Answer to the Editor

Dear Peter Knippertz,
thank you for your comment and excuse our slow response.

Reviewer 2 criticised that the title raises expectations that are not fulfilled by "only" presenting one case study and suggests adding a climatology of atmospheric deserts. These are very valid concerns, please see below for our detailed answer to the major and main minor comments of reviwer 2. In summary, we can say, that in order to address the mentioned concerns, we change the title of the manuscript and parts of the text, to make clear that we introduce the concept and illustrate it with one case study only. However, we will not incorporate a climatological analysis in this study, as this requires comprehensive analysis and would be beyond the scope of one paper, as you mentioned yourself. To address the remaining major comment, we also include a more detailed discussion about the definition/detection of ADs based on single trajectories, showing that using only single trajectories to identify AD-cells does not lead to a vast mis-identification.

With your consent we are happy to provide a complete answer letter, containing both reviewer's comments, our respective answers and the changes made to the manuscript, together with the reviewed manuscript and a document highlighting the changes made. Since some of the co-authors were out of office and we could only answer to the second review now, we would appreciate an extension of the deadline. We have requested an extension of the deadline by 15 days in the online tool already. However, there is a week-long downtime scheduled next week at the high performance computing facility we work at. Therefore, we would be very glad if you could grant us an extension until the end of October. We will gladly provide all required documents as fast as possible.

Answer to Reviewer2

Dear reviewer,
thank you for your feedback and the constructive comments. Below, we address your main comments individually.

Major Comments:

1. In my view, the title of the study promises a little bit too much. When I first read the title, I imagined that the authors were introducing a new concept and showing how this new concept affects weather in the extratropics in general. In reality, the authors "only" performed a case study, which is not negative in itself, but not enough for this title. This brings me to my main critique of this study. Although the case study is certainly very nicely analysed and interesting, the main findings of the study are not too significant. [...]

Thank you for this comment. We understand how you might expect more of the study, based on its title. To address your concern, we adjust the title to "Detection and Consequences of Atmospheric Deserts: Insights from a Case Study". We adjust the descriptions in the abstract, introduction and where appropriate accordingly, in order to not mislead the readers.

Nevertheless, we highlight that the objective of this study is to introduce the new concept of atmospheric deserts based on the idea that they should be a generalisation of EMLs. We base the conceptual interpretation on literature about EMLs and our physical understanding of the involved processes. The case study in this study is used to explain how the direct detection method is applied and to gain first insights into how ADs might be similar or dissimilar to EMLs.

2. Climatological analysis: I know that this needs very much computing time. But I would suggest that the study would extremely benefit from that. For a climatological analysis a calculation of trajectories on a much coarser resolution would be sufficient (I think this would be feasible in terms of computation time). [...]

We do appreciate that a systematic analysis of a climatology of ADs would be beneficial. Such a study is planned for the near future. However, this would be beyond the scope of this paper. The resolution of the trajectories used in this paper is not feasible as it requires a lot of computational resources and produces vast amounts of data. As you suggest, reducing the resolution is a solution, but a careful experiment setup is required, as the identification of the AD air mass is sensitive to the amount of initiated trajectories (also see our answer to your major comment 4). Additionally, ADs can be expected to be a rare phenomenon, which makes the calculation of a smooth climatology challenging. We are planning to make use of gerneralized additive models that have been shown to outperform simply using average cell-counts (i.e. Simon et al. 2017). Furthermore, a climatology of AD occurrence "only" is not sufficient to answer all the questions raised in the manuscript. A thorough analysis of the (co-)occurrence of high near-surface temperatures and thunderstorms is required as well. We also plan to use statistical methods to determine whether the presence of an AD is a useful predictor for these extreme events. While this is interesting and necessary research, incorporating all this comprehensive analysis in this paper would result in a very extensive paper, which we do not deem beenficial.

