universität innsbruck

Johannes Dahl
Co-Editor
–
Referee 1 and 2

Date
January 14, 2022

Revision of WCD-2021-68

Dear Johannes Dahl and Referees,

please find attached the revised version of our manuscript *"Differentiating lightning in winter and summer with characteristics of wind field and mass field"* (WCD-2021-68).

Thank you very much for the constructive and helpful feedback from you, the associate editor, and the referees. Based on this feedback, the manuscript has been revised. We feel that this substantially improved our contribution. The most important changes are:

- *Renaming*.
  The former mass-field cluster is renamed into CAPE-thunderstorms cluster.

- *Intermediate seasons: spring and fall.*
  We extended our analysis to the intermediate seasons spring and fall and provide this analog analysis with the supplements. Within the manuscript, we refer more to the role of seasons.

- *Limitations.*
  A section describing the limitations of our study is now included. Throughout the manuscript, we state more clearly where our results are valid.

- *Methods.*
  The methods chapter is improved by several clarifications and more detailed information. In particular, the applied transformation and scaling are now described more explicitly in terms of mathematical formulas.

All changes and additions are explained in much more detail in the point-to-point reply on the next pages.

Best regards,

D. Morgenstern

The authors

Referee 1

I thank the authors for their novel empirical investigation of thunderstorm conditions, and for their work to utilize the multi-parameter empirical information to reason about the meteorological dynamics. I think the manuscript is suitable for publication with minor revisions, and will be a helpful practical forecasting aid while supporting clear, physically-based forecast reasoning.

Thank you.

I wanted to comment on the choice of words for the two categories of lightning identified in the study.

"Wind" and "mass/moisture" could be made even more specific and descriptive. The word choice here matters because it conditions how the reader perceives the connection to what actually drives the cloud physics processes that can result in electrification. To this point, the authors note that "wind field" is, specifically, the synoptic-scale thermal wind (line 200), and implies quasi-geostrophic dynamics driving clouds formation. Likewise, mass/moisture is really the specific thermodynamics associated with conditional instability and upright moist convection. These more specific ideas are strongly implied by the authors' reasoning, and so for this reason I encourage the authors to consider adopting more specific terms.

A good name concisely describes the characteristics of a phenomenon without being wordy or introducing new abbreviations. We argue that no single variables but the interplay of variables within a certain group are important to distinguish thunderstorms associated with the wind field, the mass/moisture field, or enhanced cloud physics. Further, a name should be easy to remember. We understand, that the term mass field might not be familiar to some readers. Considering your thoughts we came up with the term CAPE-thunderstorm instead of mass-field lightning. CAPE already includes mass-field variables and moisture-field variables and is a term that is easy to remember. Regarding wind-field lightning, we found no other term describing better the characteristics of this thunderstorm type. We have thought about "shear-thunderstorms", but this reduces the complexity too much because it omits wind speed and updrafts. Therefore we have kept the term wind-field thunderstorm but we are ready to rename it when somebody comes up with a suitable suggestion.

ACTION 1: Renaming mass-field thunderstorm into CAPE-thunderstorm.

ACTION 2: Arguing for the term CAPE-thunderstorm by pointing more towards the also increased moisture-field variables in these clusters:

> Line 181: » The light red cluster extends largely along the positive part of the second principal component that is dominated by variables of the mass-field and moisture-field categories, especially CAPE. It is accordingly named "CAPE-thunderstorm" cluster. «
>
> Line 217: » Also total column water vapor (humidity) and 2 m dew point from the moisture field category is increased. «

1. If the authors reduce the number of clusters to k=3, do the dark and light, red and blue markers combine more with each other than they do with the yellow markers?

The decision to use $k = 5$ is based on the lowest sum of squared distances and the analysis of the dendrogram from hierarchical clustering. In our opinion, $k = 5$ gives the best solution. However, $k = 4$ performs not too bad and $k = 3$ is in some samples reasonable. To answer your question, we provide two more versions of the paper's Fig. 2. When using $k = 4$ (Fig. 1), the clusters characterized by "cloud physics" merge (dark red and dark blue). With $k = 3$ (Fig 2) the wind-field thunderstorm cluster (light blue) and CAPE-thunderstorm cluster (light red) merge additionally. This stresses how much the cloud-physics variables contribute to the thunderstorm type and how well the cluster analysis differentiates between lightning and no lightning in general. All configurations differentiate similarly sharp between the average cluster and the others. The average cluster always contains some observations where lightning occurred and vice versa.

