

1 Reviewer #1

Summary: The paper is mainly focused on the development of a mesocyclone detection algorithm based primarily on radar data (plus COSMOS model data). The method is then applied to a 5-year data set for Switzerland, climatological aspects are investigated, and influencing variables such as large-scale flow, diurnal variation, and orography are considered. In addition, some relationship is made to one past hail study.

Basically I enjoyed the paper, I think it is informative and well done, and it should be made available to the community. Especially in the first part (development of the algorithm/climatological consideration), I had primarily minor comments (but in sum quite many). However, in the second part I have some deeper comments, so the paper needs to be reviewed again (Major revision).

Thank you very much for your detailed review, which is very beneficial for improving our manuscript. We highly appreciate the input and are happy to improve our work based on your comments. In the following, we will address the remarks in detail.

Major Comments:

1. Minor major point, L61-66: The purpose and objectives of the paper should be better formulated in the introduction. The authors mainly describe the methodological approach. It would be more interesting to formulate the question about the physics (e.g. question about influence orography, synoptic...). What scientific questions should be addressed by the obtained data set?

The purpose of the publication is to establish a baseline description, how mesocyclones occur in an Alpine environment. To highlight this, we have rephrased part of the introduction (e.g. lines 75-77 in the revised, tracked-changes manuscript below).

2. Minor major point, L75: The description of the COSMO data is inadequate. Which time period is used, which variable exactly? Which area? Resolution? Data generated by yourself, or from others?

The description of COSMO data has been expanded and more details were added, see lines 88ff.

3. In some places it needs to be described more clearly how exactly the sample set is composed (see comments in the text; e.g. one track vs. all detection time steps).

We have added more precise descriptions of this in the figure captions and the main text.

4. Section 4.1 to 4.3: Please put the results more in context with other work in Switzerland and similar studies in Europe; compare it (not only with Nisi et al., 2018; see PDF for more details / suggestion). Overall, more literature has been added as reference. In multiple sections we expanded the comparisons to comparable work in Europe.

5. Figure 5: Please rethink the colorbar; NW, N, NE, SE is hard to see and distinguish (also think of potential Red-green color blindness). Suggestion: As a supplement you could make very well a wind rose in dependence on the frequency. Maybe you can split the analyses over the 7 months to clarify if there are time dependencies?

The colorbar has been revised, in addition to the style of the plot. As the "green" classes only represent very few cases (<5%), we summarized them in one class marked in grey. We superimposed the complete thunderstorm tracks as lines over the rotation initiation points to demonstrate the propagation of

the single storms. In addition, histograms about the class distributions have been added. With only 5 years of data and a high inter-annual variability of severe convection, a seasonal analysis is not very robust and shows artifacts from single events even more than the diurnal cycle. However, this analysis would be very interesting for future work, once longer homogeneous data series are available.

6. Section 4.2 and Figure 6b: I would be more cautious with your interpretation. Overall, Figure 6b shows a large variability. Your interpretation of 4 UTC sample should also take into account that there are very few data (8 or 9 cases) and you should be careful not to interpret too much into your data. Furthermore, which time regarding the track is the basis of your evaluation? Start time? The time in the middle of the track? All this can have an influence. When interpreting the figure, it is important to consider how the duration of the individual tracks is.

We have reprecised in the text (lines 312ff), that the time references the time of thunderstorm initiation. We also highlighted the small sample size as a source of uncertainty. However, with similar behaviour present in severe hail storms, where the sample size is much larger, we consider this an important parallel.

7. Figure 7: Maybe it is interesting to split Figure 7 regionally? 1x north and 1x south of the alpine ridge? Perhaps your statement "the majority of rotating storms move uphill" is purely coincidental and has no real systematic background, as your statement can be attributed only to the region and associated synoptic flow direction.

The uphill movement is indeed likely due to their location and propagation direction, however it still appears that tracks moving towards the main Alpine ridge into increasingly high altitude and complex terrain systematically weaken severe convection. We have rephrased this section (4.3) to clarify our conclusion. Additionally Fig. 7 has been split regionally into North and South.

8. The authors should better explain how the thresholds in Table A1 were chosen. Are there any comparable values in the literature? Have sensitivity studies been performed with varying thresholds? How sensitive are the results due to the choice of thresholds? *These thresholds were selected from the existing operational thunderstorm radar tracking algorithm TRT at MeteoSwiss. In the development of TRT extensive threshold tuning was performed. We clarified the source of these thresholds in the text.*

Minor comments:

In the attached annotated PDF-file, you will find several further minor comments, suggestions and reference suggestions.

We incorporated the vast majority of recommendations. The final changes can be seen in the revised manuscript with tracked changes, included below the response to Reviewer 2.