3. Maybe you can discuss the atmospheric desert with the opposite "atmospheric river"? Both can lead to extreme events, one to extreme precipitation and the other one to extreme temperatures? Maybe you can elaborate on this (also this discussion would need a climatological analysis)

This is indeed an interesting point. Since a climatological analysis is beyond the scope of this study, we cannot discuss this in much detail. However, we will address this in the discussion. The comparison is not very straight forward, however. While the name "atmospheric deserts" is inspired by "atmospheric rivers", the phenomena are not really each others opposite. Atmospheric rivers are defined by their water vapour footprint, but atmospheric deserts are defined solely by their source region.

4. I find the definition of an atmospheric desert in L60-61 a bit too weak. Is only one trajectory really enough to significantly affect a grid box? Maybe you could perform a sensitivity analysis and elaborate on that.

Thank you for this comment, you have a valid point. Reviewer 1 raised a similar concern. However, the number of trajectories that reach one cell is not only dependent on whether this cell is dominated by AD air, but also on how many trajectories were initiated. We aim to make this methods computationally feasible for longer time series and climatologies, and therefore have to further reduce the amount of trajectories initiated. In order to address your concern, we have re-plotted Figures 1, 4 and 5 in the manuscript so that they show the actual number of trajectories in the cells (see Figures 1-3 below). Note, that according to the comment of reviewer 1, we also only use trajectories started during the daytime (1-5pm) to avoid computing the residual layer. Hence, we are using much less trajectories now than in the original manuscript. It becomes clear that especially along the edges that are important to the discussion, the number of trajectories is high, hence not many are classified based on just one trajectory being present. We believe this demonstrates that using a threshold of at least one trajectory is a useful approach and we do not substantially misidentify the AD edges. An explaining sentence is added to the manuscript.

Minor Comments:

The remaining minor comments that are not addressed here will be addressed directly by encompassing them in the revised manuscript. We will mention the individual changes made in the final response letter.

L20-21: Is your postulation corroborated by your findings?
Thank you for raising this concern.
Based on our understanding of the EML literature, we conjecture that ADs should also greatly impact heat wave and thunderstorm formation. Our findings from the case study presented here show that in this case high temperature and thunderstorms did co-occur with the AD event. The results indicated the the AD did influence the formation of the thunderstorms along its edge. However, the high near-surface temperatures were not caused by the lid-processes that was suggested before. Whether they are still caused by the AD or coincidental cannot be definitely answered based on this case study and will be subject to further research.
In order to soften the statement in the manuscript we rephrase it as: "We conjecture that atmospheric deserts (ADs) can greatly impact heat wave and thunderstorm formation."

L21: Can atmospheric deserts also transport dust towards the mid-latitudes?
Most certainly, yes. However, if they do will be dependent on the weather situation in the source region. Therefore, dust-bringing ADs, just as EMLs are a subset of ADs. How many of the AD events bring dust will be an interesting question to investigate, once we have a climatology, especially as dusty events may influence the weather in the target region differently than non-dusty events.
We address this in the revised manuscript: "In some cases ADs may also bring dust from the source to the target region, however, this is not analysed in this study."

L 34-35: The effects of EMLs and ADs are similar. Is there a process in your case study which is new in ADs and not yet found in EMLs?
We change this to: "The consequences of EMLs and ADs can be expected to be similar, however, the latter was never studied before. Hence this study is looking at one case of an AD that would not have been classified as an EML, but that co-occurred with strong lightning activity along its edge and high near-surface temperatures in its centre." and changed the order of paragraphs in the introduction slightly to accommodate this.
Since this is in the introduction, we do not wish to go into detail of what we found. However, we mainly find that the occurrence of thunderstorms and high near-surface temperatures are indeed similar, but we show that

the mechanism causing the high temperatures in this AD case is not the one that was suggested for EMLs.

