Response to Anonymous referee #1

1 General remarks

First of all we wanted to thank you for taking your time to go through the manuscript in detail. Your contribution is very much appreciated. Before we proceed, we would like to clarify our intent of this study. The main purpose of the current manuscript is to show that the formation of cloud streets can be initiated with 3D radiative transfer alone. We want to stress that the first set of simulations that were conducted within this study are without any mean background wind or wind shear whatsoever. Of course, no wind at all is seldom the case in the atmosphere which leads naturally to the question how radiatively induced clouds streets compete or interact with dynamically induced organization. This second part of the study led to an interesting conclusion: While it was assumed that the radiative influence on the surface is smoothed by a horizontal wind, we find that the dynamical organization of clouds is capable to produce a static radiative pattern on the surface for an extended period of time, which in turn allows the radiation to change the flow.

We improved the manuscript to a) make the distinction between radiatively and dynamically aspects more clear and b) narrow down on the theory of cloud streets.

Answers to the specific comments are given below.

- *One of key aspect of the roll-type shallow convection is the presence of low-level shear associated with the Ekman boundary layer. This is really not mentioned in the introduction and I feel this is an essential omission. I think the shear explains the key impact of the mean wind as documented in Fig. 4. I have more points on that aspect in the specific comment section below, but a discussion of numerical studies (starting with Mason and Sykes QJ 1982, p. 801) as well as observational studies have to be brought in the revision (Weckwerth at el. is just mentioned in passing without any reference to the dynamics). There is also a wealth of theoretical studies on the stability of shear flows in unstable stratification focusing on the development of roll-type circulations, starting with Asai (JMSJ 1970, p. 129). I understand that the authors specialize in the radiative transfer and not in the atmospheric dynamics, but the poor treatment of the dynamical aspects needs to be corrected. My suggestion is the authors trace back citations to the papers listed above and provide an appropriate discussion on the*

role of boundary-layer shear in determining the organization. Overall, I feel the dynamics is the key, and radiation provides just a small (although quite interesting!) modification. But I feel that unequivocally separate the two is difficult.

Yes, literature separates the development of roll-vortex circulations into two regimes. Inflection point instabilities (associated with shear in an Ekman Boundary Layer) and thermal, buoyancy driven instabilities. To keep the simulations as simple as possible, we do not use a Coriolis force in the setup of the simulations and therefore do not have an Ekman boundary layer and the associated cross-wind shear. The formation of dynamically induced cloud streets in the here presented simulations are not explained by the cross-wind shear but rather stem from thermal instabilities. We therefore refrain from presenting details on inflection-point instability studies. That being said, it is clear that this reasoning and the description of the model setup needs further improvement and we hope that the revised manuscript clarifies on these points. We added a paragraph to the introductory part as well as to the description of the model and simulation setup.

- *The model setup is described with insufficient detail. For instance, sending the reader to the description of the land surface model in Heus et al is not appropriate. The $C_s kin$ parameter in Table 1 is not explained and I did not know what it really meant. In the discussion of model results this becomes obvious: this is the depth of the well-mixed layer of water that responds to radiative and surface heat fluxes. This is critical to the specifics of the simulation as the shadow on the surface is only important through its effect on the surface sensible and latent fluxes, doesnt it? Ocean response to the shadow can be argued to be quite small at spatial and temporal scales this study is concerned with, whereas land surface would respond quite rapidly. Similarly, significant wind moves the cloud and its shadow, and the surface may not have time to respond. These aspects of the model need to be presented in detail so the reader is aware of the surface response in various simulations. Are the surface momentum fluxes (i.e., surface friction) included in the model setup? If so, what is the surface drag (or whatever parameter is used to describe surface roughness) for the momentum? For instance, to mimic the difference between land-surface (small $C_s kin$) and the ocean (large $C_s kin$), the surface drag should also be changed (larger over land and smaller over the ocean). This aspect should be at least mentioned in the description of the model as the surface drag affects the shear across the boundary layer.*

We improved the model description to introduce the skin heat capacity more pronounced and explain its role in our model setup.

And yes, you are correct, the radiative effects are stronger over land-surfaces and less so over ocean. This is one of the key results of this study. Concerning other changes in surface roughness and vegetation response etc., those are intendedly neglected with the goal to minimize the number of free parameters that might have an influence on the results. I agree that if we were to put up a realistic simulation on ocean and land-surface interactions, we would need to account for these differences but we concentrate mostly on a process understanding. We added a description and explanation that we keep them constant.

- *I would like to see more analysis of bulk properties of the cloud field to put model results into perspective. For instance, the authors should show evolution of the cloud cover for various simulations, BL depth (differences in the cloud mean size evident in Fig. 1 suggests to ma that BL is deeper in the upper panel as clouds seem larger), depth of the cloud field, wind profiles across BL in various simulations, etc. etc. Differences in those bulk properties can affect organization of shallow convection as well and better isolating them from the effects of 3D radiation would be desirable. At the moment, the authors provide very speculative discussion of the model results (see specific comments) and I think some of the bulk differences may be used to better explain the results as well.*

Most bulk properties of the simulations develop very similar, irrespective of radiative transfer solver used and are primarily a function of the solar zenith angle which determines the total energy uptake of the simulations. The fact that the results give a clear signal for convective organization across the various zenith angles suggests that the mechanism is robust. Furthermore, much of the discussion compares simulations that only change the azimuth angle of the sun which exhibits exactly the same evolution of bulk properties and we feel that additional material in that respect would only elongate the paper. We added a reference to additional material concerning cloud fractions, liquid water paths and mean cloud size distributions.

- *As far as I can tell, shallow convection organization develops gradually and the time scale is relatively long (hours; this can also be better quantified in the analysis). In nature, the sun is moving around, so both the azimuth and zenith angles are slowly changing. So the idealized setup may be questioned if one has to wait long time for the organization to develop. This aspect needs at least to be recognized in the manuscript.*

I very much appreciate your comment and added a new figure to the manuscript that presents the timescales of the change in the convective

organization. From the simulation results, we find that the organization due to radiation can happen in as little time as half an hour.

2 Specific Comments:

- *The title needs revision. The role...on is not correct. In would be better, but replacing role with impact would be more appropriate.*

  Changed to "in"

- *L. 92: resolution has to be replaced with grid length.*

  Fixed

- *L. 96: I do not understand ... layers of the surface model are soaking (30Please rephrase. Is the Bowen ratio the same in all simulations? This affects buoyancy flux that drives the boundary layer dynamics.*

  We changed the wording of the sentence. The Bowen ratio primarily depends on the net energy uptake in a given simulation and changes in a subset of simulations. Regarding your question however, the moisture pool is sufficiently large as to not deplete over the course of the simulations. The Bowen Ratio is between 0.1 and 0.5.

- *L. 111. Lower sun means lower energy input, hence later convection development, correct? I would also think that this leads to different evolution of the boundary layer depth, an aspect that might be important as well.*

  That is correct. We hoped that we made a point that this parameter study aims to quantify the key mechanism of radiatively induced changes in convective organization. Particularly the discussion part of the manuscript aims to dissect the various influences of the parameters, including a paragraph specifically on the sensitivity of dynamically induced organization due to differing Q_{net}. Please see also the answer to a concern of reviewer #2.

- *I suggest adding a table with simulation acronyms and apply them throughout the text for an easy reference.*

  I think this is a matter of taste and I personally always get confused when lots of acronyms are floating around. I had hoped that the recurring scheme of the five parameters sinks into the readers mind and with that one should be able to navigate the discussion.

- *Do various simulations have different destabilization rates across the lower troposphere? This may have some impact on convection as well. See major point 3 above.*

I am not really sure what you mean by destabilization rate. If you presume that there is a background profile against which the simulations are nudged, there is none. Radiative tendencies are the only "external" forcing. In other words, the solar zenith angle in the simulations is the primary factor that will destabilize the atmosphere.