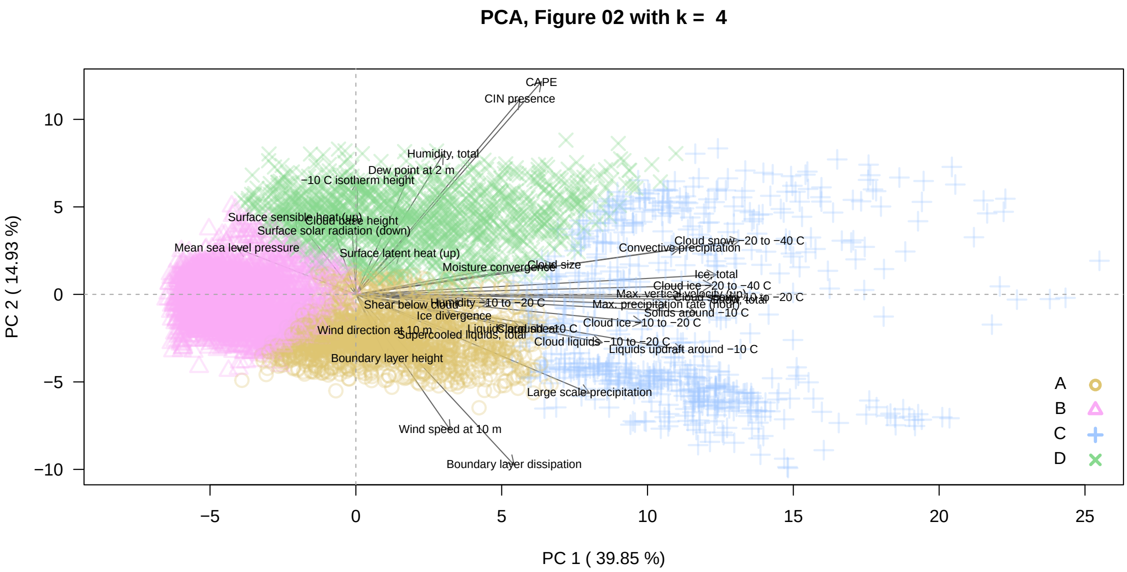

Figure 1: PCA-plot (Fig. 2) with color-coding based on k-means clustering with k = 4.

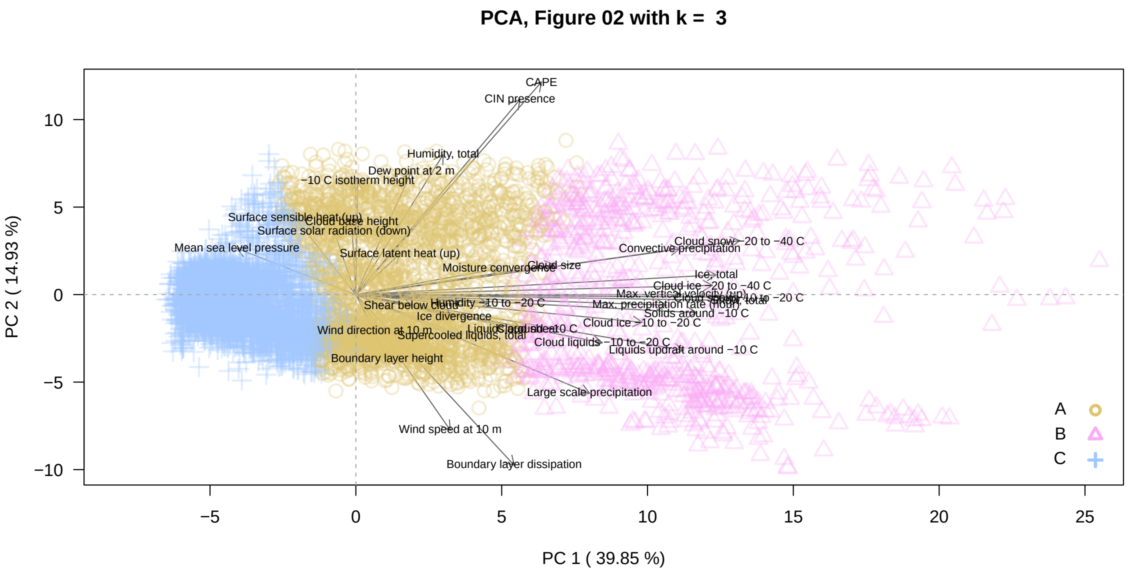

Figure 2: PCA-plot (Fig. 2) with color-coding based on k-means clustering with k = 3.

ACTION 1: A short discussion on various choices for k is included:

> Line 186: » Reducing the number of clusters in the cluster analysis would lead to a combined "cloud-physics" cluster (k = 4) and a large cluster uniting "wind-field thunderstorms" with "CAPE-thunderstorms" (k = 3). This stresses how well the cluster analysis differentiates between lightning and no lightning in general and points to the importance of the cloud physics variables to distinguish between thunderstorm types. «

ACTION 2: The similarity of the clusters with cloud physics is pronounced more, as these clusters would merge first:

> Line 162: » Together these two groups cover 24 % of the data in the lightning involving clusters and would merge when reducing the number of clusters to k=4. «

2. a) Line 36: It is predominantly differential sedimentation rates, not atmospheric motion, that separates the charges after collision. After differential sedimentation, wind shear can act. Also, on line 212 and line 290-1 and line 345: a constant vertical velocity cannot separate charged hydrometeors; the separation has to come from sedimentation within the inertial frame, or by differential motion of particles from one inertial frame to another.

The sedimentation rate of a cloud particle depends on its properties such as its shape and weight as well as on the surrounding conditions, i.e. updrafts which may reduce the sedimentation speed. Cotton (2011) describe the vector difference of air motion and condensate motion as terminal velocity.

Cotton, W., Bryan, G., van den Heever, S.: Storm and Cloud Dynamics. The Dynamics of Clouds and Precipitating Mesoscale Systems, Academic Press, 2011.

ACTION: Now the term 'terminal velocity' is used throughout the manuscript and some sentences are rephrased.

> Line 36: » The differently charged particles get separated based on their size through differential terminal velocities (Cotton, 2011) and form various charge regions within the cloud. «

> Line 42: » Differential terminal velocities with strong vertical shear of the horizontal wind cause the particle paths to become slanted and separation distances to be large despite relatively weak vertical motions and charging rates. «

> Line 251: » The large values of CAPE allow vertical velocities of 10-20 m s^{-1} and more within thunderstorms, exceeding the horizontal wind speeds resulting in a mainly vertical separation path of the particles. «

> Line 331: » Those charged regions are thought to form when different cloud particles collide and are subsequently spatially separated by differential terminal velocities (e.g., Williams, 2018). «

> Line 400: » The required terminal velocities in CAPE-thunderstorms originate from strong vertical velocities when substantial amounts of CAPE are released. Median values of CAPE in CAPE-thunderstorms in our study region is 415 J kg^{-1}. «

2. b) A related point is that the cloud life time scale is much larger in winter storms, so even relatively slow vertical motions and charging rates could still result in sufficient charge for lightning.

