. Here, this height is at about 3 km and a little bit lower than with temperature~~, at 3 km. Also in this case, the difference due to different microphysics schemes is smaller than between the CPM and the CRM runs.~~ .

Vertical profiles of relative humidity are shown in ~~Figs~~Fig. 2~~e and f. The strongest differences are again found between the CPM and the CRM runs~~c. One can notice that the biggest difference is not between CTRL, HW and VW but between the 2 resolutions. Further, VW has lower values than HW between 6 and 12 km, where water vapor content is similar to HW but temperatures are higher.

3.2 Precipitation

Before investigating vertical structures of wind and clouds, we document the impact of the surrogate climate change on precipitation, a key component of the hydrological cycle and indicator of convective activity. To give an overview, the spatial distribution of total accumulated precipitation for the 11-day period is shown in Fig. 3, for the observations and the ~~nine~~ six simulations. The observations are limited to a region of the European Alps and adjacent areas. Maxima of accumulated observed precipitation are mainly found in the western part of the domain. In the control simulations, precipitation to the ~~north-east~~ east of the Alps is overestimated, in particular in CTRL_~~12km1M~~12km. For all CRM runs, more fine-scale structures are found than for the CPM runs. ~~For HW and VW, areas with values larger than 140 mm increase compared to control, which indicates an increase of heavy precipitation events.~~

The mean diurnal cycle of precipitation, is shown in Fig. 4. Large differences are found between the ~~12km1M and 2km1M~~ 12 km and 2 km runs, such as a time shift of three hours ~~(Fig. 4a).~~ . This is in line with previous work (e.g. Langhans et al., 2013) more detail on possible reasons can be found in (e.g. Fosser et al., 2015). A validation of the diurnal cycle of precipitation against surface observations can be found in Keller et al. (2016, see Fig. 11a). ~~The diurnal cycles of the 2km2M runs are much closer to the 2km1M runs (Fig. 4b)than the 12km1M runs. This similarity in precipitation response between 1M and 2M for the control simulations has already been seen in Keller et al. (2016) and is now also observed in the surrogate warming experiments.~~ The mean precipitation amount of the CPM simulations increases ~~with~~ by +~~14.5 % and +3.4~~9.7 % for HW and decreases by -6.9 % for ~~HW and~~ VW, respectively (Table 2). These changes are twice as large as ~~the changes found in ?~~ for HW than those found in Kröner et al. (2017) in 30 years of summer climate. This difference is not surprising as our study focuses on a specific weather situation with a pronounced diurnal cycle of convection and not on ~~climate means~~the mean summer climate. Of larger interest are the differences between 12 km and 2 km simulations. ~~Indeed, in comparison to 12 km, the mean response to HW and VW are much smaller lower (or even negative) in~~ The signs of the changes are the same for the 2 km ~~, both for the 1M and 2M simulations. Both VW surrogate runs even exhibit a decrease in precipitation amount compared to control~~ simulations, with increasing precipitation in HW and decreasing precipitation VW (Table 2)~~, whereas the corresponding~~ . Fig. 4a is showing that in the 12 km ~~run shows an increase. In contrast to these our simulations, Ban et al. (2015)~~ HW case precipitation is increasing during most of the day, whereas in the 2km simulation precipitation is mainly increasing during the