- *Fig. 2 is too small. Consider splitting into separate figures or use vertically-stack panels.*

  I increased the size of the panels and of the overlap and decreased the legends.

- *L. 136. Is this the wind direction, or shear? What is along track?*

  Wind direction, there is no cross-wind shear. I rephrased it to wind direction.

- *I feel Fig. 4 is the key result of the study. But some aspects are really not mentioned in the discussion: i) The spread between simulations with different $C_s kin$ narrows with the $C_s kin$ increase. Does this suggest some dynamical effects through surface fluxes? ii) The correlation ratio is much larger for the strong wind case, no doubt because of the role of Ekman shear across the boundary layer.*

  Indeed, Fig. 4 summarizes the parameter study.

  i) Yes, that is correct. The skin heat capacity controls the capability of radiation to create surface heterogeneities, the principal mechanism of radiatively induced convective organization. There is a lengthy paragraph that explains this. I will try to rephrase to highlight it more.

  ii) There is no Ekman shear because we do not employ coriolis forces. Stronger wind speeds with a linear wind shear profile does however induce stronger cloud streets. I hope this is clearer now in the revised manuscript.

- *I found the discussion in section 3 speculative and not supported by the analysis. For instance, Fig 5 can be supported by the analysis of model data. That said, my problem is that changes in the surface fluxes do not translate immediately into changes of the boundary-layer structure. The argument is likely correct for the surface layer, but I am not sure how rapidly these changes are passed higher up. Another aspect is the role of secondary circulations that can either support or suppress development of roll- type convection. The discussion on lines 185-190 seems to suggest that the authors think this happens, but I suggest using model data in an attempt to document that. For instance, are there any systematic differences in the updraft/downdraft structure between sunlit and shadow part of the cloud? One should investigate that.*

Regarding you first question: *If surface fluxes can penetrate cloud layer dynamics. . .*

Horn et al. 2015 investigate the timescales of surface heterogeneities and find changes up into the cloud layer. In contrast, Lohou and Patton, 2014 only find an impact of surface fluxes up to $0.2z_{BL}$ but they also state that this might be because of their strong horizontal background wind and the coupling might be more direct for smaller wind speeds. Finally, Gronemeier et al.(2016) for example, find indeed a coupling into the cloud layer, similar to ours.

This brings me already to the second part of your question: *Are there any systematic differences in the updraft/downdraft structure.*

This is a good question. . . . I would like to steer you towards Gronemeier et al.(2016) who were able to average the wind field horizontally along one of the horizontal domain axis because they prescribed the surface heterogeneities. This allows to study the flow on the sunlit/shadowy sides. Our simulations do not have that rigorous symmetry. One may be able to track the clouds and analyze the wind field around individual clouds. That is, however, an involved task which, we feel, can not be part of this work.

- *How the wind (and thus the boundary layer shear) is maintained? Again, major point 2 above.*

  The simulations are started with an inital wind profile and inertia keeps it moving. The drag does not remove the wind on these short time scales.

- *L. 210 217. Can these speculations be supported by appropriate analysis of model data (e.g., shear, boundary layer depth, etc).*

  I think the theoretical foundations concerning as to where the limit of buoyancy vs. shear-stretching lies, are limited. Anyway, it is encouraging to see that the LES simulations reproduce the observations(Woodcock (1942); Priestley (1957); Grossman (1982)). We rewrote the paragraph.

- *Suggestion for the future: one can apply different surface roughness to explore the impact of shear. Also, one can vary Coriolis parameter (including a change of sign to mimic the southern hemisphere) to better separate dynamical and radiative effects.*

  Indeed, surface roughness or directly shear curvature could have been another parameter to include in the analysis. This might be a interesting application if one wants to understand the influence of atmospheric radiative heating rates.

- *L. 245-250: I am sure there are more recent references that show observational estimates of the relevant scales than Kuettner 1959.*

  Probably, nowadays one can look for cloud street patterns in so many satellite pictures. Yet, the reference is still accurate and is a testimony for how long meteorologists have been fascinated by the occurrence of cloud streets.

- *I found the conclusion section too brief and not providing the justice to the wealth of results the authors have. In particular, dynamical aspects are really not discussed at the appropriate detail level throughout the text and thus in the summary section.*

  A complete disentanglement of dynamical effects would be great and may be a topic for future studies. Here, we try to focus on radiative effects and particularly radiative surface impacts.

Many thanks,

Fabian Jakub

Response to Anonymous referee #2

1 General remarks

First of all we wanted to thank you for taking your time to go through the manuscript in detail. Your contribution is very much appreciated. Answers to the specific comments are given below.

- *The paper is very short and could do with more material. To start with it should inform the reader about the theory of streets. Line 51/52 is insufficient. The authors tend to be in a hurry to tie the paper up and not deal with details like teasing out the extent to which horizontal photon transport contributes to the results (Line 190). I would have appreciated more analysis. A few choice simulations to focus on various issues would greatly add to the impact of the paper.*

  The introduction on the theory of cloud streets was also a concern for reviewer #1 and we added a paragraph to the introductory part as well as to the description of the model and simulation setup.

  We agree that it would be really interesting to study the effects of atmospheric heating. One could probably artificially increase the radiative heating rates and hopefully see a stronger signal in order to understand as to what extent and which mechanism is changing the cloud shapes. However, we do not think that the set of simulations with the chosen setup allows for further, quantitative analysis of the effects of atmospheric heating rates. The feedback through surface fluxes is most certainly the primary effect and has precedence in this study. We therefore added the study of atmospheric heating rates to the outlook of the paper.

- *The influence of 3-D longwave cooling should be discussed.*

  Indeed, we compute the thermal radiative transfer also in 3D but we expect the impact of 3D effects not to be important for the formation of cloud streets because thermal radiative transfer does not infer any asymmetries (i.e. is rotational symmetric). We added a paragraph to the model description.

- *I liked the intuitive sketch (Fig. 5) but would appreciate a similar sketch pertaining to the dynamics of streets that might help understand the amplification/offsetting of the radiation - particularly the length scales in question.*

We are not sure if we understand your request. If you mean a figure such as for example in Gronemeier et al. (2016), fig. 3, we feel that, in our case, it does not add a lot to the explanation pertaining the radiative/wind feedback. The length and time scales vary with zenith and azimuth angles and surface heat capacity and we could not come up with a simple sketch that would improve the display of our ideas.

- *The congruence with the quote by Weckwerth (1997) and subsequent sentences (line 210 - 217) really needs some deeper thought and analysis.*

  I think the theoretical foundations concerning as to where the limit of buoyancy vs. shear-stretching lies, are limited. Anyway, it is encouraging to see that the LES simulations reproduce the observations (Woodcock (1942); Priestley (1957); Grossman (1982)). We rewrote the paragraph.

- *Please comment on how static heterogeneities might play out over land, where the 3- D solar radiation influence is significant. Particularly when the wind advects a boundary layer that includes the net effect of upstream static (and dynamic) heterogeneity. The scale of the patches and the advective wind will be important. This links in to my request to tie the discussion more tightly to the dynamic theory of streets.*

  Static heterogeneities and their influence are in part tackled in Avissar and Schmidt (1998); Patton et al. (2005); Rieck et al. (2014). Furthermore, Gronemeier et al. (2016) investigated the interplay of static surface heterogeneities and radiatively induced, dynamic heterogeneities. While studying this interplay is clearly a very interesting and important aspect, we feel that there is probably not much potential gain in yet another study with idealized setups. We mention in the outlook of the paper that we hope to study the effects of 3D radiative transfer in a more realistic setup within the High Definition Clouds and Precipitation for Climate Prediction (HD(CP)2) project.