L114: Is there a meteorological reason why you use exactly this region as source region
North Africa is the source region for typical large scale patterns that bring ADs to Europe. The premise was, therefore, to chose a polygon in Northern Africa as the source region.
Our definition of ADs requires the source region to be hot and dry (with a deep BL). Our entire source region lies within an arid, desert, hot region according to the Koeppen-Geiger climate zone classifications (BWh, see Fig. 1 and Tab. 2 in https://doi.org/10.1038/sdata.2018.214). It can be assumed safely, that if trajectories from further south also play a role, they have to pass through this source region, so we would capture them anyways. We have also investigated the soil types and vegetation cover in the region (in ERA5) and avoided the coastal regions, which have soil types and vegetation indicating that they here the oceanic climate may have a non-negligible influence. See Fig. 4. Additionally, our source region is completely in the Lee of the Atlas mountain range.

L149: where do the other 80% of the trajectories are going to?
According to the comment of reviewer 1 we only use trajectories that were started during the daytime, hence the total numbers differ from the original manuscript, the message remains the same, however.
About 45 Mio. trajectories were started during this case study (instead of 200 Mio as stated in the manuscript). 8.7 Mio. of them are used for further analysis (vs 37 before), so you ask about the remaining 80%.
The majority of those never pass 37N and remain over North Africa. The remaining 0.7 Mio. (1.5%) have left the domain by 12UTC on 19 June 2022, so that no information about their location at that time is available and they can therefore not be used in the clustering analysis (independent of whether they have passed over Europe or not). A clarifying sentence is added to the manuscript.

L164: Which heights are encompassed in the column?
This is basically a vertical integral, one may also rephrase it and say ERA5-grid cells. I.e. there is at least one trajectory above the respective ERA5-grid cell (or in the column). Effectively, this means up to 13 km, which is the level of the highest detected AD-cell.

L168: at which height is the majority of ADs?
At 12:00UTC on 19 June 2022 the majority of the trajectories is at the 500 m layer centred at 2000 m. The majority of detected AD-cells at that time is a the 3500 m level (see Fig. 5 below). This information will also be incorporated in the manuscript.

L200: Does it make sense to regard Cluster C2 still as an atmospheric desert? Because it leads to precipitation and is not dry anymore?
This is a question of definition. We do not define ADs by looking for specifically warm and/or dry air masses. The only criterion identifying an AD is its origin being the BL in a semi-arid, desert and/or elevated region. Obviously, one could refine this definition more based on the thermodynamic variables, but we do not think that this will be a helpful approach in understanding the behaviour and consequences of air masses originating in dry and hot boundary layers.

L203-204: evaporative cooling as precipitation falling ... → is this the precipitation from Cluster C2?
L207-209: You lost me at this point. C2 is ascending, heated diabatically due to latent heat release, therefore increase in cwc-variables and decrease of q due to precipitation. But why do cwc-variables of C3 act very similar to C2, although C3 is descending and cooled diabatically?
We believe that the evaporative cooling in C3 is due to precipitation falling through form C2, yes. The similar development of the **precipitation** cwc-variables (cswc, crwc) in the two clusters is an indication for this. When precipitation forms in the upper cluster and falls through the lower one, which did not form its own precipitation, then the precipitation cwc-varibales should naturally be highly correlated. We will make this more clear in the manuscript.

Section 3.4.1 → this section is a bit disappointing because it does not provide new insights into the formation of heat waves. How long was this heat waves? Typically, a heat wave should at least last three days to be defined as such.
L264: the explanation for high surface temperatures of advection and subsidence heating is not really new in the literature ... (please review papers on heat wave formation, in particular from a lagrangian point of view)

Thank you for pointing out your concern. However, the aim of this section is not to give new information about heat wave formation. Several studies about EMLs suggested that EMLs cause near-surface temperatures to rise (see studies cited in the manuscript, and especially Cordeira et al. 2017: https://doi.org/10.1175/WAF-