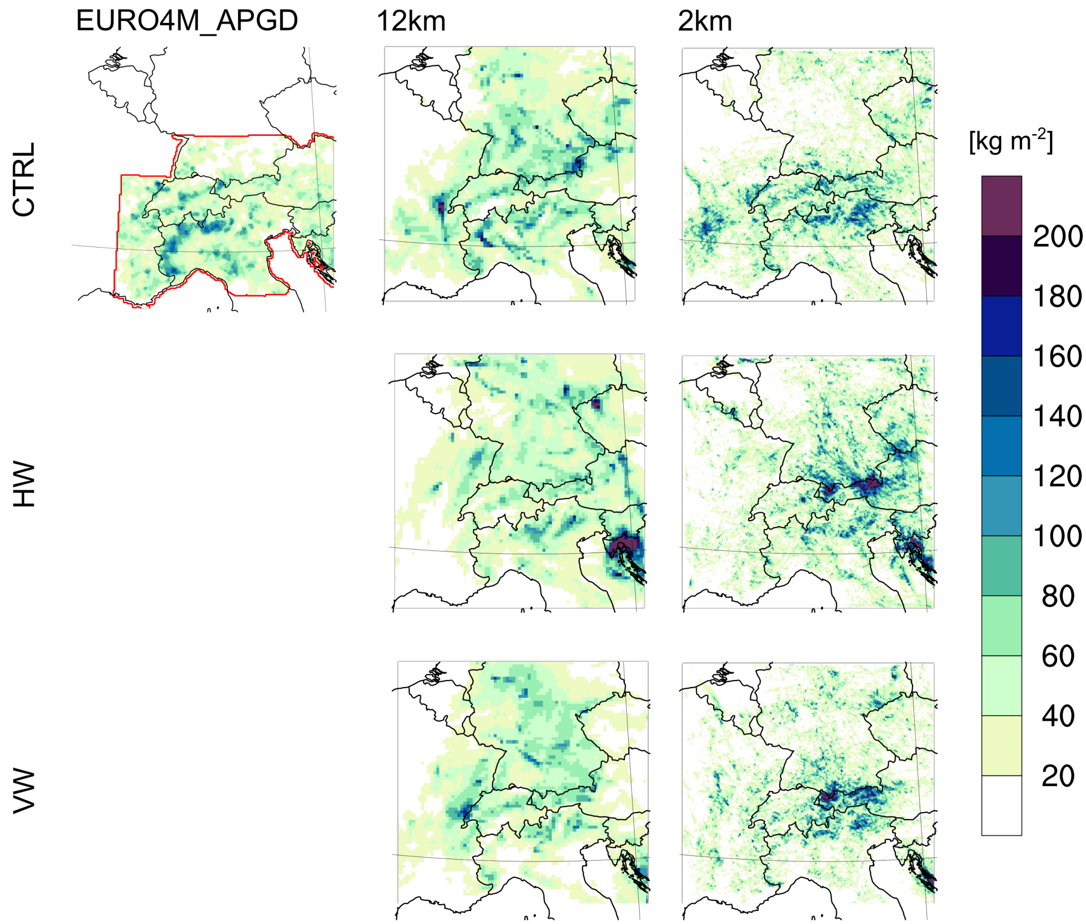

Figure 3. Total accumulated precipitation for 3 to 13 June 2007 over the analysis domain for observations EURO4M-APGD and ~~nine~~ six simulations. The area ~~of observation~~ with observations is smaller than the model domain and the border is indicated in red. The upper row shows observations and ~~three~~ two simulations for the present climate (CTRL), the middle row the ~~three~~ two HW simulations, and the lower row the ~~three~~ two VW simulations.

night but not during the day. In comparison to HW, VW shows decreasing precipitation below the amounts of CTRL although the air is much warmer and contains more moisture than in CTRL. This emphasizes the importance of the stratification effect included in VW, which is stabilizing the atmosphere and suppressing convection. The precipitation changes for VW are in line with previous studies using full climate change scenarios, which also found a decrease in mean summer precipitation for ~~CPM and CRM simulations. We attribute this reduction decrease to circulation changes with the warmer climate in their simulations, following the arguments of ?~~the same area studied here (Ban et al., 2015).

So far, total accumulated precipitation and the mean diurnal cycle have been investigated. Next, hourly precipitation intensities are analyzed. In ~~Figs. ??a and b ,~~ Fig. 4b shows the frequency of grid points and hours with precipitation exceeding a certain threshold~~is shown~~. Different dependencies are found for higher and lower thresholds. ~~Intensities with thresholds >45~~At

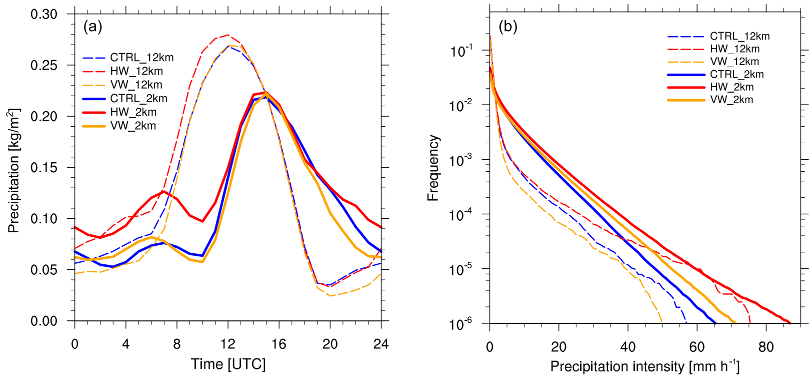

Figure 4. (a) Spatially and temporally averaged diurnal cycles of precipitation for 3 to 13 June 2007 (~~a~~b) Frequency of hourly precipitation intensity for 3 to 13 June 2007 for the three ~~12km1M~~ 12 km runs (dashed lines) and three ~~2km1M~~ 2 km runs (solid lines)~~, and (b) for the three 2km1M runs (solid lines) and three 2km2M runs (dotted lines)~~. Control runs are indicated in blue, HW runs in red, and VW runs in orange.