- *Finally, the paper contains some testable hypotheses that I urge the authors to pursue with data since it will add much value to this line of research. (Im not saying this should be done in the current paper.)* Thanks, I agree. Specifically, as noted in the point above, we very much look forward to checking whether we can reproduce the effects in a realistic setup and compare that to satellite observations. Another strategy we will try is to look for statistically significant organization of cloud streets in high resolution satellite imagery. Specifically whether the cloud streets follow the solar azimuth angles.

2 Specific Comments:

- *Line 267: I think you mean simulations rather than data.*

  Indeed, corrected.

- *Line 272: Again please include more theoretical explanation of dynamically induced cloud streets.*

  We added an additional paragraph to the introduction and rephrased this particular sentence.

- *When you use the phrase surface heterogeneities in the text, please be clear that this is a dynamical heterogeneity.*

  Yes, I went through the text and added clarifications where possible.

- *The LWP threshold > 1 for the cloud mask is much too rigid but I expect has little to no bearing on the results other than how it will bias the quoted cloud fractions. An optical depth threshold might be more useful/relevant anyhow.*

  Indeed, I checked and as you expected, it changes the cloud fraction usually by less than 1% and neither has an impact on the selection of time-steps nor on the autocorrelation ratios.

Many thanks,

Fabian Jakub

The Role of 1D and 3D Radiative Heating ~~on~~ in the Organization of Shallow Cumulus Convection and the Formation of Cloud Streets

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Abstract. The formation of shallow cumulus cloud streets was historically attributed primarily to dynamics. Here, we focus on the interaction between radiatively induced surface heterogeneities and the resulting patterns in the flow. Our results suggest that solar radiative heating has the potential to organize clouds ~~perpendicular~~ perpendicularly to the sun's incidence angle.

To quantify the extent of organization, we performed a high resolution LES parameter study. We varied the horizontal wind speed, the surface heat capacity, the solar zenith and azimuth angles, as well as radiative transfer parameterizations (1D and 3D). As a quantitative measure we introduce a simple algorithm that provides a scalar quantity for the degree of organization and the alignment. We find that, even in the absence of a horizontal wind, 3D radiative transfer produces cloud streets perpendicular to the sun's incident direction, whereas the 1D approximation or constant surface fluxes produce circular, randomly positioned, clouds. Our reasoning for the enhancement or reduction of organization is the geometric position of the cloud's shadow and ~~the~~ its corresponding surface fluxes. Furthermore, when increasing horizontal wind speeds to 5 or $10\,\mathrm{m\,s^{-1}}$, we observe the development of dynamically induced cloud streets. If in addition, solar radiation illuminates the surface beneath the cloud, i.e. when the sun is positioned ~~orthogonal~~ orthogonally to the mean wind field and the solar zenith angle is larger than $20°$, the cloud-radiative feedback has the potential to significantly enhance the tendency to organize in cloud streets. In contrast, in the case of the 1D approximation (or overhead sun), the tendency to organize is weaker or even prohibited because the shadow is cast directly beneath the cloud. In a land-surface type situation, we find the organization of convection happening on a timescale of half an hour. The radiative feedback~~on~~, creating surface heterogeneities is generally diminished for large surface heat capacities. We therefore expect radiative feedbacks to be strongest over land surfaces and weaker over the ocean. Given the results of this study we expect that simulations including shallow cumulus convection will have difficulties producing cloud streets if they employ 1D radiative transfer solvers or may need unrealistically high wind speeds to excite cloud street organization.

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1 Introduction

The advent of airborne and satellite observations allow for a bird's eye view of the atmosphere and, ever since, meteorologists have been fascinated by the striped patterns often evident in cloud systems. Kuettner (1959) presented some early pictures of cloud streets from rocket and aircraft instruments. Descriptions of cloud streets, date back as far as Steinhoff (1935), who gave a detailed description of a long-distance glider flight, or Woodcock (1942) who investigated the soaring patterns of seagulls. Scientific literature documenting the existence and explaining the prerequisites for the formation of cloud streets is plentiful. ~~and Etling and Brown (1993)~~ Brown (1980); Etling and Brown (1993); Weckwerth et al. (1997); Houze Jr (2014) provide a thorough review of past observations and theoretical frameworks. ~~They suggest that favorable ingredients for roll vortices are weak thermal instabilities with moderate horizontal wind speeds in the planetary boundary layer.~~

~~Thermal instabilities are directly linked to~~ The above literature suggests two prominent effects to be responsible for such vortices, namely inflection-point instabilities (e.g. from cross-roll wind components in a Ekman boundary layer) and thermal instabilities (buoyancy driven). Purely

buoyancy driven convection, without any horizontal wind or shear, produces a random pattern of updrafts. Introducing a linear wind shear, the convective elements become stretched out along-wind. Following Grossman (1982): "*At some point (*increasing the wind speed/shear*) the shearing becomes strong enough so that dynamic instability may interact with buoyancy to produce a hybrid roll vortex/convective cell mechanism. As the shear becomes stronger, shearing instability or roll vortex motion is predominant.*" In this work, we will focus on the radiative impact, with the most prominent effect being cloud shadows which modulate surface fluxes and consequently ~~to~~ build up surface heterogeneities. These induced surface heterogeneities are the link between radiative transfer and buoyancy driven convection (Lohou and Patton, 2014; Horn et al., 2015; Gronemeier et al., 2016). Our focus is therefore more on buoyancy driven roll vortices in a linear shear environment (Asai, 1970) and less so on inflection-point instabilities. To that end, we omit cross-wind shear by neglecting Coriolis force and correspondingly neglect the horizontal turning of the wind as it would be the case in an Ekman boundary layer. Several studies investigated the role of surface fluxes on the development of such boundary layer circulations ~~with a focus on cloud streets~~. Here the literature distinguishes between static heterogeneities, i.e. differences in land-surface parameters such as vegetation, surface roughness or surface albedo and dynamic heterogeneities, such as moisture budget or temperature fluctuations. Static heterogeneities in conjunction with shallow cumulus clouds and cloud streets have been examined for example by Avissar and Schmidt (1998); Patton et al. (2005); Rieck et al. (2014). In contrast, Schumann et al. (2002); Wapler (2007); Frame et al. (2009); Gronemeier et al. (2016) investigated the influence of dynamic heterogeneities in surface shading and even considered 3D radiative effects (i.e. the displacement of the shadow). However, they did not include a realistic surface model, but rather adjusted the surface fluxes instantaneously. This does not allow to study the timescales on which radiation and dynamics may interact. Others investigated the influence of shading coupled to an interactive surface model (Vilà-Guerau de Arellano et al., 2014; Lohou and Patton, 2014; Horn et al., 2015). However, one particularly questionable issue with those studies was the application of 1D radiative transfer solvers, which are known to introduce large spatial error in surface heating rates (O'Hirok and Gautier, 2005; Wapler and Mayer, 2008; Wissmeier et al., 2013; Jakub and Mayer, 2015).

Overall, we can summarize that the formation of cloud streets has been extensively explored from theoretical and observational perspectives. The above mentioned studies shed light on the various aspects of interaction with the cloud field but either lack a realistic representation of surface processes, neglect 3D radiative transfer effects or do not examine the relationship concerning the background wind speed.

In this study we strive to overcome these shortcomings and determine the prerequisites for the formation of cloud streets, while our main focus lies on dynamic heterogeneities and (3D) radiative transfer. We try to disentangle the underlying processes with a rigorous parameter study using Large-Eddy-Simulations (LES).

Section 2 briefly outlines the LES model, explains the setup of the simulations and introduces a scalar metric to quantify the organization in cloud streets. In section 3 we interpret the magnitude of cloud street formations in the parameter space spanning surface properties, background wind speeds and the sun's angles. Section 4 finally summarizes key findings of the parameter study.