2 Reviewer #2

Summary: Overall, the manuscript is of interest to the science community and within the scope of Weather and Climate Dynamics. The scientific approach is mainly good. However, the results are not discussed thoroughly and more relevant references are needed. The presentation is mainly good. The figure captions are often too short and not precise; important information that is needed to understand and interpret the analysis is “hidden” in the rather long appendix.

Thank you very much for reviewing this manuscript. We value your feedback and hope to improve our manuscript with it. Below we will address your comments in more detail.

Specific Comments:

1. The discussion of the influence of the radar quality index on the derived spatial distribution of (mesocyclonic) storms is not very clear. E.g. What does a quality index of 0.5 mean? Should the results in this area be considered correct? Or underestimated?

With no additional means of establishing a database of mesocyclones, we cannot derive a quantitative relationship between the quality index and the likelihood of successfully detecting a present mesocyclone. Generally, the lower the index, the higher the likelihood of underestimation.

We present the quality index in this manuscript to remind the reader of the fact that the capability of detection of mesocyclones by a radar network in complex orography is limited by a number of factors, in particular visibility, minimum and maximum altitude of measurements, spatial resolution and data quantization. We merge these into one value, the quality index, in order to give a synthetic view of the underlying detection capability. We have added additional information on the interpretation in section 4.

When looking at phenomena that are more influenced by a single component of the quality index (e.g. spatial resolution for small storms), one may choose to directly use said component. However, here, we are dealing with more complex limitations that need to be respected.

2. Meteorological expectations, derived distributions, limits of the radar network as well as assumed correlations between mesocyclones and hail are often mixed or used to support findings or assumptions in a rather ambiguous way.

We have revised section 4, including the subsections 4.1-4.3 to clarify, which statements are derived from other studies, which refer to analyses in the publication, and which are hypotheses.

3. In the discussion it says “The accompanying relative quality index map helps interpret, where the mesocyclone detection is impeded by the physical limitations of the radar network.” However, this information is not thoroughly used in the presentation and discussion of the results.

We have included additional references to the quality index throughout the analysis in section 4.

4. The discussion of the “synoptic weather situation” is rather short. This could be elaborated. Also, it should be clearly stated which sentences are hypotheses and which are based on analyses (references).

We have expanded this section, also by referencing further work done on this subject in Europe. We have clarified where our statements are derived from.

Technical corrections:

1. L. 62: Including these place names in a map would help those readers not familiar with the study domain.
Reference points were added in the description, to help identify these regions. To avoid overloading Fig. 1, which is used as a geographical reference in this paper, we refer to another paper showing the exact locations (line 69 f in the revised manuscript included below).
2. L. 88: 1 Apr to 31 Oct
In the context of restructuring this section, the sentence has been rephrased, referring to the period as the months April through October (line 83).
3. L. 123: distance from the radar.
Added to text (line 154)
4. Fig. 1 Caption: Is this the quality index only for mesocyclone detection or for all radar derived products?
Generally the quality index is applicable to all radar derived products, however not all limitations are valid for all meteorological phenomena. Including the max. altitude of measurements has particular relevance for convection, thus the quality index is tailored to convective phenomena and in particular rotation in convection. The figure caption has been expanded accordingly and we added information on this in lines 168 ff.
5. L. 151: Typically, negative velocities indicate a component of the wind towards the radar and positive values indicate a component away from the radar. Please clarify.
In Switzerland it is convention to label positive values as inbound. To remain consistent with other publications in the Swiss context, we opt to use the same convention, but highlight it in the text (line 191).
6. Fig. 3 Caption: Individual mesocyclone detections (there could be detections in successive radar scans – thus multiple detections per storm) or mesocyclone storm tracks per km²? Wording should be clear and consistent throughout the manuscript.
These are indeed individual mesocyclone detections, this has been clarified in the caption of Fig. 3. Additionally we made adjustments throughout the manuscript to clarify, whether we are referring to complete tracks, or single detections.
7. Fig. 5 Caption: Spatial distribution of detected mesocyclones classified by the synoptic flow. The colours denote the prevailing wind at ... level. The percentages given in the box
After revising this Figure, the caption was rephrased and expanded.
8. All maps: Could you use latitude / longitude instead of “swiss x-/y-coordinates”?
Using the local geographical projection provides us with a greater deal of accuracy in the projection of the maps. For orientation purposes the coordinates are now shown in km instead of m, to provide a better idea of scale, and the lower left corner is labelled with lat/lon coordinates for reference.