Table 2. Relative changes in total accumulated precipitation with surrogate warming compared to control in %. The calculations consider spatial means over the analysis domain accumulated for 3 to 13 June 2007.

	~~12km1M~~ 12km	~~2km1M 2km2M~~ 2km
HW	~~14.5~~ 9.7	~~1.8 6.2~~ 18.4
VW	~~3.4~~ -6.9	~~-11.4 -5.2~~ -4.5

low intensities between 5 mm h^{-1} ~~depend mainly on the atmospheric conditions (CTRL, HW, or VW) and the choice of the microphysics scheme (1M or 2M), but intensities with thresholds <25~~and 35 mm h^{-1}~~depend mainly on the convection setup (parameterized or resolved) and the resolution (~~, the simulations depend strongly upon resolution (2 vs 12 km~~or~~) whereas at higher intensities >35 mm h^{-1} the atmospheric condition (CTRL, HW, VW) become important. For HW the 12 km and 2 ~~km) .~~

~~The 99.99th percentiles of the relative changes of hourly accumulated precipitation with respect to control, normalized by the averaged 2 m temperature change, for 3 to 13 June 2007. The relative change is called scaling rate (SR) and indicated in % K^{-1}. 12km1M 2km1M 2km2M HW 10.0 4.0 3.9 VW 7.7 2.4 3.5~~

~~(a,b) Frequency of hourly accumulated precipitation intensity for 3 to 13 June 2007 for (a) three 12km1M runs (dashed lines) and three 2km1M runs (solid lines), and (b) the three 2km1M runs (solid lines) and three 2km2M runs (dotted lines). (c,d) SR, as a function of percentile, in % K^{-1}. Control runs are indicated in blue, HW runs in red, and VW runs in orange. The gray lines in (c) and (d) indicate the expected upper limit (6–7 % K^{-1}) according to the Clausius-Clapeyron relation.~~

~~The relative change of hourly accumulated precipitation intensities , normalized by the spatially and temporally averaged 2 m temperature change, is called scaling rate (SR) and investigated next (Table ??, Figs. ??c, d, see Sect. ??) . For~~ km simulations are very close together and exhibit an increase in the incidence of heavy events. Interestingly for the VW simulations the ~~CPM~~