D-16-0122.1). These studies imply that the EMLs acts as a lid on top of the local BL, which favours clear-sky conditions and prevents the local boundary layer from growing. This can lead to extreme temperatures below. High near-surface temperatures also occur during this case study of an AD. As the AD is also a warm and dry air mass, it could be expected that the reasons for the heat are similar to EML cases. We find, however, that the AD does not reside close to the BLH for long, so it is unlikely that a lid is the reason for the high temperatures in this case. This then raises the question what causes the high temperatures if it is not this.
As we are aware of the literature, we calculate backtrajectories to find out which of the possible processes mentioned in literature may be responsible for the high surface temperatures in this case. Their analysis implies that subsidence heating is a plausible explanation for the high temperatures. We are not suggesting that this is a new insight into the formation of heat waves, as we are aware of the literature you highlighted. We simply find subsidence to be how the high temperatures in this case study can be explained.
There are many ways to classify heat waves based on different measures for strength or length and often one has to chose arbitrary thresholds (like the 3 days you are suggesting). We avoid doing that in this case and just identify anomalously high near-surface temperatures.

L261-262: perhaps you should look for another period, in which high temperatures persisted at least 3 consecutive days in order to fulfil the criterion of a heat wave? Then you would maybe see that AD form a lid.
We do not want to prove that in some cases ADs may form a lid, but we wanted to show that it is not the lid that is responsible for high temperatures during this AD event. Therefore, choosing another period will not add anything to the argumentation. In a future climatological study we will address the question how frequently ADs form a lid and what the consequences are.

L269-L270: Hence, the analysis of the AD event ... → yes, this is correct but it still can be a coincidence, especially when you don't compare this with climatology (either your own or from existing literature on this subject)
We do not state that it could not be a coincidence.
To make our intent more clear, we rephrase the paragraph in the manuscript as: "Hence, the analysis of the AD event in June 2022 supports the hypothesis that ADs co-occur with anomalously high near-surface temperatures. We find that not the previously suggested mechanism of a lid, but subsidence heating was responsible for the high temperatures in this case. Whether this is caused or facilitated by the presence of the AD, or whether the co-occurrence is coincidental cannot be determined with one case study and will be subject of future research."

Section 3.4.2: I don't get the message of this section. Is penetration of air into the boundary layer not just a normal process when the boundary layer grows during the day? What is now the special with ADs?
As the concept of ADs is a generalisation of EMLs, it could be expected that the air is (much) warmer and dryer than the local air and therefore not able to penetrate. Therefore, seeing AD air penetrate was surprising to us, which is why we added this section, explaining why some of the AD air was still able to penetrate the local BL.

L284: ... while thunderstorm tend to erupt violently along its edges → is this always the case or only under certain circumstances, e.g. a cold front at its edge?
Literature suggests that thunderstorms tend to erupt at the edges of EMLs. It has been mentioned that in Europe, this may be related to cold fronts in the vicinity of the edge, while in the US it is more often a dry-line (e.g. Carlson and Ludlam, 1968). Pre-frontal convergence lines have been shown to develop in these situations (e.g. Dahl and Fischer, 2016). Whether this is always the case we cannot say. This is why further research in a generalised version of EMLs is necessary with regard to understanding the impact on severe thunderstorms.

L289: ... the warm AD air still suppresses thunderstorm formation in most parts. → okay, but I assume that the major reason for suppressing the convection is the large-scale subsidence in the anticyclone
You are right, with the results at hand we cannot disentangle the individual impacts of the AD and the high pressure. We change the sentence in the manuscript to soften the conclusion: "This implies that thunderstorms are suppressed, probably due to a combination of subsidence in the high pressure system and the presence of the (warm) AD aloft."

Conclusion: a critical assessment of the approach used in this study is lacking Thank you for pointing this out. In the revised version of the manuscript we will provide a critical discussion.

Figures

Figure 4: Why 00 UTC instead of 12 UTC? 12 UTC perhaps better due to the BLH topography?
00 UTC was chosen because the lightning activity was higher during this time (see Fig. 3) and this figure is

used to explain the processes behind thunderstorm formation.

Also the remaining comments about the figures will be addressed directly in the revised version of the manuscript and changes will be highlighted in the final response letter.