9. L. 224-225: Please explain.
With the revision of Fig. 5, this section now has a better graphical reference and should be more clear to the reader (lines 285 ff)
10. L. 239: How are storm area and track length defined?
The definitions have been added in line 307.
11. L. 245: The influence of the low number of cases on the results should be discussed.
We have added statements discussing the low number of cases, and why this feature is still noteworthy, in spite of the uncertainty (lines 312 ff).
12. L. 255: What is the influence of the radar data quality on the mesocyclone detections at high altitudes and its intensity estimation?
We reinforce the observed spatial trend by referring to radar-independent thunderstorm climatologies (lines 337 ff).
13. Fig. 7: Use a boxplot instead. Also provide the number of cases per selected altitude bin.
The observed decrease is a decrease in the maximum achievable rotational intensity. In any given location the majority of detections have weak rotational intensities. An investigation of the behaviour of different quantiles showed that the decrease is mainly present in the upper quantiles. We added additional information about this to the text (lines 323 ff).

Below we include the revisions with tracked changes.

A Characterisation of Alpine Mesocyclone Occurrence

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Abstract. This work presents a characterization of mesocyclone occurrence and frequency in the Alpine region, as observed from the Swiss operational radar network. Five years of radar data are processed with a thunderstorm detection and tracking algorithm and subsequently with a [new](#) mesocyclone detection algorithm. A quality assessment of the radar domain provides additional information on the reliability of the tracking algorithms throughout the domain. The resulting data set provides the first insight into the spatio-temporal distribution of mesocyclones in the Swiss domain, with a more detailed focus on the influence of synoptic weather, diurnal cycle and terrain. Both on the northern and southern side of the Alps mesocyclonic signatures in thunderstorms ~~are frequent~~ [occur regularly](#). The regions with highest occurrence are predominantly the Southern Prealps and to a lesser degree the Northern Prealps. The parallels to hail research over the same region are discussed.

1 Introduction

Severe convection in Europe is an increasing weather hazard, that causes significant damage and loss every year (~~Munich Re, 2016~~) ([Hoeppe, 2015](#); [Púčik et al., 2019](#); [Kron et al., 2019](#)). Switzerland's Prealpine areas are known to be one of the most active regions in Europe (~~Munich Re, 2016~~). ~~With supercells being~~ ([Taszarek et al., 2019](#); [Nisi et al., 2018](#)). [Supercells are](#) a part of severe convection, the consequential hazards ~~including include~~ lightning, downbursts, ~~straightline winds~~ [severe precipitation](#), hail and tornadoes (Markowski and Richardson, 2010). [Thus](#), they pose a risk to infrastructure, property and lives. Identifying mesocyclone structures in [deep, moist](#) convection allows the ~~identification~~ [detection](#) of supercell thunderstorms and a monitoring of their occurrence (Zrnić et al., 1985; Miller et al., 2013).

Supercells and particularly tornadoes have largely been studied in the Great Plains and Southeast of the United States, where the terrain is flat. Many field campaigns have taken place there to obtain in situ and close-range measurements of supercell environments, ranging from early campaigns in the 70s (Bluestein, 1999), the 25-year VORTEX project (NSSL, 2019) and ongoing TORUS campaign (Frew et al., 2020; Garcia de Jesus, 2019). VORTEX-SE ([NSSL, 2021](#)) began covering the beginning of the Appalachian chain, including more complex orography. The observational climatology established in this region is also one of the longest, with mesocyclone detection algorithms having been introduced in the 90s (Zrnić et al., 1985; Stumpf et al., 1998). However, terrain is no obstacle to the initiation of supercells and recent studies have focused more on studying supercells in diverse geographical contexts. The data stemming from the [recent](#) RELAMPAGO-CACTI (Varble et al., 2021; Nesbitt et al., 2021) field campaign contains the potential to dissect the role of terrain (here the conjunction of the Andes and the Sierra de Cordobas) in the upscale growth of supercells to mesoscale convective complexes (Mulholland et al., 2019, 2020).

~~Most~~ However, most studies focus on single cases or a small number of cases, as the amount of data from a field campaign is limited. The ongoing TEAMx project (Serafin et al., 2020) in the Alps specifically targets transport and exchange processes over the mountains, and also contains a section targeting the evolution of convection. ~~These~~ All these recent campaigns show
30 the relevance of investigating the nature of severe convection in mountainous areas.

Only very little research in Switzerland has thus far focused on mesocyclones and supercells specifically. Houze et al. (1993) investigated the behaviour of severe convection in the Northern Prealps, with 7 years of data from a single-polarization radar. Rotation was inferred from radar reflectivity images. This analysis produced 42 rotating storms during the observation period within the 60 km range of the radar. Only little more right-moving storms occurred than left-moving storms, indicating that
35 there is no strict preference in rotation direction. The study also showed a significant overlap with hailstorms observed during this period.