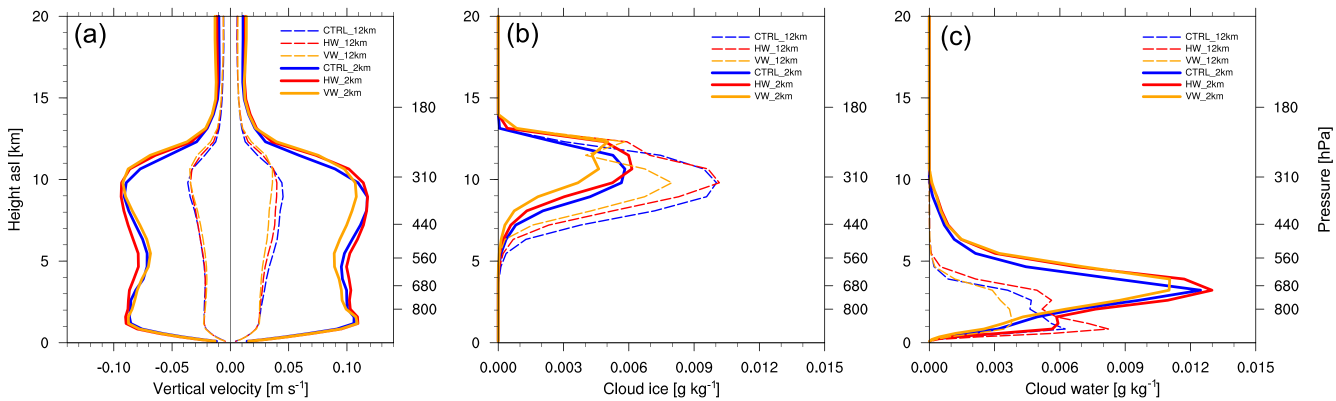

Figure 5. Vertical profiles of (a~~,b~~) grid-scale vertical velocity~~and (c~~, ~~d~~(b) cloud ice content and (~~q_i~~c) ~~and~~ cloud water content ~~(q_c) from nine~~ for six simulations, averaged horizontally over the ~~full~~ analysis domain and temporally over all hours from 3 to 13 June 2007. Control runs are indicated in blue, HW runs in red, VW runs in orange, ~~12km1M~~ 12 km runs with dashed lines ~~(left column), 2km1M~~ and 2 km runs with solid lines ~~(both columns), and 2km2M runs with dotted lines (right column)~~. Vertical velocity is ~~divided~~ separated into averages of negative and positive values. Height is indicated in km on the ~~left~~ left-hand side and in hPa on the ~~right~~ right-hand side of every graph.

~~simulations , the increase in extreme precipitation intensities converges with increasing percentiles to values above 7 % K^{-1} (Table **??**, Fig. **??**c), which is consistent with findings of previous studies (Lenderink and Van Meijgaard, 2008; Kendon et al., 2014). According to the Clausius-Clapeyron relation, values below 6–7 % K^{-1} would be expected (e.g. Allen and Ingram, 2002). Indeed, for the CRM simulations , independent of the microphysics scheme, values below the upper limit of Clausius-Clapeyron are found. These differences between 12km1M and 2km1M are similar to findings of Ban et al. (2015) for their comparison of 10 years simulated summer climate. They also found an increase above the Clausius-Claperyron relation for the CPM simulation and below for the CRM simulation~~resolution plays an important role, with the 12 km simulation showing a reduction of heavy events, and the 2 km simulation an increase.

3.3 Vertical profiles and clouds

In the following, the formation of clouds is investigated. In ~~Figs~~Fig. 5a~~and b~~, vertical profiles of grid-scale vertical velocity are shown, which are split into averages over the negative and positive components. Mean upward motion is slightly larger than mean downward motion, but the values are comparable for the two sets of simulations (12 and 2 km). In Fig. 5a, large differences are found between CPM and CRM simulations. This is because for CPM, ~~a part of the vertical transport is calculated~~ the vertical redistribution of energy and moisture is accomplished inside the convection scheme, and not represented by the grid-scale vertical wind component~~used for this analysis~~. Apart from this difference, the values for all CPM simulations, and all CRM simulations, are comparable. ~~Below 10 km, the lowest values are~~ The most pronounced difference is found for VW ~~. Above~~ below near the positive maximum near 10 km, ~~higher values are found for HW and VW than for control with the highest values for VW. In Fig. 5b, similar results are found for all 2 km simulations. In more detail, grid-scale vertical velocity~~

~~is larger for 2km2M than 2km1M above 1500 m height. This result differs from the results of~~ where mean vertical motion is slightly weaker.

Fig. ~~??b where more heavy precipitation events for 2km1M than 2km2M were found. But in contrast to Fig. ??b, only mean values are shown in Fig. 5b . In comparison to mean precipitation amounts (Table 2), the increased values for 2km2M are not surprising.~~

~~Figs. 5c and d show~~ 5b shows vertical profiles of grid-scale cloud water (q_c) and Fig. 5c of cloud ice (q_i) content. ~~For 12km1M, higher values are found~~ In comparison to the 2 km simulations, the 12 km simulations show systematically higher values for q_i~~than~~, and lower values for q_c. ~~For 2km1M and 2km2M, the situation is opposite. The largest difference between 2km1M and 2km2M is found with the vertical distribution of q_i. Due to ice sedimentation, q_i is also found at lower altitudes for 2km2M~~Also in the 2 km simulations the vertical overlap between q_i and q_c is increased. A more detailed discussion of this effect can be found in Keller et al. (2016). Figure 5b also allows to assess the effects of thermodynamic and lapse-rate changes. Overall it is evident that differences due the atmospheric conditions are weaker than differences due to resolution. For all simulations, the amounts of q_i and q_c are similar for ~~control and HWbut reduced for VW. The highest values of q_c are found for HW with 1M and for CTRL with 2M. Further, HW and VW have higher values above the peaks than control~~CTRL and HW. The amounts for VW are reduced especially for q_i. This is the case for both the 12 km and 2 km simulations. The reduction in q_i and q_c for the VW simulations is in line with the precipitation decrease shown in table 2 . Note that ~~subgrid~~ subgrid-scale clouds are not considered in the calculation of q_c and q_i.