ACTION: This information is now included.

> Line 42: » Differential terminal velocities with strong vertical shear of the horizontal wind cause the particle paths to become slanted and separation distances to be large despite relatively weak vertical motions and charging rates. «

3. Line 75: In k-means clustering, k is chosen a priori, but the text says it "yielded k=5 clusters," which implies the the algorithm itself determined k and might be confusing to readers. The manuscript later clarifies how this k was chosen (sec. 3.3). I suggest changing "yielding" to "using."

ACTION 1: The sentence is rephrased:

> Line 88: » Using only these 35 ERA5 variables a k-means cluster analysis with k = 5 clusters is carried out to determine groups of "typical" atmospheric conditions. «

ACTION 2: And later in Sect. 3.3, another sentence is rephrased:

> Line 144: » k is set to five clusters because the sum of squared distances clearly decreases for every additional cluster until $k = 5$ but levels out for more than five clusters. Analyzing dendrograms from hierarchical clustering further support this decision.«

4. Line 110: "on the scenarios without lightning": was the normalization done separately for the summer and winter populations, or aggregated across all no-lightning subsamples? It would also help to describe this process in order as a mathematical formula: first introduce the calculation of the mean and standard deviation of the no-lightning cases, and then state how the other variables were normalized using these quantities. Line 124 and 174 repeats this phrase, and with careful explanation here it can be removed there, unless I misunderstand and normalization is being applied several times.

Normalization and scaling are performed based on all no-lightning observations in summer and winter within a given sample.

ACTION 1: We made this information more explicit:

> Line 138: » μ and σ are the empirical mean and standard deviation based on all cell-hours in winter and summer *without* lightning. «

ACTION 2: Formulas for the transformation and scaling are now included in lines 129-139 together with a hint to the supplementary material, where the algorithm is provided.

ACTION 3: The repeated information on these methods is now omitted in lines 150 and 207 (Diff-file lines 165 and 227).

5. a) Section 3.3: Were the PCA and the k-means methods applied independently? It seems so. Does independent application of the two methods help give confidence in the interpretation of the results?

PCA and k-means are applied independently. The independent application of the two methods does give confidence in the interpretation of the results because the results are similar. We made this implication more explicit.

ACTION 1: We explicitly state that PCA and k-means clustering are applied independently.

> Line 149: » Independent of the cluster analysis, the PCA is applied to the 6,304 cell-hours of 35 ERA5 variables. «
>
> Line 387: » Following a data-driven approach, we used 35 atmospheric variables from the ERA5 reanalysis belonging to five meteorological categories (mass field, wind field, cloud physics, moisture field, and surface exchange) and fed them independent of each other into a clustering and a principal component algorithm. «

ACTION 2: We stress that the two independent methods lead to the same results:

> Line 210: » Figure 4 (cluster analysis) confirms what the loadings in Fig. 2 (PCA) already indicated: Variables with larger arrows towards a given cluster in Fig. 2 correspond to higher values for that cluster in Fig. 4. «

5. b) Section 3.3: What were the key principles used to judge high- and low-meaning clusterings and PCA projections?

The decision for high- and low-meaning clusterings in Fig. 2 is based on the length of the arrows/value of the loadings. A variable associated with a large arrow is able to explain much of the variance towards the direction it is pointing. The vast majority of variables from the cloud physics cluster point right and almost no variable points mainly left. Hence the x-axis is labeled with high and low cloud physics. Most of the variables within the categories wind field, mass field, moisture field, and surface exchange point predominantly towards up or down. Large values of the respective variable are hence important for the underlying cluster. However, the sign of many surface exchange variables depend on the direction in which fluxes are defined. Labeling the secondary y-axis with high surface exchange values pointing upwards or downwards is in consequence a matter of definition, not of interpretation. We often use upward = positive. Therefore, most surface exchange arrows point upwards. We have changed the label at the secondary y-axis in Fig. 2 accordingly.

PCA is a tool for dimension reduction. This is achieved by projecting the variables on principal components and keeping only those principal components that contribute substantially to the variance within the data. The variance explained by the first few principal components is: PC1: 39.8 % PC2: 14.9 %, PC3: 7.7 %, PC4: 5.5 % (numbers from the representative sample, but the other 49 samples have very similar values). The first two PC explain about 50 % of the variance within the data. PC3 and PC4 add only a little more information. Looking at them in detail revealed no further insights or useful interpretations, so we excluded them from the paper.

ACTION 1: Figure 2: Label “surface exchange on the secondary y-axis is now pointing upwards.

ACTION 2: A new sentence about the chosen PCA projections is added:

> Line 151: » PC 1 and PC 2 are sufficient for a reasonable interpretation because they together explain about 50 % of the variance within the data, whereas the additional explained variance of PC 3 is already down to 7.6 %. «

6. Line 243 and following: the definition of the cloud used to diagnose the relative cloud temperatures in summer and winter uses only droplets. Concerning the conclusion, “during lightning in winter clouds are – integrated over their depth – overall warmer than summer clouds”, how would it change if both ice crystals and droplets were used together to define the cloud? Is there something special about droplets that makes them alone worth considering?

It seems that our description was not precise enough. With respect to our data, we define a cloud as the sum of cloud ice water content, cloud snow water content, cloud liquid water content, and cloud rain water content exceeding a mass of 1e-6 kg / kg within an ERA5 model level. We use the term cloud particles when referring to all four (ice, snow, droplets, rain) cloud physics types. We have added a panel to Fig. 6 with the cloud particle sums displaying the full cloud.