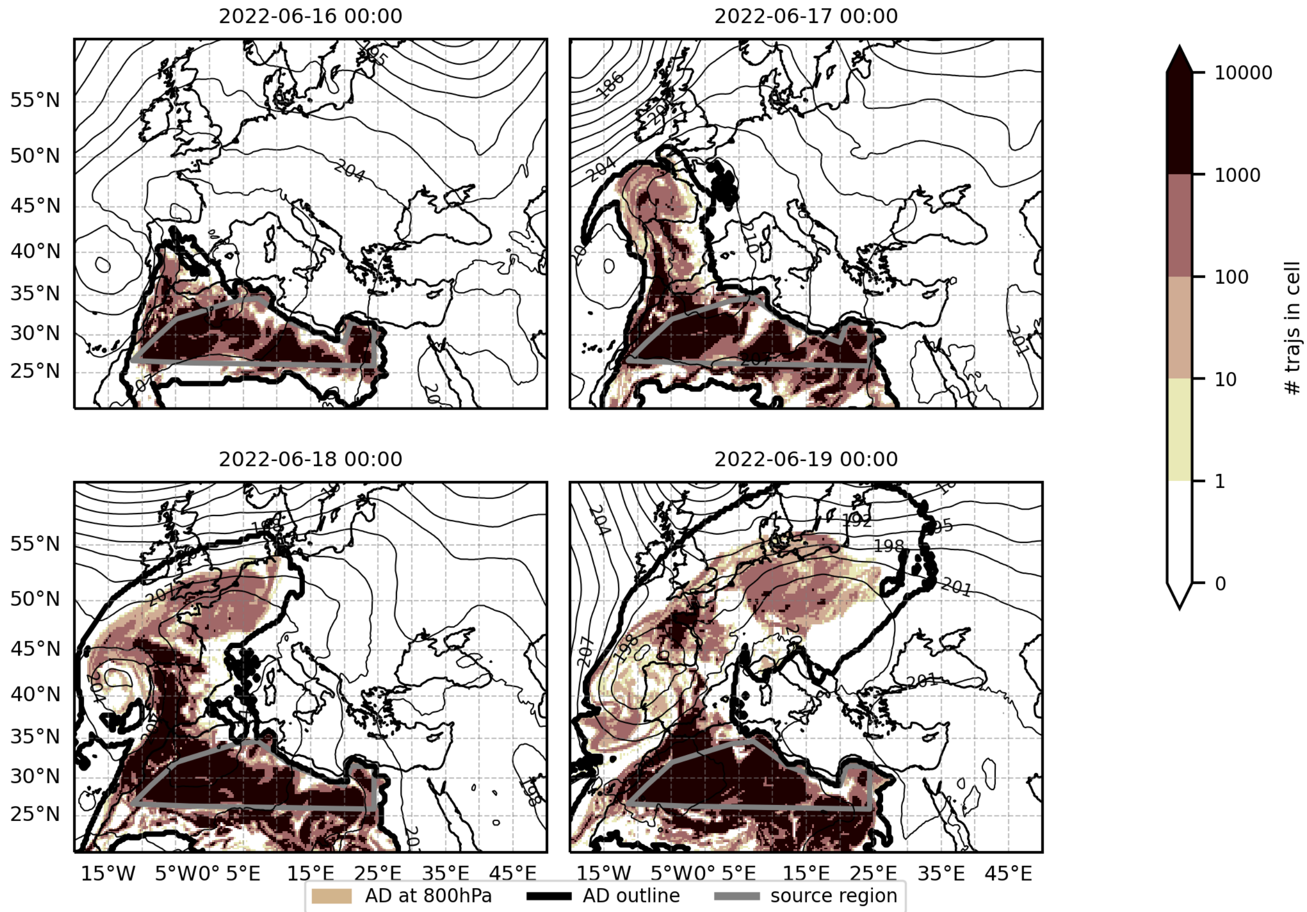

Figure 1: As Figure 1 in manuscript: AD extent in 800-750 hPa level in shaded contours, maximum extent outlined in black. Fronts and lightning omitted in this case, for better visibility. Colour scale refers to number of trajectories in the respective cell.