With hail being a prominent risk factor of severe convection in Switzerland, it is the focus of many recent studies. They range from case studies on hail storms (Trefalt et al., 2018) over collecting crowd sourced hail reports (Barras et al., 2019) and investigating hail in radar data (Nisi et al., 2016, 2018, 2020) to building a conclusive hail climatology from multiple data
40 sources (NCCS, 2021). Barras et al. (2021) investigates the dynamic conditions leading to hail clusters, as opposed to single hail events, whereas Schemm et al. (2016) analyzes the connection between hail and approaching fronts. The link between lightning jumps and hail occurrence for the purpose of nowcasting has also been investigated (Figueras i Ventura et al., 2019). Particularly Nisi et al. (2018) describes the general occurrence and frequency of hail events in Switzerland, taking into account the effects of the seasonal and diurnal cycle and investigating the influence of the synoptic weather situation. Key takeaways are
45 the importance of weather situations with south-westerly and westerly flow, as well as the dominance of rather large, persistent hailstorms at low convective activity hours of the night.

While tornadoes are rare in Switzerland, they nonetheless occur approximately once per year, as estimated by the Swiss severe weather database (Sturmarchiv Schweiz, 2021). Most tornadoes are very weak and classify as F0 events, but on rare occasions, a more significant event can take place. Both Peyraud (2013) and Grazioli et al. (2019) show case studies of tornadoes in
50 Western Switzerland. Avolio et al. (2020) describe the case of a supercell, that media reported to have a suspected tornado, just beyond the Southern Swiss border.

In Germany, mesocyclone detection has been implemented more recently (~~Hengstebeck et al., 2018~~) (Hengstebeck et al., 2018; Wapler et al.
. Studies there also show that supercells can occur in all parts of the country, including areas with complex topography, such as the Bavarian Prealps (~~Wapler et al., 2016; Wapler, 2017~~) (Wapler et al., 2016; Wapler, 2017, 2021). The majority of
55 hailstorms have a mesocyclone structure before and during the production of hail, indicating the relevance of detecting mesocyclones for nowcasting purposes. Mirroring the overall behaviour of convection, there is a pronounced seasonal and diurnal cycle, with a large influence of the synoptic weather situation. In comparison with (Nisi et al., 2018), the dominant flow situations initiating severe convection in Germany differ from Switzerland due to the different geographical location. Over Southern, Western and central Europe in general Southwesterly situations can lead to deep, moist convection
60 (Piper et al., 2019; Mohr et al., 2019; Wapler et al., 2016; Morris, 1986), as the advection of moist, warm air from the Mediterranean provides favourable conditions. In addition, other flow situations can be beneficial regionally, depending on the geographic

situation (Piper et al., 2019; Nisi et al., 2018; Wapler et al., 2016). Mohr et al. (2020) show the influence of synoptic weather on a series of severe thunderstorms from Southwestern France to Northeastern Germany in June 2018, highlighting the importance of the large-scale flow on widespread severe weather outbreaks including supercells. With the potential of severe convection rising not only globally (Diffenbaugh et al., 2013), but also in central Europe (Rädler et al., 2019; Mohr and Kunz, 2013) (Rädler et al., 2019; Mohr and Kunz, 2013; Púčik et al., 2017), we have a large incentive to better understand and characterize mesocyclones in the Swiss domain.

Our work focuses on the region covered by the Swiss operational radar network Rad4Alp (Germann et al., 2016; MeteoSwiss, 2018a), which extends over the main Alpine ridge, Prealps, Jura mountains (along the Northeastern border between Switzerland and France, see locations in Nisi et al. (2016), Fig. 1) and parts of the neighbouring countries Germany, France, Italy and Austria. The Alps dominate the topography of this area, allowing a study of supercell behaviour in complex terrain and high altitude environments. We here establish a systematic detection of mesocyclones in the entire radar domain over 5 years. This allows a first-time characterization of the spatio-temporal distribution of mesocyclones in the Swiss domain and builds the basis for operational automatic mesocyclone detection and nowcasting. Recent improvements in the processing of radar Doppler velocity (Feldmann et al., 2020) now allow the implementation of a robust, radar-data based mesocyclone detection algorithm. The data set established here permits us to investigate the occurrence and evolution of supercells in high altitude, complex terrain. The analysis focuses on identifying spatial patterns, the influence of the synoptic flow and the diurnal cycle.

Our work presented is organized as follows. Section 2 describes the datasets data sets used in our analyses, while Sect. 3 introduces the methods applied. The results are presented and discussed in Sect. 4, followed by our conclusion (Sect. 5). The appendix includes more detailed descriptions of the thunderstorm detection algorithm (A), mesocyclone detection algorithm (B), the radar network quality assessment C) and further example cases (D).