The conclusion “during lightning in winter clouds are – integrated over their depth – overall warmer than summer clouds” is based on the cloud mass (sum of all four cloud particle types) below vs. above the -10 ○C isotherm. We have made this clearer in Sect. 4.2 and supported the interpretation by some numbers.

ACTION 1: Figure 6 contains now an additional panel with the sums of the other four panels.

ACTION 2: The paragraph describing Fig. 6 in Sect. 4.2 (lines 300-325) is now more precise.

> The biggest changes occur in lines 286-289: » Looking at the cloud mass (sum of all cloud particles) below and above the -10 °C isotherm (dashed lines) of wind-field thunderstorm clouds (blues), the larger part (factor 1.7 without and factor 2.3 with cloud physics) is warmer than -10 °C. CAPE-thunderstorm clouds (reds) have similar or larger cloud particle concentrations (factor 1 without and factor 2.9 with cloud physics) in regions that are colder than -10 °C resulting in rather cold clouds. Hence, during lightning in winter clouds are – integrated over their depth – overall warmer than summer clouds. «

7. Line 310: HSLC storms (because some CAPE is present) typically do release upright convective instability even though they are during the cool season, so I appreciate the authors having introduced the HSNC idea here. It is not the month of the year but conditions associated with the synoptic pattern that control the mechanism by which lightning is generated.

Thank you. This is a good summary of our conclusions.

Referee 2

Overview

This manuscript explores the meteorological processes leading to lightning in winter and in summer in Northern Germany in an attempt to isolate conditions that differentiate between lightning and no-lightning in summer and in winter. The authors use a pure data-driven approach selecting cluster analysis and principal component analysis to group parameter derived from ERA5 reanalysis data into physically meaningful groups representing wind-field-dominated and mass-field dominated lightning conditions. While this manuscript is generally well written and informative, I have a number of suggestions that follow. Additionally, I have two major concerns that are highlighted below, which will require more thought and effort.

Thank you for your careful considerations to our manuscript. Your thoughts help to improve the paper.

Major Comments

1. Northern Germany was chosen as study area to represent an area in the mid-latitudes and in flatland to minimize topographical triggering influences on lightning. The selected area is rather small. The results obtained in such a restricted area cannot be transferred to southern Germany nor to the rest of central Europe, which includes the Alpine region. Minimizing topographical triggering influences on lightning is a considerable restriction. Orography often acts as a trigger mechanism in summer as well as in winter. The limitations of the choice of the study area are not stated clearly in the manuscript. What would the results look like for other regions, e.g. southern Germany, the Alpine region or along the Mediterranean coast? Are the findings valid in other regions of (central) Europe? If not, how do they variate?

By choosing a small region, we are able to treat this region as homogeneous and can use objective, data-driven approaches. The applied scaling implies, that the means and their anomalies are assumed homogeneous within the domain. A larger domain would require scaling techniques using spatial varying means and variances to account for regional differences and local climatological characteristics. This spatial varying scaling is a challenge that must be applied sensitively in order not to distort the results and is beyond the scope of this paper. Our working group is already working on expanding this analysis to other regions to give a more comprehensive overview of different lightning conditions in Europe.

ACTION 1: A paragraph on limitations in the discussion section is added (lines 369-377), describing several limitations.

> The limitation regarding the domain size is treated in lines 396-372: » The study area was deliberately limited to a topographically uniform region (northern Germany) to reduce the complexity of the problem. The data-driven approach used here should easily transfer to other regions. When larger, non-homogeneous regions are studied, the data scaling techniques will have to be extended to be able to deal with spatially varying means and anomalies. «
>
> Further limitations are stated in the following lines.

ACTION 2: At the end of the introduction (lines 46-56) a new paragraph states more clearly our hypothesis and approach.

> Regarding the domain size, line 52 is relevant: » To clearly make the distinction between processes and a mere seasonality of favorable thunderstorm conditions, we focus on winter and summer seasons only at a fairly small and flat study region to avoid having topography as an additional forcing mechanism and to have homogeneous lightning conditions with a uniform annual lightning cycle over the entire domain «

ACTION 3: In the Data-section, the reasons for choosing such a small study area are explained better.

> Line 63: » The study area was chosen to be in the mid-latitudes, to be covered by a lightning location system with high detection efficiency, and to be topographically fairly uniform. A region in northern Germany shown in Fig. 1 fulfills these criteria. It includes some small hills but the elevation is mostly some decameters above mean sea level. «

ACTION 4: We pronounce more clearly that our conclusions are restricted to this study area. See also 12.

2. a) Is it really necessary to group the data into seasons? If lightning occurs or not should not be defined by the calendar but rather by the synoptic and atmospheric conditions that lead to the mechanisms of thunderstorm generation and the formation of lighting.

This is exactly our motivation. We think it is better to describe the driving atmospheric conditions for lightning instead of applying a seasonal distinction. We hypothesize that in central Europe north of the Alps where most lightning occurs in summer and least lightning in winter different lightning conditions dominate summer and winter whereas spring and autumn act as transitional seasons. Since lightning in winter is so rare in our study region, we have to assure that enough of the thunderstorm type responsible for these rare events is present in our data. Therefore we use data from winter and oppose it to the season with most lightning (summer). Choosing only the 'extreme' seasons with least and most lightning isolates the lightning conditions from likely transitional variants in the transitional seasons. The statistical methods do not get information on the season and group only by meteorological characteristics.

ACTION 1: The end of the introduction (lines 46-56) states our motivation and hypothesis better and describes why we group into seasons.