2   Methods and Experiments

2.1   LES Model

The Large-Eddy-Simulations (LES) were performed with the UCLA–LES model. A description and details of the LES model can be found in Stevens et al. (2005). The land surface model included in the UCLA–LES follows the implementation of the Dutch Atmospheric Large-Eddy Simulation code Heus et al. (2010). The simulations presented here use warm micro-physics formulated in Seifert and Beheng (2001) where the formation of rain is turned off to prevent any further complications such as cold pool dynamics. The radiative transfer calculations are performed with the TenStream package (Jakub and Mayer, 2015), which includes a 1D Schwarzschild (thermal only), a δ-Eddington two-stream (solar and thermal), as well as the 3D TenStream (solar and thermal) solver.

The TenStream is a MPI-parallelized solver for the full 3D radiative transfer equation. In analogy to a two-stream solver, the TenStream solver computes the radiative transfer coefficients for up- and downward fluxes and additionally for sideward streams. The coupling of individual boxes leads to a linear equation system which is written as a sparse matrix and is solved using parallel iterative methods from the "Portable, Extensible Toolkit for Scientific Computation", PETSc (Balay et al., 2014) framework. In Jakub and Mayer (2015, 2016), we extensively validated the TenStream by comparison with the exact Monte Carlo code *MYSTIC* (Mayer, 2009).

The most pronounced differences between 1D and 3D radiative transfer solvers, pertaining the setup here, is the displacement of the sun's shadow at the surface. In the case of 1D radiative transfer, the shadow of a cloud is by definition always directly beneath it (so called independent pixel or independent column approximation). Contrarily, 3D radiative transfer allows the propagation of energy horizontally and correctly displaces the clouds shadow depending on the sun's position. The features of 3D radiative transfer in the thermal spectral range are an increased cooling on cloud edges and a

Figure 1. Virtual photograph of LES simulations at a cruising altitude of $15\,\text{km}$. Top panel: cloud formation of a simulation driven by 3D radiation (TenStream with sun in the east, i.e. right ($\varphi = 90°$)). Lower-panel: cloud formation of a simulation which was performed with 1D radiation (Two-stream). The specific model setup is the same as referenced in fig. 2, i.e., no background wind and a continental land surface. The simulations differ with respect to cloud size distributions and the organization in cloud streets, the cloud fraction though is the same ($27\,\%$). The visualization was performed with a physically correct rendering with MYSTIC (MonteCarlo solver in libRadtran (Mayer, 2009; Emde et al., 2015)).

smoothed distribution of surfaces fluxes. While we compute thermal radiative transfer in a 3D fashion, we expect these effects to be less important for this setup because feedbacks on the dynamics appear to happen only longer timescales of a day (Klinger et al., 2017) and more importantly because it does not infer any asymmetries in the heating or cooling pattern.

The spectral integration is performed using the correlated-k method following Fu and Liou (1992). The coupling of the TenStream solver to the UCLA–LES follows the description in Jakub and Mayer (2016). One exception is the use of the Monte-Carlo-Spectral-Integration (Pincus and Stevens, 2009) which we do not use because of limitations with regards to computations involving interactive surface models (Pincus and Stevens, 2013).

2.2 Model Experiment Setup

The base setup of the UCLA–LES simulates a domain of $50\,\text{km} \times 50\,\text{km}$ with a horizontal ~~resolution~~ grid length of $100\,\text{m}$ and $50\,\text{m}$ vertically. The simulations start from a well-mixed initial background profile with a constant virtual potential temperature ($292\,\text{K}$) in the lower $700\,\text{m}$ and increases by $6\,\text{K}\,\text{km}^{-1}$ above. Water vapor near the surface amounts to $9.5\,\text{g}\,\text{kg}^{-1}$, decreasing with $-1.3\,\text{g}\,\text{kg}^{-1}\,\text{km}^{-1}$. The layers of the surface model are soaking wet ~~(30 % vmr) and~~ (30 % water volume mixing ratio) and are stripped of vegetation with an initial temperature of $291\,\text{K}$. The surface albedo for shortwave radiation is set to $7\,\%$. The land-surface model solves the surface energy balance equation for an imaginary skin layer which often has no heat capacity. We manipulate the heat capacity of the surface skin layer C_{skin} to mimic a water layer covering the surface. The heat capacities are chosen to be representative for situation ranging from continental land surfaces to well mixed ocean. The thickness of this imaginary water layer lends the simulations and the radiative transfer a memory on the surface. All other parameters of the land-surface model such as surface resistances or roughness lengths for momentum or heat are kept constant in order to focus on these memory effects.

The focus of this study is to determine the interplay of radiation with the atmosphere, the surface and the clouds, and finally take a closer look on the formation of cloud streets. To that end we run the simulations with five free parameters, namely the heat capacity of the surface skin layer (C_{skin}), the background wind ($\boldsymbol{u}$, i.e. west-winds), the solar zenith (θ) and azimuth (φ) angle as well as with different radiative transfer approximations (see table 1). The ~~heat capacities are chosen to be representative for situation ranging from continental land surfaces to well mixed ocean. The~~ coupling of radiative transfer to the land-surface model is realized in

Table 1. Parameter space for the LES simulations: the mean west wind $\boldsymbol{u}$, the solar azimuth and zenith angle φ,θ, the surface skin heat capacity C_{skin} as a water column equivalent and three settings for the computation of net radiative surface fluxes (Q_{net}). The radiative transfer computations are done either with a 1D δ-Eddington two-stream , with the 3D TenStream solver or simulations with constant mean net irradiance. Variations of the solar azimuth φ are only applied for 3D radiative transfer. Values of Q_{net} in case of simulations without interactive radiative transfer were set to the mean surface irradiance of the 1D simulations. In total a number of 192 simulations.

$\boldsymbol{u}$	0, 5, 10	$\mathrm{m\,s^{-1}}$
φ	90, 180	°
θ	20, 40, 60, 75	°
C_{skin}	1, 10, 100, 1000	cm
Q_{net}	constant, 1D, 3D	

four ways. We either compute the net surface irradiance Q_{net} with a 1D δ-eddington two-stream solver , or employ the 3D TenStream solver, with two azimuth angles. Additionally, we conducted the experiments where Q_{net} is set to a prescribed constant value (spatial and temporal average of the surface irradiance of the corresponding 1D simulation).

The time it takes the simulations to form the first clouds depends on the choice of the parameters. Foremost the solar zenith angle determines the energy input into the atmosphere and the surface (lower positioned sun hence leads to a later onset of cloud development). To compare the heterogeneous simulations we limit the following analysis to the time-steps (output every $5\,\mathrm{min}$) where the cloud fraction is between $10\,\%$ and $50\,\%$ (typical for shallow cumulus convection, e.g. Seifert and Heus (2013)). Most simulations produce clouds after about one hour and show an increase in cloud cover up to and beyond $50\,\%$ in the first $6\,\mathrm{h}$. Simulations with low positioned sun took longer and were hence run for a longer period of $12\,\mathrm{h}$. Our analysis is mostly independent of the specific, individual course of each simulation as we find robust signals across the various groups of parameters. The interested reader, however, is referred to Jakub (2016, sec. 3.2) for further details (e.g. liq. water path, cloud fraction, mean cloud size distribution) on the evolution of a typical simulation.

Figure 1 shows a photo rendering of the LES cloud field for two simulations with differing options for the radiative transfer solver. In the top panel, 3D radiative transfer is considered with the sun positioned in the east (zenith $\theta = 60°$) and in the bottom panel panel 1D solver is applied where the shadow is by definition always cast directly beneath the clouds. In the former the organization in cloud streets perpendicular to the sun's incident angle is evident whereas the latter (1D) does not seem to organize in any way. Figure 2 presents the liquid water content and the surface heat flux

for the same two simulations plus one 3D simulation where the sun is in the south. This time we look at volume rendered liquid water content and surface heat fluxes for the full domain. In figs. 1 and 2, simulations with 3D radiative transfer show organization in cloud streets with length scales of up to $20\,\mathrm{km}$, perpendicular to the sun's incident angle. We can clearly identify these coherent cloud structures with the naked eye. However, to solidify our claims, we present a quantitative measure for the cloud distribution.