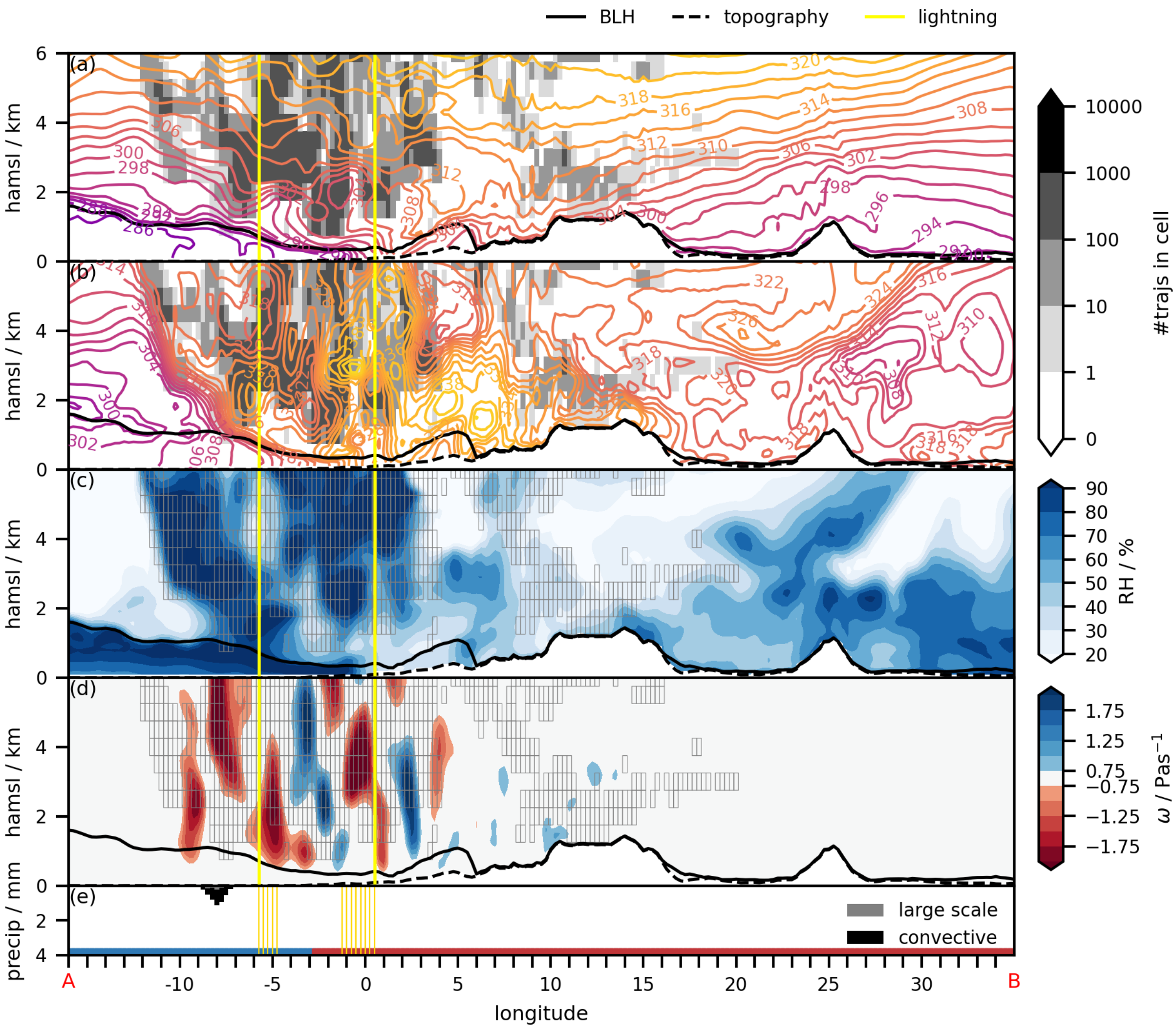

Figure 2: As Figure 4 in manuscript: AD air is marked in grey shading in the top 2 panels, the colour scale refers to number of trajectories in the respective grid box.