> Regarding the selection of seasons, line 49 is relevant: » If thunderstorm types are differentiated by processes instead of seasons, more insights can be gained and a contradiction arising from a seasonal classification can be resolved, for example, that of the annual lightning maximum in fall in the northern Mediterranean compared to central Europe where lightning peaks in summer (Taszarek et al., 2019). To clearly make the distinction between processes and a mere seasonality of favorable thunderstorm conditions, we focus on winter and summer seasons only [...] «

ACTION 2: The introduction to the methods section (Lines 80-82) describes now more precisely that only winter and summer are used to provide clearer results.

> Line 80: » To clearly isolate the effects of seasonality, only the two extreme seasons winter and summer are chosen and a methodological approach is selected that can properly handle the vastly different lightning frequencies in these two seasons. «

2. b) The study is limited to the two seasons winter (December, January and February) and summer (June, July and August). What about spring and autumn? How would the cluster analysis and principal component analysis deviate in these seasons from the presented seasons?

We have now expanded the analysis described in the paper to the whole year using eight scenarios: winter, spring, summer, fall, with and without lightning. As expected, the same clusters are robustly found but not as pronounced as with the 'extreme' seasons only. The distinction between the clusters with enhanced cloud physics is weaker than using only winter and summer. Because the characterizations of the clusters are somewhat blurred by transitional thunderstorm variants, we stick to the clearer results in the manuscript but supply the additional analysis for the full year with the supplements.

Figure 4 : The intermediate seasons (spring and fall) in our observational region consist of all four thunderstorm types but are dominated by CAPE-thunderstorms.
Figure 3 and Figure 5 : When using the full year, the difference between the two CAPE-thunderstorm types becomes weaker because the cloud-physics & wind-field cluster takes now a larger fraction of the cell-hours with high cloud physics as the PCA shows.

ACTION 1: The full analysis has been repeated for the full year and the results are provided with the supplements. The manuscript hints at this material in lines 56, 81, 108, 201, and 245.

ACTION 2: The analysis of the stacked bar plot (Fig. 3) is expanded by a description of the other seasons.

> Line 201: » Extending our analysis to the full year (see supplements) reveals that spring and fall both consist of around 36 % CAPE-thunderstorms, 25 % wind-field thunderstorms, 20 % cloud physics & CAPE-thunderstorms, and 10 % cloud physics & wind-field thunderstorms. «

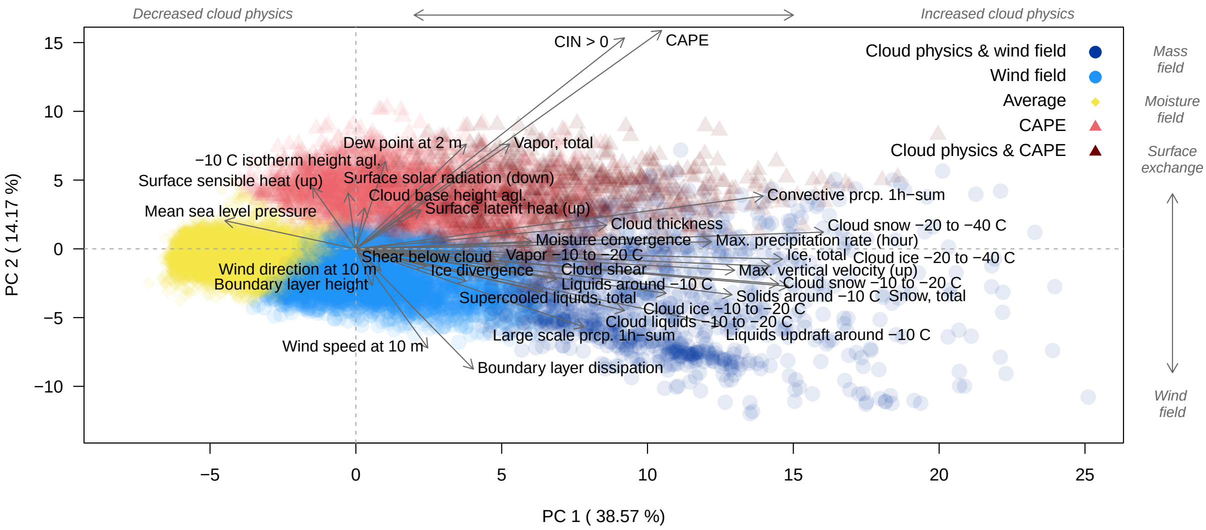

Figure 3: PCA-plot (Fig. 2) based on 12,608 cell-hours from eight scenarios including data from the whole year.

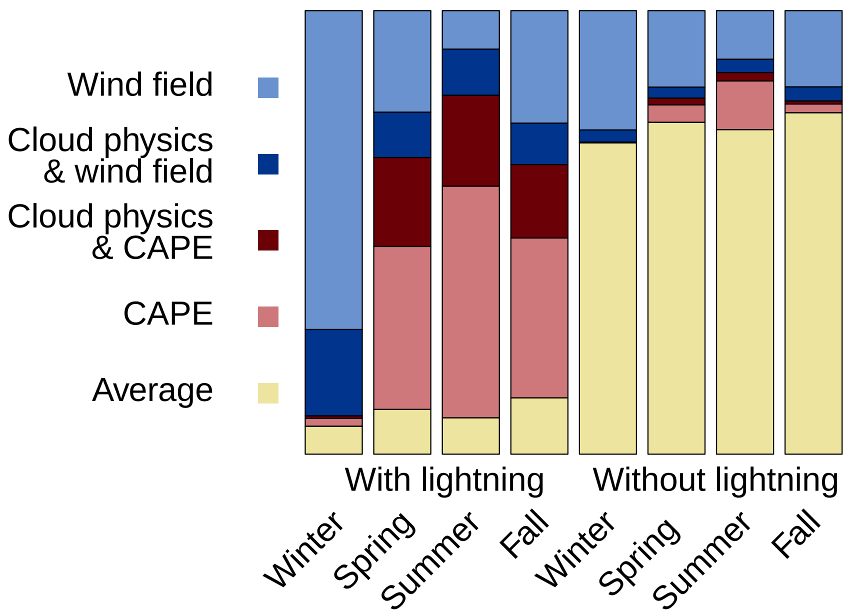

Figure 4: Stacked bar plot (Fig. 3) of the clusters found in the eight scenarios covering the whole year.