2.3 Correlation Ratio

Since we do not deal with towering and tilted or multilayer clouds we can use the cloud mask as a proxy to separate individual clouds. We derive the cloud mask as the binary field of the liquid water path (LWP > 0). We then use the normalized 2D auto correlation function of the cloud mask to analyze the spatial distribution of cloudy and clear-sky patches. The three upper panels of fig. 3 illustrate the 2D correlation coefficient for the three simulations presented in fig. 2.

Next, we use the transects of the correlation coefficient along the x- and y-axis (indicated as a black line). The lower panels in fig. 3, respectively, show the linearly interpolated ~~linecuts~~ line-cuts of the discrete auto-correlation function. The location where the normalized correlation coefficients goes to zero defines the mean distance from a cloudy pixel where it is more likely to find a clear-sky pixel. We use the north-south and the east-west distances d_{NS} and d_{EW}, respectively, to define the correlation ratio R_{c} as:

$$R_{\mathrm{c}} = d_{\mathrm{NS}}/d_{\mathrm{EW}}$$

This definition would miss cloud streets in diagonal direction which, however, is no limitation for our analysis. For one, we know that the background wind induces cloud streets along ~~track~~ the mean wind direction, i.e. here in the west-east component (see e.g. Weckwerth et al. (1997)). At the same time we hypothesize that radiatively induced effects will be either along or perpendicular to the incident solar beam, i.e. follow the surface inhomogeneities (see, e.g., Gronemeier et al. (2016). The two major directions should therefore capture the dominant effects of dynamically and radiatively induced cloud dynamics.

The correlation ratio reduces a cloud field snapshot into a scalar which yields $R_{\mathrm{c}} = 1$ for symmetrically distributed clouds, $R_{\mathrm{c}} < 1$ for organized cloud fields along the north-south direction and $R_{\mathrm{c}} > 1$ if cloud features are arranged east to west. ~~We finally~~

3 Results and Discussion

As an example for the evolution of convective organization, fig. 4 illustrates the correlation ratio R_{c} over time for one of the earlier introduced simulations (depicted in fig. 2). The simulation develops first cumulus clouds after about half an
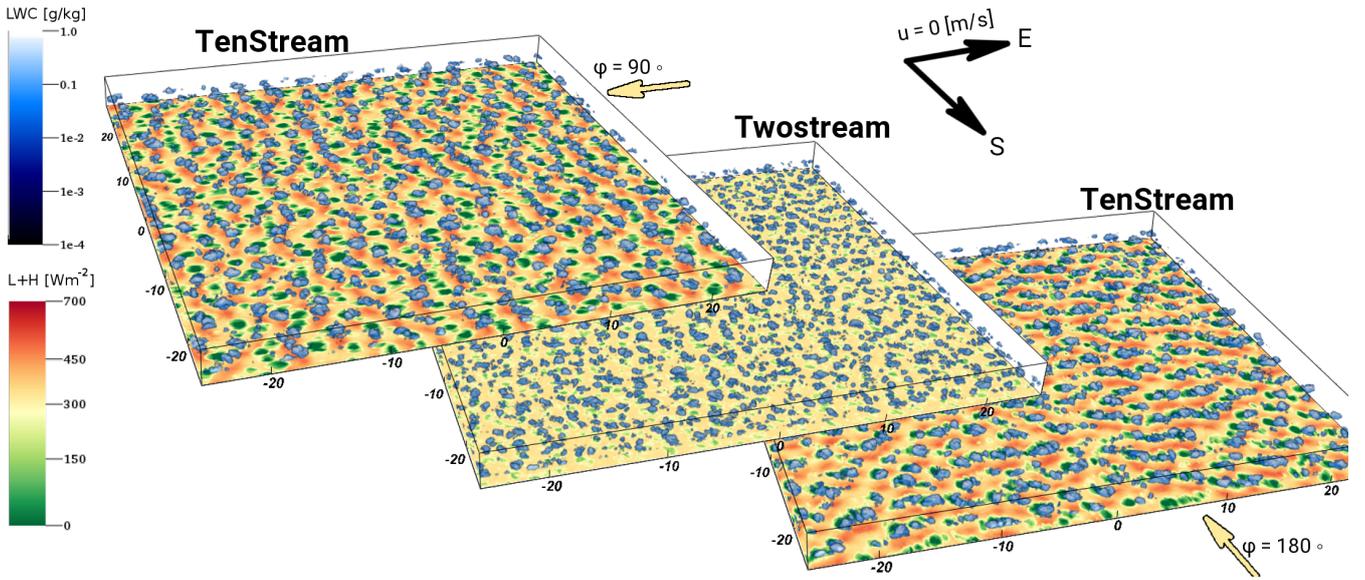
Figure 2. Volume rendered liquid water mixing ratio (LWC) and surface latent and sensible heat flux ($L + H$) for three simulations. The cloud scene of the left and mid panel have already been presented in fig. 1. In the left panel, radiative transfer calculations are performed with the TenStream solver and the sun is positioned in the east ($\varphi = 90°$). The simulation in the mid-panel is driven by a 1D two-stream solver, whereas the right panel simulation also employs the TenStream solver but the sun shining from the south ($\varphi = 180°$). The solar zenith angle is in all three simulations $\theta = 60°$, the mean background wind speed is $0\,\mathrm{m\,s^{-1}}$ and the surface skin heat capacity set to an equivalent of $1\,\mathrm{cm}$ water depth (representative for continental land surface). The snapshot shows the simulations after $3\,\mathrm{h}$ model time at a cloud fraction of $27\,\%$. Volume rendered plots were created with VISIT (Childs et al., 2012).

hour with the clouds being oriented randomly. The resulting shadowing of these clouds introduces surface temperature heterogeneities which in turn act on the flow through changes in latent and sensible heat fluxes. About one hour after the onset of clouds, we find the convection to organize into bands from north to south ($R_c < 1$). To further highlight the involved timescales, we restart the simulation from $2\,\mathrm{h}$ onwards with a 90° rotated sun and find that convection changes from a north to south orientation to bands from east to west in approximately one hour. This example yields a $1/e$ timescale for convective organization of half an hour. This timescale will however, depend on several factors, most certainly on the solar zenith angle and the surface heat capacity which determine the timescales at which surface heterogeneities can be introduced.

To reduce the information of convective organization into a single scalar value, we compute the mean correlation ratio $\overline{R_c}$ as the arithmetic mean of R_c calculated at all output timesteps time-steps (every 5 minutes) where the cloud fraction is between $10\,\%$ and $50\,\%$. The aim of the cloud fraction filtering is to allow a comparison of simulations with varying temporal evolutions due to different energy inputs (solar zenith angles) and heat sinks (C_{skin}).

4 Results and Discussion

The basis for the following analysis is the evaluation of mean correlation ratios as a function of the five free parameters, u, φ, θ, C_{skin}, and the radiative transfer solver (for details, see table 1). Figure 5 shows the mean correlation ratio $\overline{R_c}$ for each of the 192 simulations. The three panels show results for different horizontal background wind speeds, $0\,\mathrm{m\,s^{-1}}$, $5\,\mathrm{m\,s^{-1}}$ and $10\,\mathrm{m\,s^{-1}}$. Each panel's x-axis is divided into four categories for the surface skin heat capacity and the colorbar describes the solar zenith angle. Additionally, four different markers denote the various options concerning the radiative transfer solvers while the rotation of triangle markers (3D RT) denote the azimuth angle.