2 Data

All data are analyzed for the years 2016-2020, for the months April through October. As the occurrence of supercells in Switzerland was a priori unknown, we consider an extended convective season to ensure an analysis of all significant events. As shown in Barras et al. (2021), this time frame extends beyond the expected seasonal occurrence of severe convection. In this study we largely rely on the operational radar data of the Swiss Rad4Alp network. To pre-process the Doppler velocity data, the numerical weather prediction model COSMO (Consortium for Small Scale Modelling, 2018) (Consortium for Small Scale Modelling, 2018) provides velocity data as an initialization. We here use COSMO-1 analysis data which is produced operationally by MeteoSwiss at a spatial resolution of 1 km and a temporal resolution of 1 hour, extracted within the Swiss radar domain. The model assimilates data from surface observations, radiosonde and wind profiles, as well as radar data. It is a convection-permitting model that partially resolves convective dynamics. As we use hourly model data to initialize a first-guess for 5 minute radar data, the data is convolved using a 20 km kernel to smooth out smaller scale convective dynamics and retain primarily the larger scale flow (Feldmann et al., 2020).

Additional information is drawn from an operational classification of the general weather situation (Weusthoff, 2011) and

95 a digital elevation model of Switzerland (©swisstopo, 2005; Jarvis et al., 2008). The digital elevation model, which is a merged product from ©swisstopo (2005) and Jarvis et al. (2008), provides elevation data over the Swiss radar domain. It is used to provide topographical context for our analyses and investigate the first-order influences of terrain. To characterize the meteorological and topographical environment of convection, we use a synoptic type weather classification and a digital elevation model. The so-called Gross Wetter Types (GWT) weather classification provides 8 different weather types over
100 Switzerland that are based on the synoptic flow at 500 hPa geopotential height (Weusthoff, 2011). The classes directly correspond to the eight cardinal flow directions.

2.1 Operational Radar Network

The operational radar network of Switzerland, Rad4Alp, consists in 5 polarimetric C-band radars (see Fig. 1), as described in ~~Germann et al. (2016); MeteoSwiss (2018a)~~Germann et al. (2016) and MeteoSwiss (2018a). They are situated throughout the
105 country at altitudes from 900 m ASL to 3000 m ASL and provide a good coverage of both the plains, as well as the Alpine region. The data is processed at a resolution of ~~500m~~500 m x 1°. With the observation range extending up to 246 km, the coverage extends far beyond the country boundaries and allows the observation of convective evolution that is approaching Switzerland. Each radar performs 20 elevation scans between -0.5° and 40° every 5 minutes. The high temporal resolution facilitates observing convective life cycles, particularly in complex environments such as the Alpine terrain. The large range of
110 elevation scans provides a dense vertical layering of observations, allowing an as close to the surface as possible measurement of precipitation over complex terrain and extending up to high altitudes to cover the vertical extent of convection.

~~Here, we focus on data from the convective seasons, which we define as 1. April – 31. October, from 2016-2020.~~ We use the 2-D Cartesian maximum reflectivity product, as well as the 3-D dealiased Doppler velocity in polar coordinates. Due to relatively low Nyquist velocities in the raw Doppler velocity and complex airflow situations in thunderstorms, the aliased
115 Doppler velocity poses a challenging de-aliasing problem. Therefore, we initialize the ~~dealiasing algorithm~~ Region-based Recursive Doppler Dealiasing (R2D2) algorithm (Feldmann et al., 2020) with a radial wind estimate from COSMO-1 analysis data (Consortium for Small Scale Modelling, 2018) to remove all velocity aliases. During this 5-year period, all 5 radars provide homogeneous data coverage with the same, synchronised scan strategy and COSMO-1 data is available. Prior to 2016 the two high altitude radars were not yet installed and COSMO was operated at a 2 km spatial resolution.

120 2.2 Supplementary Data

~~To characterize the meteorological and topographical environment of convection, we use a synoptic weather classification and a digital elevation model. The Gross Wetter Types (GWT) weather classification provides 8 different weather types over Switzerland that are based on the synoptic flow at 500 hPa geopotential height (Weusthoff, 2011). The classes directly correspond to the eight cardinal directions. The digital elevation model (©swisstopo (2005) extended with Jarvis et al. (2008))~~
125 ~~provides elevation data over the Swiss radar domain. It is used to provide topographical context for our analyses and investigate the first-order influences of terrain.~~

3 Methods

To reliably detect mesocyclones in an Alpine context, we combine a [2-D](#) thunderstorm detection and tracking algorithm with a [3-D](#) mesocyclone detection algorithm. The mesocyclone detection activates within the identified thunderstorms.