The influence of ~~the surrogate climate change~~ thermodynamic and lapse-rate changes on clouds (including ~~subgrid~~ subgrid-scale clouds) is also investigated with two-dimensional histograms of cloud optical thickness (COT) and cloud top pressure (CTP) at 13 UTC (cf. Keller et al., 2016). These histograms define several cloud types. After Rossow and Schiffer (1999), high, middle, and low clouds are distinguished at 440 and 680 hPa, and thin, middle, and thick clouds at 3.6 and 23 COT. In Fig. 6, a positive bias in high clouds and a negative bias in mid-level clouds are found for CTRL_~~12km1M~~ 12km and CTRL_~~2km1M~~ 2km compared to the observations. ~~For CTRL_2km2M, the bias in high cloud occurence is small and differences are mainly found regarding the thicknesses of these clouds. For the mid-level clouds, the bias of CTRL_2km2M is similar to the bias of CTRL_2km1M.~~ The negative bias in mid-level clouds coincides with the low values of q_c and q_i around 6 km height in Figs. 5~~c and d~~b and c. Note that the histogram ~~,~~calculated from observational satellite data, shows some differences with respect to a previously published version (Keller et al., 2016). This is partly due to the use of raw data from a different satellite sensor, but mainly due to a revised algorithm to produce the dataset (version 2.0 versus version 1.0).

Between control and HW, only small differences are found, but a substantial reduction in high clouds is found for VW. Therefore, the thermodynamic effect (CTRL to HW) is small in this case, but the ~~lapse rate~~ lapse-rate effect (HW to VW) is large. The strong similarity between CTRL and HW is a surprising result, since higher amounts and intensities in precipitation were found for HW than for control. The reduction of high clouds in VW cannot be explained completely with the reduction of vertical velocity for heights below 310 hPa (~~Figs~~Fig. 5a~~, b~~) because this reduction is very small. Moreover higher vertical velocity is found above this height compared to control. But the reduced relative humidity, found for VW compared to control and HW at these heights (~~Figs~~Fig. 2~~e, f~~c) due to higher temperatures (~~Figs~~Fig. 2a~~, b~~) and similar specific humidity (~~Figs~~Fig. 2~~e,~~