We will first focus on the left panel which shows the correlation ratios for the simulations without any background wind and later move on to simulations with wind. In other words, we start by focusing on purely radiative effects and their influence on the organization of convection and eventually add dynamically induced cloud streets to the discussion.

3.1 Without Wind: $u = 0\,\mathrm{m\,s^{-1}}$

The three simulations presented in section 2 are located on the far left panel of fig. 5 with a surface skin heat capacity equivalent of $1\,\mathrm{cm}$ water column (furthest to the left shaded area). Correspondingly, the markers for 3D radiative trans-
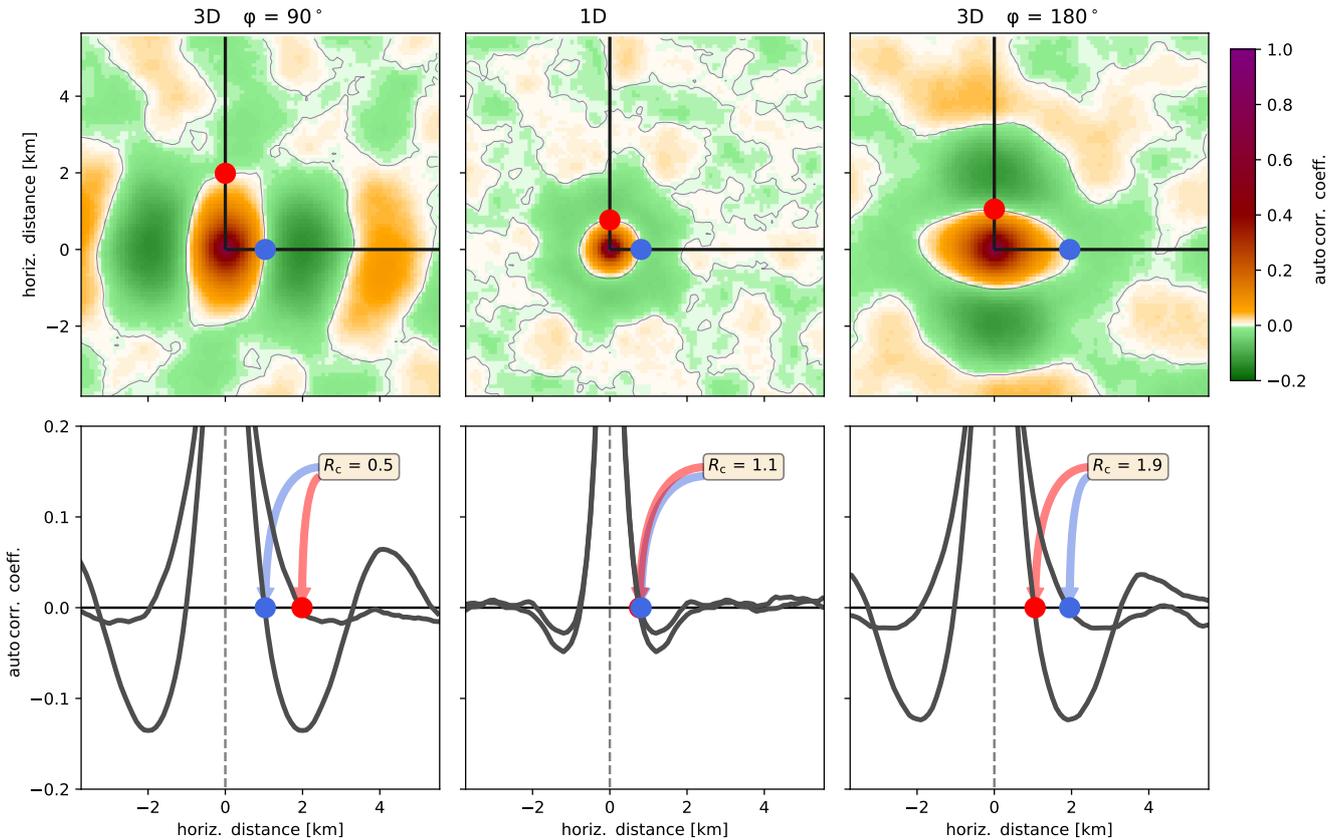
Figure 3. The panels exemplarily depict the auto-correlation coefficients of the cloud distribution in the three simulations presented in fig. 2. The upper panels show the normalized 2D autocorrelation coefficient with two intersection lines in the North-South (vertical) and the East-West (horizontal) direction. The markers pinpoint the distance in N-S (red) and E-W (blue) direction, respectively, where the auto-correlation coefficient reaches a zero value and therefore denote the distance where it becomes more likely not to find a cloud. The lower panels follow the black ~~linecuts~~ line-cuts and further describe the two transects depicting the correlation function's root points from which we derive the correlation ratio. Simulations with 3D radiative transfer (left and right panels) shows in contrast to 1D radiative transfer (mid panel) a distinct asymmetry perpendicular to the solar incidence angle. The organization of clouds and their alignment is represented in values of the correlation ratio R_c being less than or greater than one for alignment along the y- or x-axis, respectively.

fer are shown as triangle markers in light blue (zenith angle of 60°). The upward triangle represents the sun positioned in the south and yields a mean correlation ratio of 1.5 (rolls produced west to east). In contrast, the left rotated triangle presents a sun positioned in the east and shows a mean correlation ratio of .7 (rolls produced south to north). The simulation with 1D radiative transfer is presented with a diamond shaped marker and shows a mean correlation ratio of ≈ 1 (no organization).

To explain the concept of why 3D RT creates rolls, we may setup a quick thought experiment. First start with the assumption that there already is a single cloud which will cast the shadow along the sun's incident angle. The surface fluxes for latent sensible heat will be smaller in the shadowy area and hence we expect the next convective plume to rise in sun-lit areas. Figure 6 illustrates the concept for a single cloud and the resulting pattern for surface fluxes.

The schematic only constrains convection to be less favorable on the shadowy side but it does not necessarily favor the perpendicular directions over the direction towards the sun. However, if a cloud would evolve on the sun-facing side, the resulting shadow would in turn lead to a faster dissipation of the initial cloud and is thereby an unstable environment for persistent cloud patterns. Following this, we expect the convection to occur favorably perpendicular to the sun's incident angle purely from geometric reasoning.

It is also clear from the horizontal axis of fig. 5 that higher heat capacities lead to less pronounced formations of cloud streets which is to be expected because it weakens the radiative impact and consequently reduces the dynamically induced surface heterogeneities. Yet, though weaker, we still find an impact in 3D radiative transfer simulations even for a water column equivalent of $10\,\mathrm{m}$. In this case with such high surface heat capacities, the ~~simulation~~ simulations do not ex-
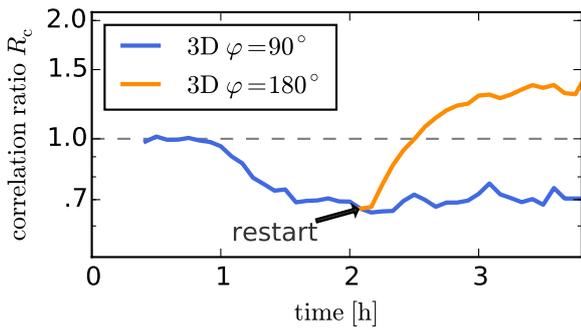
Figure 4. Shown is the time evolution of the correlation ratio R_c (e.g. as in fig. 2). The solar zenith angle is $\theta = 40°$, there is no mean background wind speed ($u = 0\,\mathrm{m\,s^{-1}}$) and the surface skin heat capacity is set to an equivalent of $1\,\mathrm{cm}$ water depth (representative for continental land surface). The radiative transfer is computed with the TenStream solver and the sun is positioned in the east ($\varphi = 90°$) The first shallow cumulus clouds develop with a random orientation ($R_c = 1$). The radiative response (i.e. surface shadows) changes the organization of convection to bands from north to south $R_c < 1$ in about one hour. Additionally, to examine the timescales of radiatively induced organization of convection, we perform a restart of the simulation with the sun positioned in the south ($\varphi = 180°$). Once the sun is rotated, it takes the simulation again about one hour to change the orientation of convection into bands from east to west ($R_c > 1$).