130 3.1 Thunderstorm Detection And Tracking (T-DaTing)

The thunderstorm detection is based on a dynamic threshold algorithm, which works very similarly to MeteoSwiss's operational ~~thunderstorm tracking algorithm~~ [TRTThunderstorm Radar Tracking \(TRT\) algorithm](#) (Hering et al., 2004). Cells are identified based on thresholds in the Cartesian maximum reflectivity field. Adjoining cells' boundaries are identified by using a watershed algorithm. From one timestep to the next, the motion of the cells is estimated by the pySTEPS optical flow (Pulkkinen et al.,
135 2019) approach. Newly identified cells in the next time step with a large [spatial](#) overlap to previously advected cells are then matched. A more detailed description of the T-DaTing algorithm can be found in Appendix A. [Key differences between TRT and T-DaTing are a fixed minimal detection threshold in T-DaTing, as opposed to the dynamic minimum threshold in TRT and the cell advection with optical flow in T-DaTing versus extrapolating previous motion in TRT.](#)

3.2 Mesocyclone Detection

140 Within the contours of the identified thunderstorms cells, the mesocyclone detection [algorithm](#) becomes active. [This algorithm is modelled after the existing approaches of Stumpf et al. \(1998\) and Hengstebeck et al. \(2018\), but tailored to the specific requirements of the Swiss radar network.](#) Identifying mesocyclonic rotation in radar data relies on estimating vertical rotation (around a vertical axis) from Doppler velocity data (Stumpf et al., 1998). As Doppler velocity only measures the radial component of the full velocity vector, it denotes the incoming or outgoing velocity of particles with respect to the radar. The azimuthal
145 derivative is an approximation of vertical rotation (Miller et al., 2013) and corresponds to roughly half of the vertical vorticity component (see Sect. B, [equation Eq. B2](#)). Areas of consistently high [positive or negative](#) azimuthal derivative indicate rotation phenomena. [As there is no clear preference in rotation direction in Switzerland \(Houze et al., 1993\), we retain detections for both directions.](#) At each radar elevation we employ object detection techniques to identify these areas and compute additional rotational metrics such as rotational velocity and vorticity per object (see Sect. B, [equations Eqs. B2 and B1](#)). All identified
150 objects that meet the detection criteria are grouped within each cell and evaluated for vertical and temporal continuity (Hengstebeck et al., 2018). The definition of a mesocyclone applied here requires a minimum vorticity of 10^{-2} s^{-1} (Hengstebeck et al., 2018), a minimum rotational velocity of 10 m s^{-1} (Stumpf et al., 1998) and a signature depth of 3000 m (Stumpf et al., 1998). All of these criteria linearly decrease towards far ranges to compensate for decreasing spatial resolution ([Stumpf et al., 1998](#)), allowing for detections at more than 100 km distance [from the radar and compensating for the decreasing spatial resolution.](#)
155 Signatures must persist over at least three detections, each at maximum two time steps apart. A detailed description of the algorithm is provided in Appendix B.

3.3 Data Quality Assessment

160 Considering the complexity of radar observations in mountainous terrain, this section introduces a method of estimating observational uncertainties within a radar network. We combine different aspects of the radar network to obtain a qualitative index that represents the relative quality of observations at a given location.

The considered properties are theoretical visibility, minimum and maximum altitude of measurements, spatial resolution and numerical noise stemming from data quantization. These metrics are assessed for each radar and merged onto a Cartesian grid, where the highest quality metric is retained. The metrics are then rescaled between 0 (lowest quality) and 1 (highest quality) and combined into a general quality index. A detailed description of the computation of the quality index is in Appendix C.

This results in a spatial map of the quality index of the radar network. It is a qualitative index and only represents a relative comparison of detection probability, not a quantitative measure of correcting for detection gaps.

170 While the components contributing to the quality index are based on the full radar network and represent impacts to all radar products, not all observed meteorological phenomena are impacted equally by the limitations. The selection here is tailored to convective phenomena that can reach very high altitudes and require a high spatial resolution. Other combinations of these components lead to differing results, however the overall spatial pattern of the quality index is robust and representative of radar product quality in general.