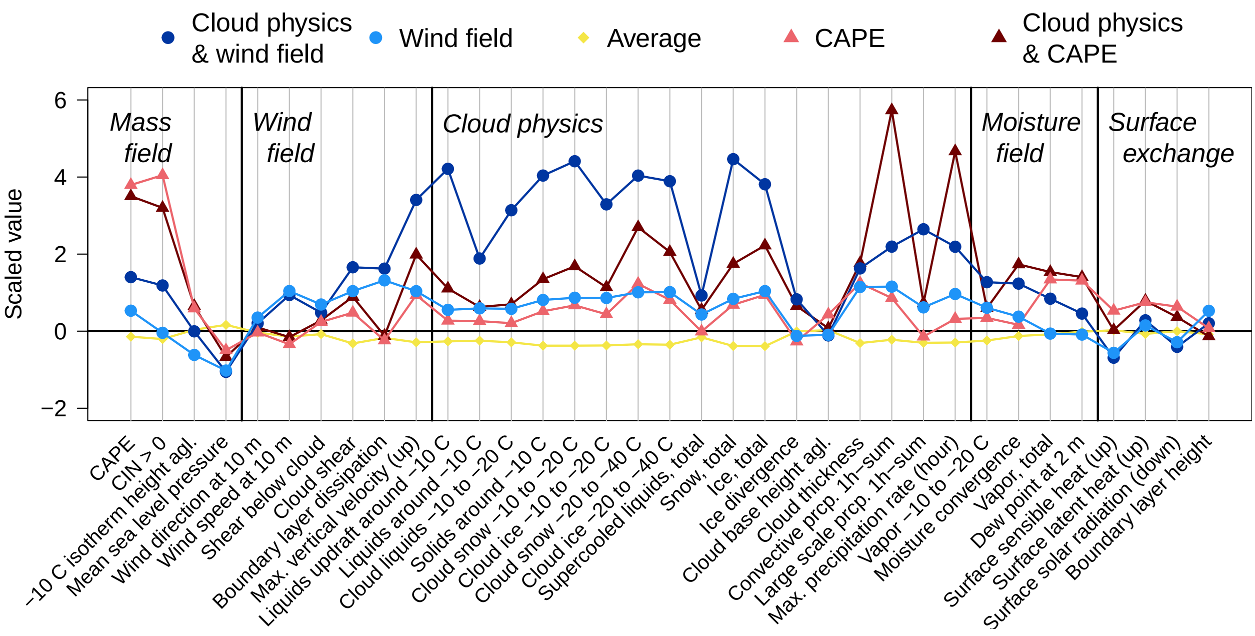

Figure 5: Matplot (Fig. 4) of cluster means (scaled) based on a cluster analysis with data covering the whole year.

Minor / Grammatical Comments

1. Line 22: "copious amounts of moisture" – What type of moisture is meant here? Moisture near the ground or in the atmosphere? Moisture in form of specific humidity or relative humidity?

ACTION 1: The sentence refers to near-surface water vapor and is changed accordingly:

> Line 21: » The required large values of convective available potential energy (CAPE), copious amounts of near-surface water vapor and the presence of a vertical instability (Doswell III, 1987) are normally absent in winter. «

ACTION 2: The names of some ERA5-variables are changed to be more specific:

> Humidity → (water) vapor
> CIN presence → CIN > 0
> cloud size → cloud thickness
> -10 C isotherm → -10 C isotherm agl.
> cloud base height → cloud base height agl.
> convective precipitation → convective prcp. 1h-sum
> large scale precipitation → large scale prcp. 1h-sum

2. Line 54: Figure 1

The manuscript preparation guidelines of Weather and Climate Dynamics state:

» The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that..." « (https://www.weather-climate-dynamics.net/submission.html#figurestables).

NO ACTION: The manuscript is already in line with the wcd guidelines.

3. Line 68: Although a .csv file is provided with a detailed description of the variables used in this study, I suggest to add a table with name, unit and meteorological category of the selected variables.

ACTION: The suggested table is now included in Sect. 3.2. (line 114).