hibit any variability in surface fluxes and radiation solely acts through atmospheric heating. We recover this behavior also in simulations with a fixed sea surface temperature or with constant latent and sensible surface fluxes (not shown). In Jakub (2016, fig. 3.22), we show that the asymmetric heating of the cloud sides (or similarly in Wapler (2007); Gronemeier et al. (2016) for displaced surface shadows) introduces a secondary circulation by lifting the sun-lit side and enhancing subsidence on the shadowy side. This asymmetry introduces a wind shear component consisting of a horizontal wind away from the sun at cloud height and towards the sun near the surface. Given that the effects of atmospheric heating is much smaller and happens on longer timescales compared to the surface feedback we put the interpretation aside for another time.

Simulations with one-dimensional radiative transfer or constant Q_{net} do not produce cloud streets which is reflected by correlation ratios $R_c \approx 1$. If we apply the same geometric reasoning from fig. 6 for these simulations, where the shadow is either directly beneath the cloud or with no heterogeneity at all, it is clear that there can be no preferential direction for convective organization.

Three-dimensional radiation calculations with high or low solar zenith angles also show a reduced production of cloud streets. This is, (a) because low zenith angles (sun above head) practically behave just as 1D radiative transfer, and (b) because large zenith angles (low sun, smaller heating rates) have a weaker potential to create surface heterogeneities.

3.2 Medium Wind: $u = 5\,\mathrm{m\,s^{-1}}$

The middle panel of fig. 5 presents the correlation ratios for simulations with a horizontal background wind of $5\,\mathrm{m\,s^{-1}}$. If we first shift our attention to the simulations with constant surface irradiance Q_{net} (round markers), it is evident that the introduction of a mean wind profile leads to the formation of cloud streets ($\overline{R}_c > 1$), irrespective of radiatively induced surface heterogeneities. ~~This is consistent with~~ The fact that we find cloud streets also without any radiation is not surprising and is expected from the literature on the formation of ~~cloud streets which was~~ buoyancy driven cloud streets (introduced in section 1. ~~Interestingly~~Furthermore, we find a spread in the development of cloud streets depending on the magnitude of the prescribed Q_{net}, with correlation ~~ratio~~ ratios ranging from 1 to 5. ~~While thermally driven convection in conjunction with a vertical wind shear is a key ingredient for the formation of cloud streets, we find less pronounced organization in cases with high surface fluxes. This may be explained following the remark of Weckwerth et al. (1997): "…rolls are most commonly observed within slightly unstable environments. As the convective boundary layer becomes more unstable it is generally expected that growth of two-dimensional convective instabilitiesis less preferred." Strong radiative heating, such as we get for high sun (i.e.small θ) results in an increased atmospheric instability. Fully quantifying the intricate relation between thermal instabilities and the formation of cloud streets is an endeavor in itself and to the best of our knowledge, there is not yet a definitive answer.Anyway, from our results, it is evident that a medium background wind profile dynamically induces cloud street organization with correlation ratios on the order of $R_c \approx 1.5$~~The fact that buoyancy driven cloud street organization is favored in slightly unstable conditions (low sun) compared to stronger instabilities (high sun) agrees well with observations (e.g.Woodcock (1942); Priestley (1957); Grossman (1982);

So far we discussed only the simulations with constant Q_{net}. When we look at land surfaces that are coupled to radiative transfer calculations (1D and 3D markers in fig. 5), we find that radiative heating may either enhance the organization ($\overline{R}_c$ up to 13) or counter-act it ($\overline{R}_c < 1$). The following paragraph examines the superposition of dynamically and radiatively induced tendencies to organize the clouds.

Let's consider the case that there is a dynamically induced cloud street along the mean background wind, i.e. from west to east. Quasi 1D radiation (1D and 3D if sun is close to zenith) casts a shadow onto the cloud's updraft region and therefore hinders further development of the cloud. This results in values for the correlation ratio of $\overline{R}_c \approx 1$. ~~Similarily~~Similarly, 3D radiation where the azimuth is in the
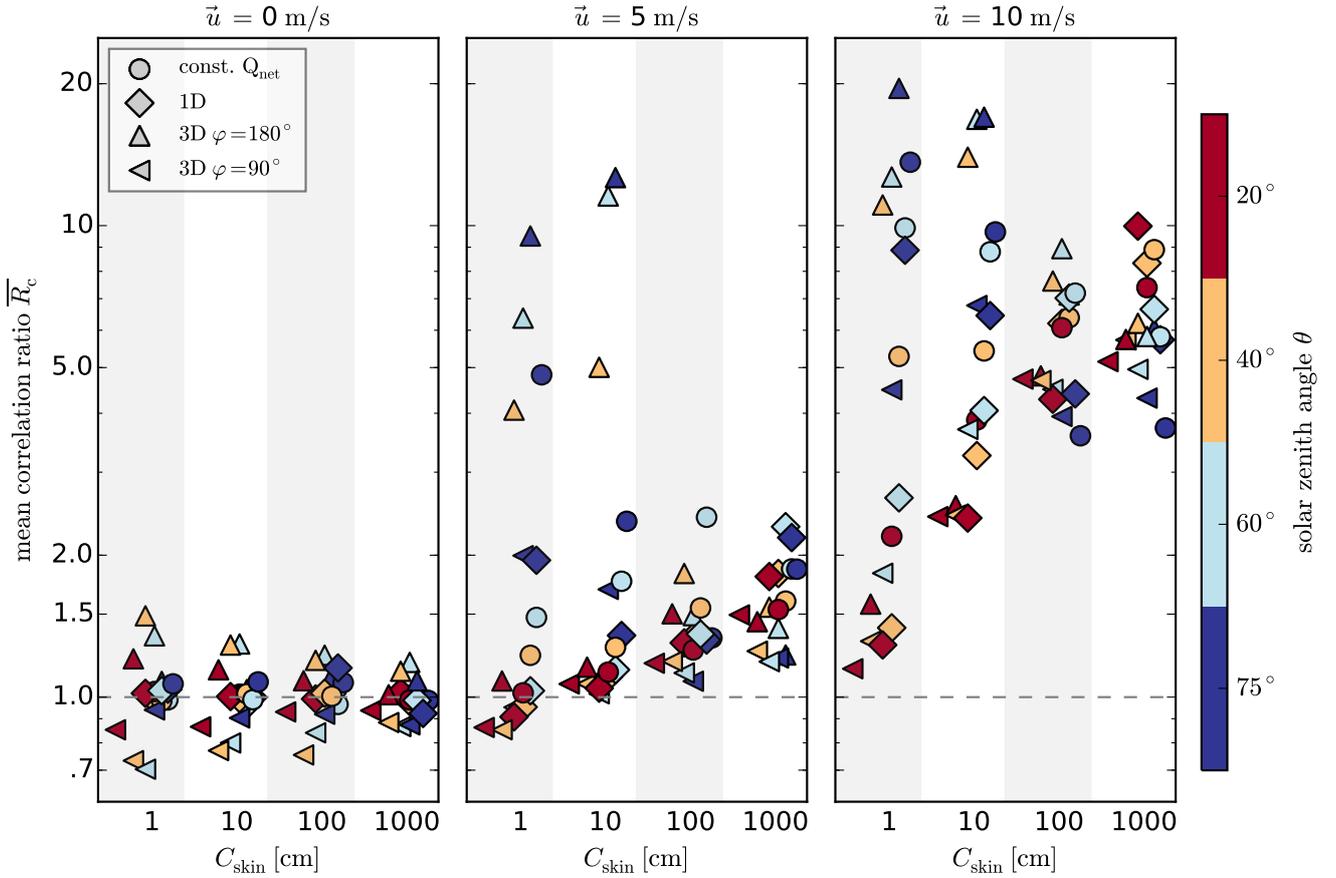
Figure 5. Correlation ratio for simulations with a variable surface skin heat capacity (C_{skin}), solar zenith angle (θ), and three wind velocities (panels left to right). Shaded areas group simulations with a constant C_{skin} according to their respective values, while the horizontal spread inside a group is merely to separate ~~datapoints~~ data-points visually. Wind-component u is always from west to east while the individual markers denote simulations where the surface irradiance Q_{net} is set to a constant value, or is computed either with a 1D two-stream solver, or with the 3D TenStream where the sun is either shining from the south ($180°$) or from the east ($90°$). The correlation ratio is averaged over all ~~timesteps~~ time-steps where the cloud fraction is between $10\,\%$ and $50\,\%$.