Figure 1 depicts the results of the quality index assessment over the Swiss domain (the influence of each considered property is shown in Fig. C1 in the Appendix C). The black dots indicate the locations of the 5 radars, ~~the Swiss border is also indicated in black~~. With the topography underlain in the background, we can see the clear influence orography has on the quality index. This is primarily a consequence of radar beam blockage, which decreases visibility, particularly at low levels. Two noticeable artefacts are a dip in quality ~~over the Jura, caused by beam blockage in the vicinity to the Northeast~~ of La Dôle radar; and a similar gap in observations to the West of Lema radar. These artifacts stem from constructions in the vicinity of the radars blocking the visibility. The obstruction of Lema is more recent and does not affect the entire analysis period. The decrease in quality in the main Alpine ridge is caused by beam blockage of terrain.

4 ~~Results~~ Mesocyclone Characterization

As an introduction to mesocyclonic rotation in an Alpine context, we first show an example case from ~~Ticino, which is in the~~ Southern Prealps ~~and that are~~ very prone to thunder- and hailstorms (~~Nisi et al., 2018~~)(Nisi et al., 2018; Schemm et al., 2016) . Figure 2 shows ~~both the radar reflectivity and Doppler velocity~~, Doppler velocity and vertically integrated liquid (VIL) measured from Monte Lema radar (radar and storm location see Fig. 1, A) at 17:30 UTC on August 20th, 2019; and the location of this case marked as A in the map. In the reflectivity data we can clearly see the location of the convective cell at 10-15 km range and 90-150° azimuth with values exceeding 45 dBZ, indicating strong convection. The shape of the area of high reflectivity shows the typical hook-echo, which suggests the presence of prominent rotation (Markowski, 2002; Kumjian and Ryzhkov, 2008) . The storm here is observed at an altitude of approximately 2500 m ASL. In the Doppler velocity data, we can see the oppo-

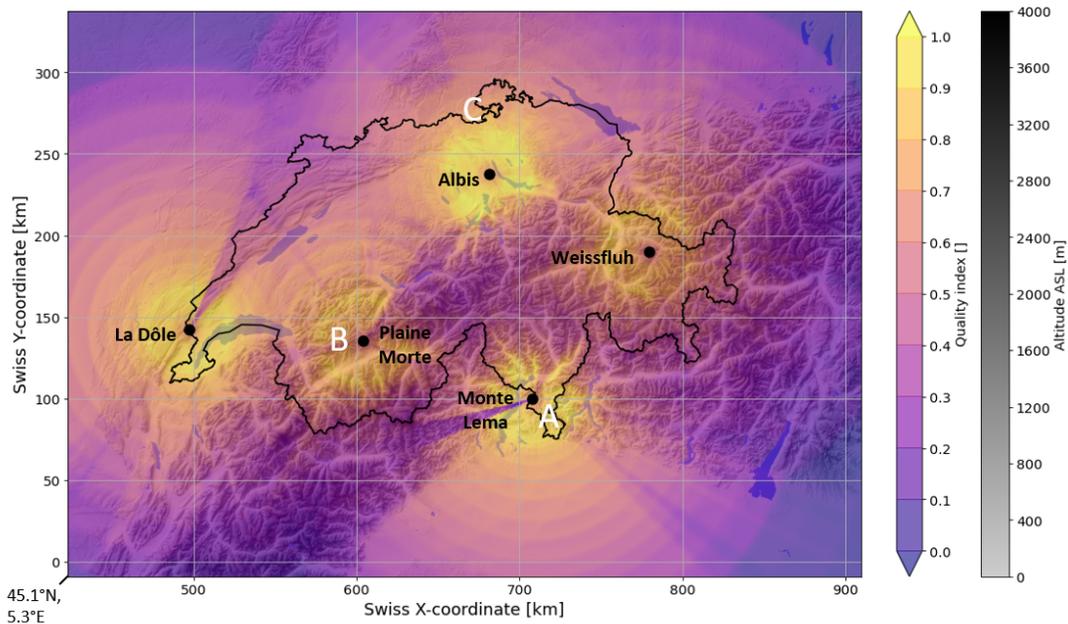


Figure 1. Relative quality index for mesocyclones-mesocyclone and thunderstorm detection in the Swiss weather radar network depicted over elevation map; case study locations (Figs. 2, D1 and D2) indicated with white letters; radar locations shown with black dots; radar altitudes: Albis - 938 m, La Dôle - 1682 m, Monte Lema - 1626 m, Plaine Morte - 2937 m, Weissfluh - 2840 m.

sition of inbound (red, following the Swiss convention of depicting Doppler velocity) and outbound (blue) velocities close to the hook, here presenting anticyclonic rotation (indicated with arrows), confirming the presence of a mesocyclone. While these signatures are quite clear, the rotational velocity is not particularly high in comparison to supercells in other regions (e.g. in the Great Plains, USA), here averaging around 12 m s^{-1} . To represent the spatial heterogeneity in Switzerland, two additional case studies from the high Alpine region (Bmarked B in Fig. 1) and the Rhine valley (C) are provided in Appendix D. **Their locations B and C are also marked on the map.**

They show that supercells in Switzerland exhibit a range of rotational intensities and reflectivity features.