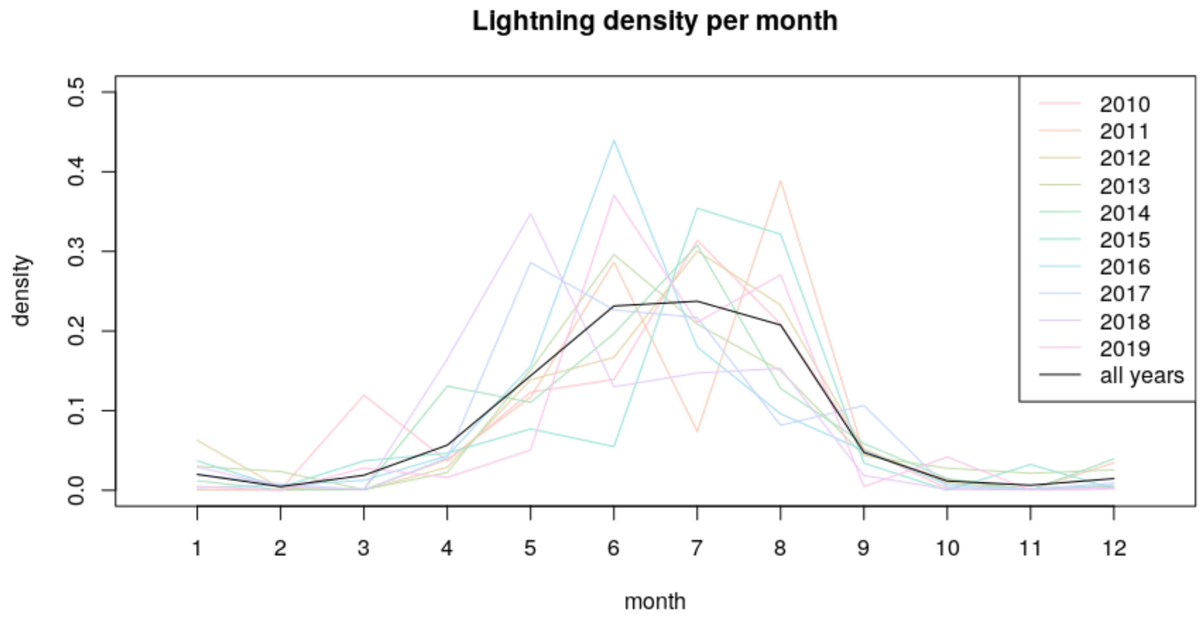

Figure 6: Time series of all 40,378 cell-hours with at least one lightning stroke between 2010-2019 in the study region. Lightning density is given for every year (colors) and the whole period (black).

4. Line 71: How are equally-sized subsamples formed? Randomly?

The samples are drawn preserving the diurnal lightning cycle of the respective season. The sample for lightning in summer is drawn unconditionally because the observations already follow the diurnal cycle and so does each sample. The samples for the no-lightning scenarios are drawn conditional on the diurnal cycle for lightning in that season. Therefore we calculated the lightning probability for each hour in summer and winter separately and assured that the number of observations in the drawn samples follow those diurnal cycles. This procedure is known as stratified sampling in statistical literature.

ACTION 1: Additional information is given in this introductory sentence:

> Line 84: » First, equally-sized samples from four scenarios of lightning observations are formed: Lightning in winter, no lightning in winter, lightning in summer, and no lightning in summer, each following the diurnal cycle of lightning in the respective season. «

ACTION 2: More details are provided to the concept of stratified sampling:

> Lines 98-102, especially line 100: » This sampling is done conditional on the diurnal cycle for lightning in the respective season, known as “stratified sampling in statistical literature. All sampling is performed without replacement and on the basis of cell-hours. «

5. Lines 81-92: Can you provide a time series of all lightning that occurs within the selected domain? I assume there are years with higher lightning activities in the respective seasons? How were the “cell-hours” selected? Are they representative for an “average” season?

Figure 6 gives a time series of all lightning cell-hours within our study region. There is interannual variability but the overall pattern with little lightning in winter and much lightning in summer is conserved. The black curve describes the lightning density of all years and can be seen as the “average” distribution from which all samples are drawn.

In our calculations, all cell-hours in winter with at least one lightning stroke are used. For summer with lightning, we use random drawn samples without replacement. The samples for the no-lightning scenarios are drawn conditional on the lightning probability for each given hour of the respective season so that these samples contain cell-hours proportional to the diurnal cycle.

Each of our 50 samples is representative of an “average” season in the sense that the samples are drawn from the black curve in Fig. 6 and are hence characterized by a similar smooth “average” distribution because the sample size is large enough (1,576). This becomes evident as most samples reveal similar results. Since we are considering cell-hours instead of single strokes the influence of single but efficient thunderstorms vanishes.

ACTION 1: See Action in your minor 4; i.e. lines 84 and 98-102.

ACTION 2: We point out that sampling with a sufficiently large sample size over enough data reflects average conditions in each sample.

> Line 106: » Each sample is drawn from the whole 10 years of data so that single anomalous seasons do not have a proportionally large influence. The similarity of the 50 samples gives further confidence in the robustness of our results. «

6. Lines 110-112: It is not entirely clear to me exactly how this is done. Please add more information or a concrete example.

See answer to statement 4. of Referee #1.

ACTION: The procedure is now described in terms of formulas in lines 129-138.

7. Line 119: What does “yielding k=5 clusters” mean?

k-means clustering returns exactly *k* clusters, as *k* is an argument to the algorithm. There are several methods helping to find the optimum number of clusters for given data. We use "sum of squared distances" and subjectively look at dendrograms from hierarchical clustering. Based on these analyses we decided to use *k*=5 clusters.

ACTION: See 1. and 3. from Referee #1.

8. Line 129: Use PCA as this was already introduced in line 120.

ACTION: done.

9. Figure 2: Variables derived from ERA5 reanalysis data are not observations. The labeled arrows are very hard to read. Could the readability of the figure be improved?

ACTION 1: The term ‘observation’ in combination with ERA5 is omitted from the entire manuscript. Instead, the terms ‘cell-hour’ or ‘event’ is used.

ACTION 2: In Fig. 2 the font of the labeled arrows is now increased and some labels are pushed a little aside to avoid overlapping of labels.

10. Figure 3: How would the stacked bar plot of the clusters differ for spring and autumn?

See Fig. 4 in major 2. b)

11. Line 148: Figure 2. Please be consistent with the usage of Figure x or (Fig. x) throughout the manuscript. E.g. use Figure in the text and Fig. in brackets.

NO ACTION: See minor 2.

12. Line 188: Within the mid-latitudes, there are many regions where lightning occurrence does not peak in summer months. Please check Taszarek et al. 2019.