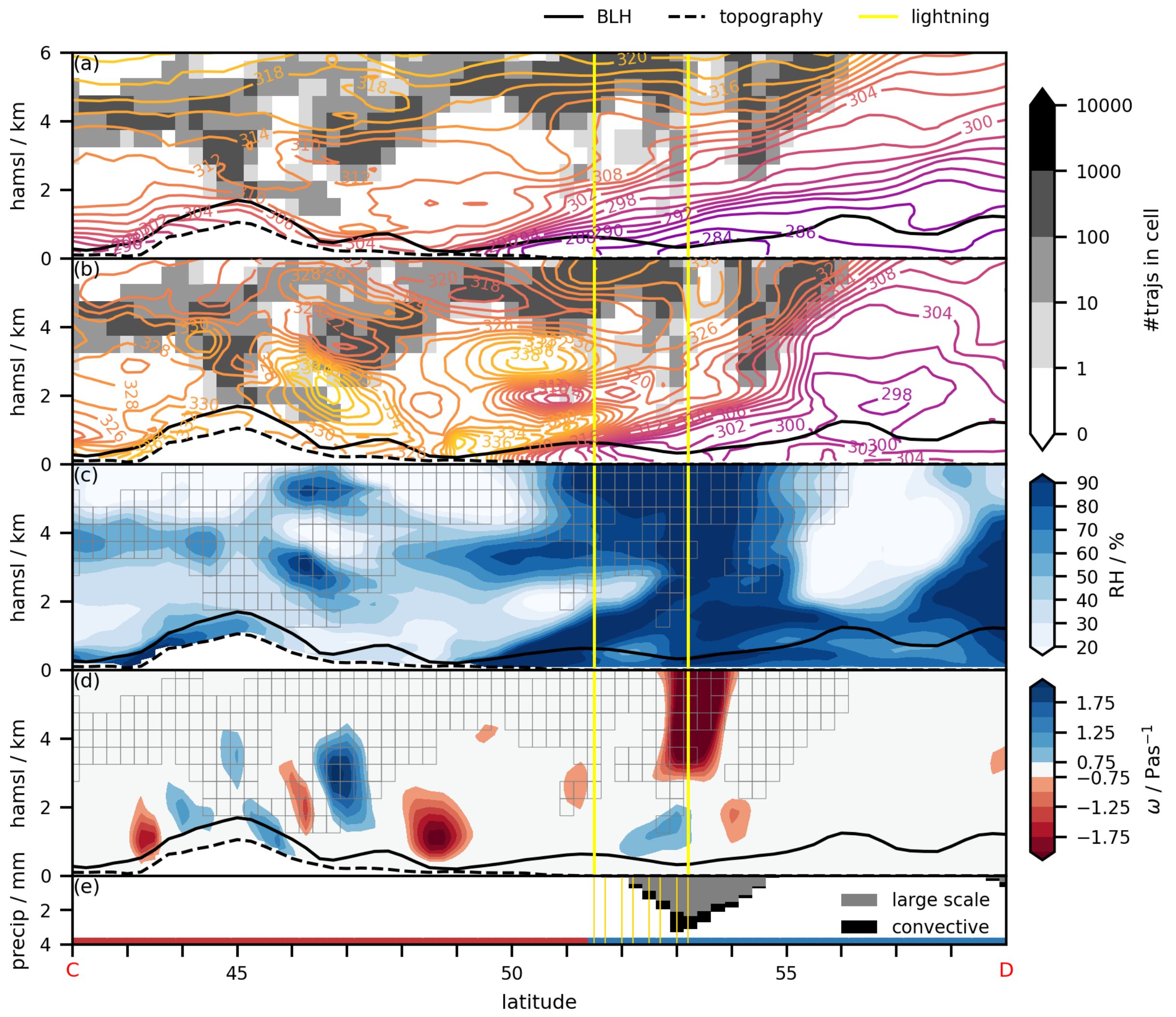

Figure 3: As Figure 5 in manuscript: AD air is marked in grey shading in the top 2 panels, the colour scale refers to number of trajectories in the respective grid box.