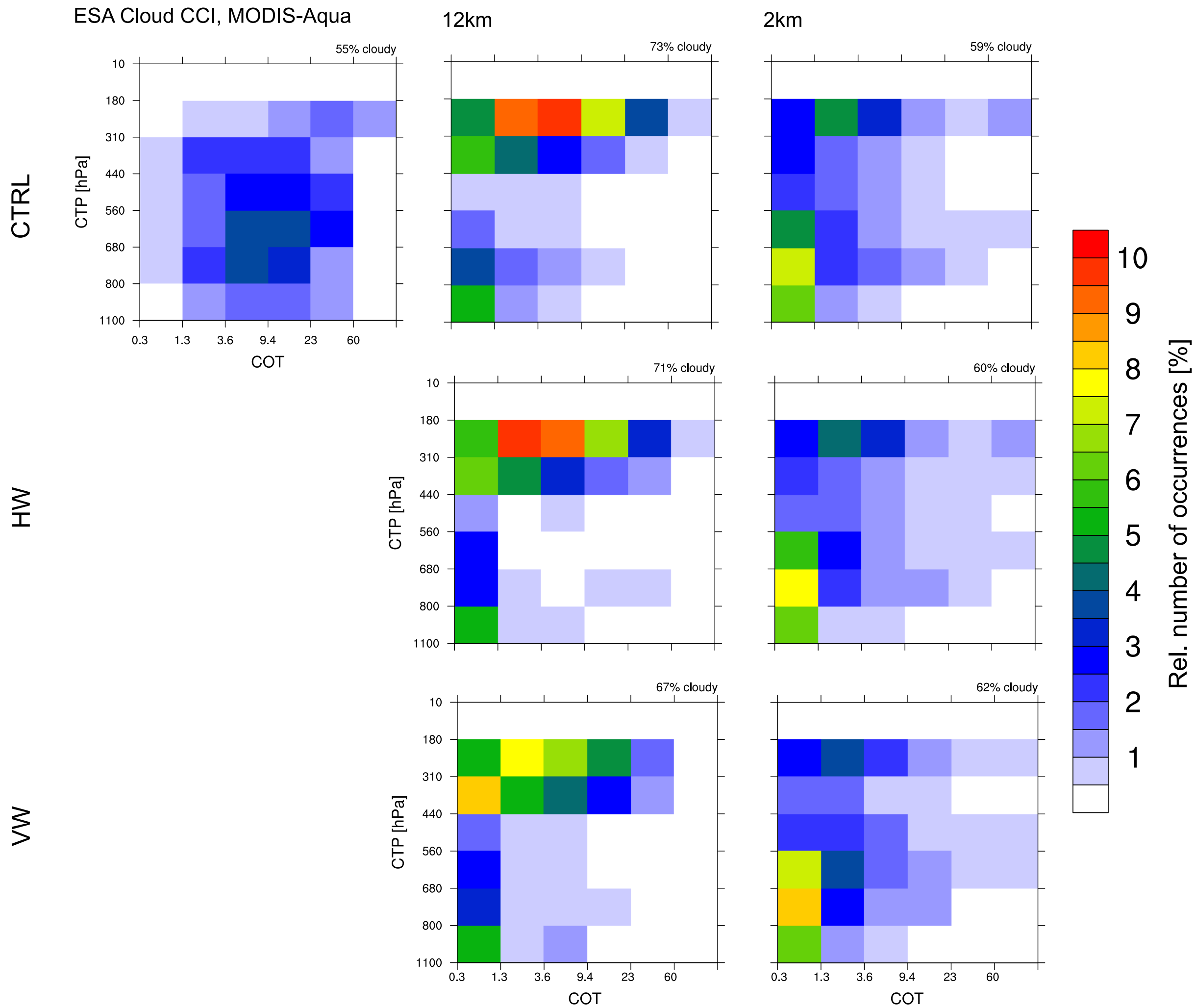

Figure 6. Histograms of cloud frequency as a function of cloud optical thickness (COT) and cloud top pressure (CTP) arranged as ~~for~~ in Fig. 3 but ~~as an average~~ showing averages at 13 UTC (for ~~the models~~each model) over the period of 3 to 13 June 2007. For ~~observation~~the observations, the average is ~~over local~~ taken the time of the Aqua satellite passage (approx. 01:30 pm). Fractional cloud cover (defined by COT $>$ 0.3) is indicated in the right upper corner of all panels.

~~d~~b), may explain the reduced ~~high cloud frequency~~ frequency of high clouds. We assume that the similar amounts of specific humidity of HW and VW close to the ground, where most water vapor is found, lead to similar absolute water content in convective updrafts of both cases but in VW convective condensation is reduced due to the higher temperatures at higher levels.

The diurnal cycles of cloud cover and ground temperature impact outgoing longwave radiation (OLR) (~~Figs~~Fig. 7a~~, b~~). While ground temperature has its minimum in the morning, cold cloud tops are mainly present during the afternoon in ~~this~~ the

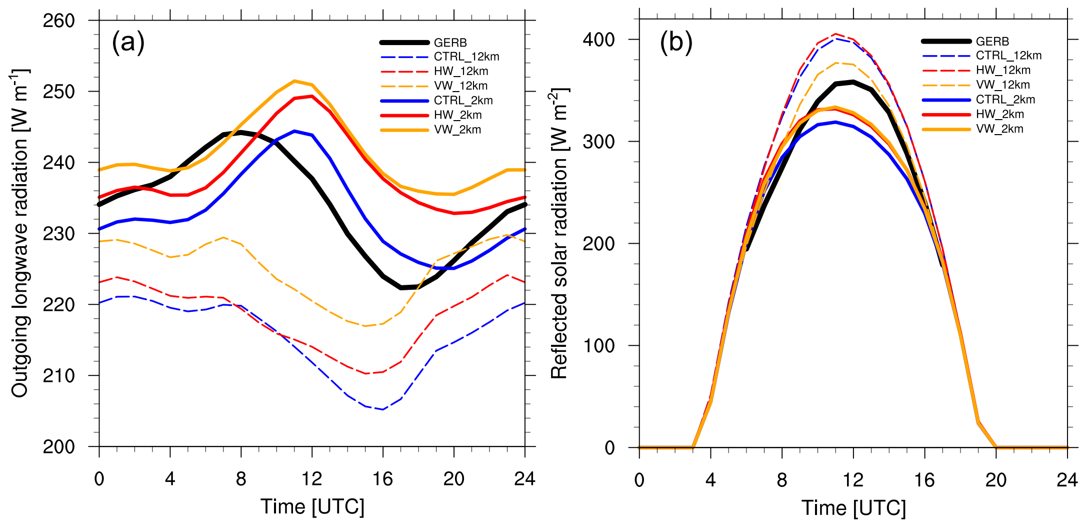

Figure 7. Spatially and temporally averaged diurnal cycles of top of the atmosphere (a~~,b~~) outgoing longwave radiation (OLR) and (~~c,d~~b) reflected solar radiation (RSR) for observations from GERB and ~~nine~~ six simulations for 3 to 13 June 2007. Observations are indicated in black, control runs in blue, HW runs in red, VW runs in orange, ~~12km1M~~ 12 km runs with dashed lines~~(left column)~~, ~~2km1M runs~~ and 2 km runs as well as observations with solid lines~~(both columns), and 2km2M runs with dotted lines (right column)~~.