Reference:
Taszarek, M., Allen, J., Púčik, T., Groenemeijer, P., Czernecki, B., Kolendowicz, L., Lagouvardos, K., Kotroni, V., & Schulz, W. (2019). A Climatology of Thunderstorms across Europe from a Synthesis of Multiple Data Sources, Journal of Climate, 32(6), 1813-1837. Retrieved Dec 5, 2021, from https://journals.ametsoc.org/view/journals/clim/32/6/jcli-d-18-0372.1.xml

The regions where lightning occurrence does peak in summer according to Taszarek 2019 et. al. (Figs. 4, 9–15) are Northern Europe (except Stavanger), Northwestern Europe (except London), Central Europe, Eastern Europe, and Southeastern Europe (except Athens). This includes our study region.

ACTION 1: We restricted our message to central Europe where summer is the main lightning season and rephrased the sentence.

> Line 223: » Overall, CAPE-thunderstorms are responsible for most flashes in our study region because 84 % of the lightning cell-hours in summer (JJA) are clustered as CAPE-thunderstorms. As summer is the main lightning season in our study region, we expect CAPE-thunderstorm processes to be the predominant lightning mechanism there. «
> Line 1: » Lightning in winter (December, January, February, DJF) is rare compared to lightning in summer (June, July, August, JJA) in central Europe north of the Alps «
> Line 49: » If thunderstorm types are differentiated by processes instead of seasons, more insights can be gained and a contradiction arising from a seasonal classification can be resolved, for example, that of the annual lightning maximum in fall in the northern Mediterranean compared to central Europe where lightning peaks in summer (Taszarek et al., 2019). «

—

We hypothesize that there are different lightning processes instead of "winter lightning" and "summer lightning". We assume that lightning in a given season at a given place is dominated by a specific lightning process (infrequently, other processes might also occur) and that a lightning process dominating in summer at one place could be responsible for lightning in fall at another place. Therefore we analyze lightning in the two "extreme" seasons in a small domain with homogeneous conditions. After this study, we aim at expanding this analysis to other regions where maybe even more lightning conditions could occur.

ACTION 2: Our approach and our hypothesis are stated more clearly in lines 46-56. See also major 2. a).

13. Line 274: Is the approach really purely data driven and completely independent of the season?

Is difficult to define what makes a thing "purely" data-driven and "completely" independent of something. Therefore we omit these words from the manuscript and speak simply of "data-driven" approaches.

We call our approach data-driven because we apply the same algorithm to all data, i.e. we do not treat the seasons differently. The cluster analysis and PCA are applied to all our 35 ERA5 variables in the same way and without restrictions.

ACTION: Omitting the phrases "purely" data-driven and "completely independent of the season".

> Line 210: » This corroborates again that clustering reflects physical meaning. «
> Line 316: » Rather than taking the common approach of looking at differences between thunderstorms in winter and summer, we have taken a data-driven approach.«
> Line 46: » The goal of this paper is to take a step back from the obvious seasonality of lightning frequency (Vogel et al., 2016; Matsui et al., 2020) and apply a data-driven approach [...] «
> Line 487: » Following a data-driven approach, [...] «
> Line 421: » In summary, the data-driven approach yielded [...] «

14. Line 285: What are "large amounts of CAPE" values?

The statement beginning with line 326 points out the differences between thunderstorms and strong moist convection in general. Therefore the actual value of CAPE is irrelevant and the sentence is rephrased to be more general in this regard. Later when we talk specifically about our results, we include median values of CAPE for our study region (see statement 16.).

ACTION: Rephrasing:

> Line 327: » Strong moist convection depends upon high vertical velocity and deep clouds, which requires the presence of CAPE and a trigger to release it. «

15. Line 295: Please check the order of the references throughout the manuscript. The years of the publications should be ascending.

Previously the order of reference has been by importance to the given statement.

ACTION: All references are now arranged in ascending order.

16. Line 346: What are "substantial amounts of CAPE"?

A table summarizing cluster median values for each ERA5 variable is now provided together with explicit values at various places in the manuscript. This gives a clearer picture of the clusters and similar questions for other variables are easily answered.

ACTION 1: Median values of CAPE are now included:

> Line 400: » The required terminal velocities in CAPE-thunderstorms originate from strong vertical velocities when substantial amounts of CAPE are released. Median values of CAPE in CAPE-thunderstorms in our study region is 415 $\mathrm{J\,kg^{-1}}$. «

ACTION 2: A table of cluster medians is now included (Table 2). Lines 206 and 228.

ACTION 3: Numbers from Table 2 support now several statements in various places of the manuscript, especially in Sect. 4 results.

Community Comment

Milind Sharma, 2021-10-25

Section 3.2 and supplementary information: The authors mention deriving 35 parameters from ERA5 data but do not discuss the methods used to derive those additional variables. Supplementary csv file only mentions "parameter derived by lightning group at UIBK" which does not tell much to the reader.

The selection of the 35 ERA5 variables was done subjectively based on our own meteorological expertise and results in the literature. We chose atmospheric variables that contribute to the formation and ultimately to the separation of electric charges needed for lightning to occur. This requires variables from all five categories (wind field, mass field, cloud physics, moisture field, and surface exchange processes). Within these categories, we chose variables that concisely and comprehensively describe the lightning-relevant aspects. The variables are either directly available in the ERA5 data set or derived from them. We will include this information in the paper.

ACTION: The procedure how we selected our 35 ERA5 variables is better described now:

> Line 116: » The 35 variables presented in Table 1 are selected subjectively from the extended ERA5 data set based on our own meteorological expertise, results in the literature, and an explorative analysis of the data. This explorative analysis worked out variables that show a distinct distribution for the four scenarios and we kept only variables that are not strongly correlated to other selected variables. The chosen atmospheric variables contribute to the formation and ultimately to the separation of electric charges needed for lightning to occur. «