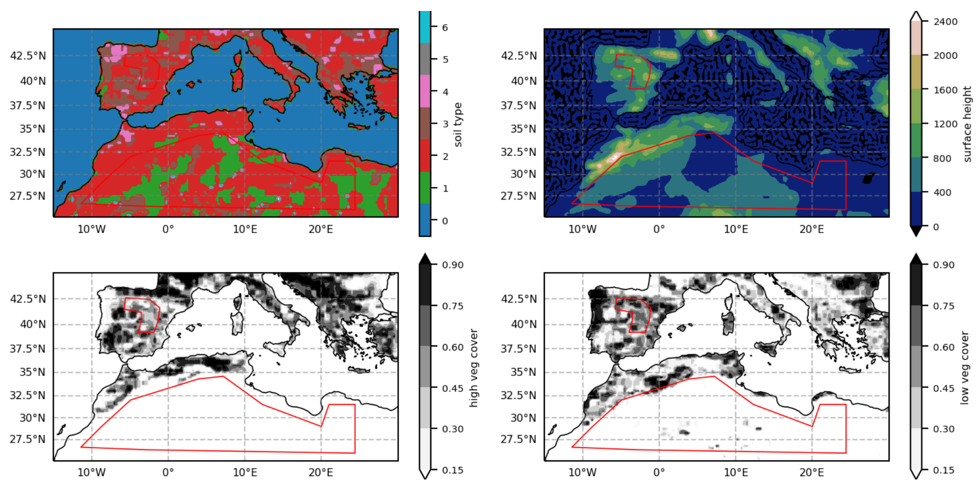

Figure 4: Map showing the source region (red) with ERA5 surface type, surface elevation, high and low vegetation.

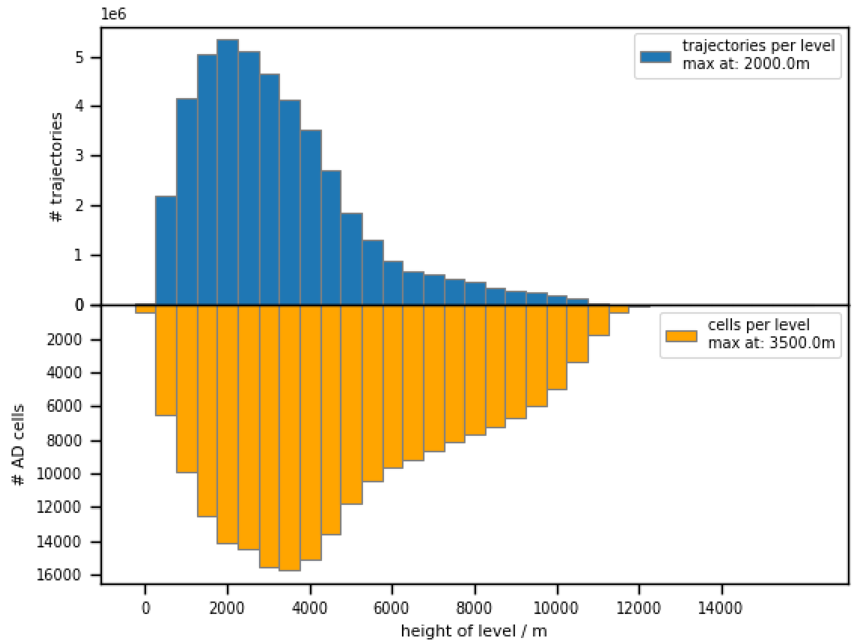

Figure 5: Number of trajectories (top, blue) and detected AD-cells (bottom, orange) per 500 m thick layer.