convective period. The minimum of OLR in the afternoon is expected to be some hours later than the maximum of precipitation~~since clouds are faster formed~~, since clouds form faster than they dissipate. The maximum in OLR for noon is caused by rising ground temperatures during day until around 12 UTC enough convective clouds are formed which decrease OLR again. Negative mean biases for CTRL_~~12km1M~~ 12km and CTRL_~~2km1M, a slightly positive mean bias for CTRL_2km2M, and a~~ 2km as well as a delay in the diurnal cycles ~~of all control simulations~~ are found compared to the observations, but the overall bias is much larger for CTRL_12km. The timing of OLR stays the same with the surrogate runs, which indicates a similar timing in the diurnal cycle of clouds. ~~The~~ Large OLR mean values compared to control are seen for the surrogate runs which have several reasons: (1) warmer cloud temperatures due to the increased surrounding air temperatures~~and the~~, (2) warmer ground temperatures~~of HW and VW, and further the~~, and (3) a reduction of high cloud cover for VW~~lead to larger OLR mean values than for control~~. Reflected solar radiation (RSR) is mainly impacted by changes in cloud cover (Figs. 7~~c, d~~b). It is underestimated in CTRL_~~2km1M and CTRL_2km2M~~ 2km but overestimated in CTRL_~~12km1M~~12km. In addition, all control simulations show a too early peak, which corresponds to the ~~OLR-minima~~ OLR minima in the morning. With the surrogate simulations, the diurnal cycles do not change in timing but in amplitude, particularly for VW_~~12km1M~~ 12km due to the reduced cloud cover.

For the energy budget at the top of the atmosphere (ToA), consisting of the sum of OLR and RSR, rather small changes are found for HW_~~12km1M~~ 12km and VW_~~12km1M~~ 12km compared to CTRL_~~12km1M with 4.0 and –0.8~~12km with 3.8 and –2.0 W m^{-2}, respectively. For HW_~~2km1M~~ 2km and VW_~~2km1M~~ 2km compared to CTRL_~~2km1M~~2km, much larger changes are found with ~~11.8 and 14.0~~11.1 and 13.1 W m^{-2}, respectively. ~~For HW_2km2M and VW_2km2M compared to~~

Table 3. Changes in the ToA energy budget (OLR + RSR) with surrogate warming compared to control in W m^{-2}.

	~~12km1M~~ 12km	~~2km1M~~ ~~2km2M~~ 2km
HW	~~4.0~~ 3.8	~~11.8~~ ~~9.9~~ 11.1
VW	~~-0.8~~ -2.0	~~14.0~~ ~~10.8~~ 13.1

~~CTRL_2km2M, the situation is similar to 2km1M with 9.9 and 10.8 W m^{-2}, respectively.~~ These values of the ToA energy budget are summarized in Table 3. Therefore, the CPM runs suggest that the surrogate warming has no or only a small impact on the ToA energy budget during this period. In contrast, the CRM runs suggest a much larger increase in outgoing energy fluxes, and therefore a cooling of the heated atmosphere. These differences are crucial, as they ~~will~~ would influence the results of long-term climate simulations.

4 Conclusions

The impact of surrogate climate change on precipitation and clouds has been investigated for an 11-day period with a pronounced diurnal cycle of convection. Two different warming scenarios are considered: a homogenous warming (HW) and a vertically-dependent warming (VW) with an increase in mid-tropospheric stratification (lapse-rate). The surrogate approach has been successfully applied to convection-resolving model (CRM) simulations. The CRM simulations at 2.2 km resolution are complemented by convection-parameterizing model (CPM) simulations at 12 km resolution. ~~These simulations use a one-moment microphysics scheme (1M), while the CRM simulations are also available with a two-moment microphysics scheme (2M). The 2M is used due to the positive impact of its ice sedimentation on the high cloud cover bias, which was found in Keller et al. (2016).~~ To our knowledge, this is the first application of the surrogate approach for Alpine summer climate using CRM simulations. Note that the VW simulations are more representative to the full climate change signal, and will below be compared against conventional climate change simulations.