same direction as the wind (here east, $\varphi = 90°$, left-rotated markers) also inhibits the formation of cloud streets or may even oppose the dynamically induced organization and produce correlation ratios $\overline{R}_{\mathrm{c}} < 1$.

In contrast, for 3D radiative transfer with solar incidence perpendicular to the mean wind, i.e. sun from south or north, and permitted that the sun's zenith angle allows to illuminate the surface beneath the cloud ($\theta > 20°$), we find that the radiative tendency to organize the clouds amplifies the dynamically one. This synergistic behaviour results in correlation ratios $\overline{R}_{\mathrm{c}}$ between 5 and 13.

As mentioned previously in section 3.1, we again find a ~~generelly~~ generally diminished influence of surface radiative heating in simulations with larger surface heat capacities.

3.3　Strong Wind: $u = 10\,\mathrm{m\,s^{-1}}$

A stronger background wind profile of $10\,\mathrm{m\,s^{-1}}$ principally shows similar behavior as the case that was presented with medium wind speeds (see right panel of fig. 5). The mean correlation ratios of purely dynamically induced cloud streets (simulations with constant Q_{net}, i.e. circle markers) cover an increasingly large range of ratios from 2 to 14. Strong solar radiation coupled with small surface heat capacities still manage to efficiently suppress the formation of cloud streets (i.e. $\overline{R}_{\mathrm{c}}$ consistently smaller than purely dynamic values). Whereas illumination perpendicular to the wind direction ($\varphi = 180$ and $\theta > 20°$) again greatly amplifies the occurrence of cloud streets. This might be surprising if we consider that horizontal wind should indeed smooth out the impact of radiative surface heating. Lohou and Patton (2014) for example also suggest that wind speeds of $10\,\mathrm{m\,s^{-1}}$ may decouple the effects of dynamically induced surface het-
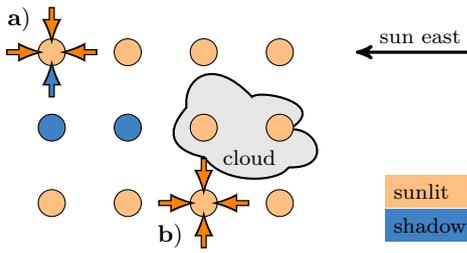
Figure 6. Sketch from an aerial view depicting surface fluxes in the vicinity of a cloud with a tilted solar incidence. The cloud casts a shadow on the westward surface pixels (blue dots). The available convective energy is directly proportional to latent and sensible heat release of the surface in the vicinity of the convective updraft. Arrows illustrate the confluence of near surface air masses from adjacent pixels in a thermally driven updraft event. Convective tendencies will be weaker on pixels that are adjacent to shaded patches, e.g. at $a)$. In contrast, pixels that are surrounded by sun-lit patches, e.g. $b)$, are likely to show enhanced convective motion. This pattern favors the organization of cumulus convection in stripes perpendicular to the sun's incident.

erogeneities from the evolution of clouds. However, if we consider that the dynamically induced cloud streets have typical length scales of $50\,\mathrm{km}$ (Kuettner, 1959), then, as far as radiative heating at the surface is concerned, the cloud appears to be standing still. In other words, when a dynamically induced cloud feature aligns in such a way that it persistently shades a surface region for an extended period of time, we expect that the ~~surface heterogeneities due to radiative transfer~~ radiatively induced surface heterogeneities in turn interact with the flow. It is this intricate linkage between dynamically induced cloud structures and (3D) radiative transfer that may enable or prohibit the formation of cloud streets.

4 Summary & Conclusions

The formation of cumulus cloud streets was historically attributed primarily to dynamics. This work aims to document and quantify the generation of radiatively induced cloud street structures. To that end we performed 192 LES simulations with varying parameters (see table 1) for the horizontal wind speed, the surface heat capacity, the solar zenith and azimuth angle, as well as for different radiative transfer solvers (section 2.2). As a quantitative measure for the development of cloud streets, we introduce a simple algorithm using the autocorrelation function on the cloud mask (section 2.3), which provides a scalar quantity for the degree of organization in cloud streets and the alignment along the cardinal directions.

We find that, in the absence of a horizontal wind, 3D radiative transfer produces cloud streets perpendicular to the sun's incident direction whereas the 1D approximation or

constant surface irradiance produce circular, randomly positioned, clouds. Our reasoning for this is the geometric position of the cloud's shadow and the corresponding feedback on surface fluxes which enhances or diminishes convective tendencies (see fig. 6 for details). While the ~~data indicates~~ simulations indicate that there exists an influence due to atmospheric heating rates, we find that the differences between 1D and 3D radiation stem predominantly from surface heating, i.e. the horizontal displacement of cloud shadows. Furthermore, with increasing horizontal wind speeds of 5 or $10\,\mathrm{m\,s^{-1}}$, we observe the development of dynamically induced cloud streets. ~~So far, this is consistent with the literature on the~~ The dynamical formation of cloud streets ~~which is introduced in section 1~~ is not particularly surprising, but leads to the question if and how radiative transfer interacts with the organization of convection.

~~However,~~ We find that if solar radiation illuminates the surface beneath the cloud, i.e. when the sun is positioned orthogonal to the mean wind field and the solar zenith angle is larger than $20°$, the cloud-radiative feedback may significantly enhance the tendency to organize in cloud streets. In contrast, in the case of the 1D approximation (or also 3D if the sun is aligned with the mean wind), the tendency to organize in cloud streets is weaker or even prohibited because the shadow is cast directly beneath the cloud, weakening the cloud's updraft. The ~~radiative feedback on~~ timescale of the convective organization through radiative transfer is found to happen typically on the order of one hour (see fig. 4). The radiative feedback, creating surface heterogeneities is generally diminished for large surface heat capacities. We therefore expect radiative feedbacks to be strongest over land surfaces and less so over the ocean. Given the results of this study we expect that simulations including shallow cumulus convection will have difficulties to produce cloud streets if they employ 1D radiative transfer solvers or, may need unrealistically high wind speeds to excite cloud street organization.

~~Future studies have to~~ An interesting future topic would be the influence atmospheric heating rates on the evolution of cloud shapes, particularly the corresponding timescales and how the introduced asymmetry and shear changes the local flow. Moving forward, we will examine if the relationship between radiative transfer and convective cloud streets also applies to the real world with all the complexities of static surface heterogeneities and complex wind fields. A promising start is an analysis of the simulations within the HDCP[2] project (Heinze et al., 2017) which will allow us to test the here proposed interpretations in a more realistic setup.

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