~~For the CRM simulations , an increase in hourly heavy precipitation events is found for both surrogate warming experiments (HWand VW) compared to control, independent of the microphysics scheme. These increases are consistent with~~ The differences between the CTRL simulations at 12 and 2 km resolution are generally consistent with previous studies. In particular, the mean diurnal cycle of precipitation is strongly affected by the horizontal resolution, with the 2 km convection-resolving simulation producing a more realistic late-afternoon precipitation peak. Also the distributions of hourly precipitation are very different, with the 2 km simulation producing less drizzle and more intense events.

In comparison to these differences, the thermodynamic (HW) and the ~~Clausius-Clapeyron relation. In contrast, the CPM simulations exhibit a stronger~~ lapse-rate changes (VW) have comparatively small effects on the diurnal cycle of precipitation. However, mean precipitation shows consistent changes for both resolutions, with precipitation increasing for HW, and decreasing for VW, respectively. Already Kröner et al. (2017) found a strong influence of stratification changes on precipitation, but their finding was not as clear because they could not discriminate between convective and other types of precipitation. The decrease in precipitation is also seen in full climate change studies over the same area (Ban et al., 2015). The decreases of mean precipitation in climate change projections over Central and Southern Europe are often attributed to large-scale circulation changes, like an expansion of the Hadley Cell (Seager et al., 2014). The current study highlights the role of externally driven stratification changes. Conventional climate change simulations also show an increase in heavy ~~precipitation events . This difference between CPM and CRM simulations has previously been noted in Ban et al. (2015)~~events (despite decreases in mean), which is also consistent with the results of the 2 km VW simulation.

The vertical structure of the warming, represented by HW and VW, also has a significant impact on the clouds ~~of~~ associated with the diurnal cycle of convection. ~~For both microphysics schemes,~~ On one hand the clouds of HW experience virtually no change compared to control, apart from changes in their temperature. On the other hand, in VW the amount of high clouds ~~of VW is reduced, indicating a strong influence of the lapse rate on cloud cover~~is significantly reduced. This change in cloud cover is consistent with the role of the ~~lapse rate~~ lapse-rate for convection. ~~Despite these differences in cloud type frequencies between HW and VW, all four~~

We have also shown that for some variables the response to the warming depends on model resolution. An especially strong dependence was found for the energy budget at the top of the atmosphere. Both surrogate simulations with 2 km resolution ~~suggest~~ found a cooling effect ~~in the energy budget at~~ at the top of the atmosphere ~~with 9.9 to 14.0~~amounting to 11.1 and 13.1 W m^{-2} compared to control, and this represents a negative feedback on the regional warming. The corresponding ~~increases~~ changes in the energy budget of the 12 km simulations ~~are~~ were much smaller, and amount to merely between ~~-0.8 and 4~~ -2 and 3.8 W m^{-2}. This finding could have important consequences for long-term high-resolution climate change studies and merits further attention.

~~The results of the CPM simulationslargely coincide with manythe CRM results.~~ It should be mentioned that the surrogate method as used in the current study excludes circulation changes, and such changes will also contribute to future precipitation and cloud changes. Therefore our approach needs to be complemented by conventional climate change simulations.

However, the significant differences in the response to the HW and VW forcing between the two ~~setups, which are found,~~ resolutions also underline the importance to complement ~~CPM simulations with CRM simulations~~conventional climate scenario with convection-resolving simulations, although long-term simulations are computationally still very expensive.

~~Finally, there are large differences between CPM and CRM in terms of timing and amplitude of the diurnal cycle of precipitation, and regarding the occurrence of low precipitation intensities. Previous studies have shown that the CRM simulations generally validate better against observations. It is worth noting, however, that these differences are larger than the sensitivity of CTRL with respect to HW and VW.~~

5 Data availability

The Cloud_cci data is publicly accessible at www.esa-cloud-cci.org. The EURO4M-APGD data can be ordered from MeteoSwiss at dx.doi.org/10.18751/Climate/Griddata/APGD/1.0. The GERB data can be accessed after a registration is accepted at http://gerb.oma.be/ → "Data Access (ROLSS)" → "Register to the ROLSS mailing list". The model output from all the numerical simulations is stored on the Swiss National Supercomputing Centre (CSCS, Lugano) and available on request from the corresponding authors.

Competing interests. The authors declare that they have no conflict of interest.

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