From here we will inspect the overall distribution and occurrence of mesocyclonic rotation over the Swiss domain during the 5 analyzed years and compare this to the general occurrence of thunderstorms and the quality of the radar network. Table 1 gives an overview of the annual average convective activity.

Approximately 10 % of days during the convective season had at least one mesocyclone within the Swiss domain. T-DaTing is configured to detect storms exceeding 50 km^2 to focus on more significant convective systems (see Appendix A). 0.3 % of all detected thunderstorms showed mesocyclonic rotation. Overall the earliest detected mesocyclone was in the last week of

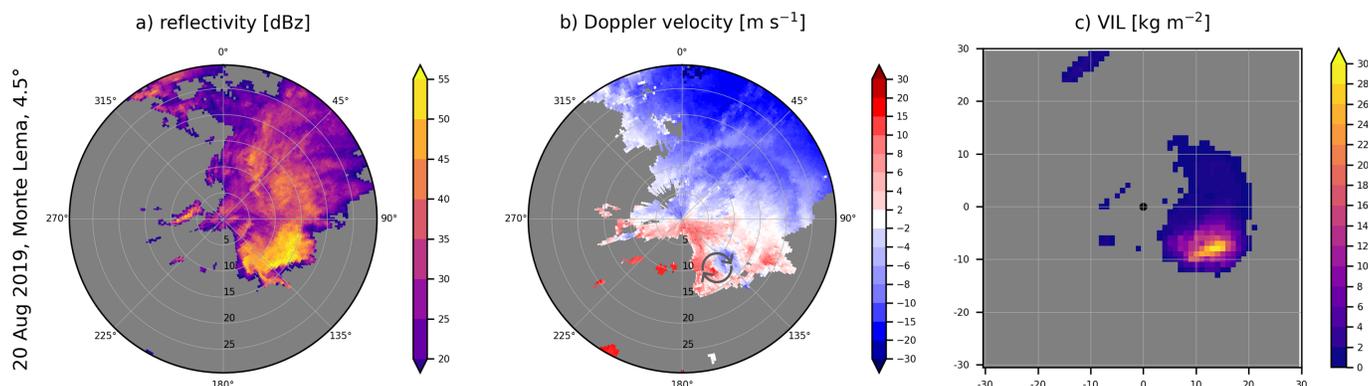


Figure 2. Example of supercell in the Southern Prealps; August 20th, 2019 at 17.30 UTC.

Table 1. Overall annual average occurrence of mesocyclones and thunderstorms during 2016-2020 in the Swiss weather radar network.

	number of detections	number of storm tracks	number of active days
mesocyclones	690	80	22
thunderstorms	203'700	25'200	170

Overall annual average occurrence of mesocyclones and thunderstorms during 2016-2020 in the Swiss weather radar network

205 April and the latest in the beginning of the last week of October.

Figure 3 a) shows the annual average spatial distribution and density of the 5-year thunderstorm and mesocyclone analysis. Thunderstorms are clustered in the Prealpine valleys in moderately high topography. In absolute terms the main hot spot is to the South of the Alps in the canton Ticino. The Alps serve as a meteorological divide, separating Northern Switzerland from
 210 Mediterranean air masses (MeteoSwiss, 2018b). Ticino experiences more subtropical, Mediterranean conditions than the rest of Switzerland, with generally higher temperatures and frequently high relative humidity (Nisi et al., 2016; MeteoSwiss, 2018b). These conditions are more conducive to convective initiation and development. Topography can induce convection through valley wind systems (Linder et al., 1999; Rampanelli et al., 2004; Nisi et al., 2016). Particularly in the afternoon hours, upslope winds cause convergence over ridges and can provide the initial lift needed to overcome convective inhibition. We can
 215 also see that the frequency of thunderstorm detections is higher in the vicinity of the radars. If we compare the spatial distribution of thunderstorms to the relative quality map of the Swiss domain, we can clearly see that the likelihood of detecting thunderstorms is larger, when the relative quality index is high. While we do not establish a quantitative relationship, a lower quality index increases the probability of underestimating thunderstorm occurrence. Nonetheless, the dominant spatial trends of convective preference in the Prealps are meteorologically consistent with orographic convection and can be confirmed with
 220 lightning climatologies (Enno et al., 2020; MeteoSwiss, 2016). The clearest deviation from meteorological expectations can be seen to the Northeast and Southwest of the Jura. Beam blockage and sensitivity issues significantly lower significantly lowers

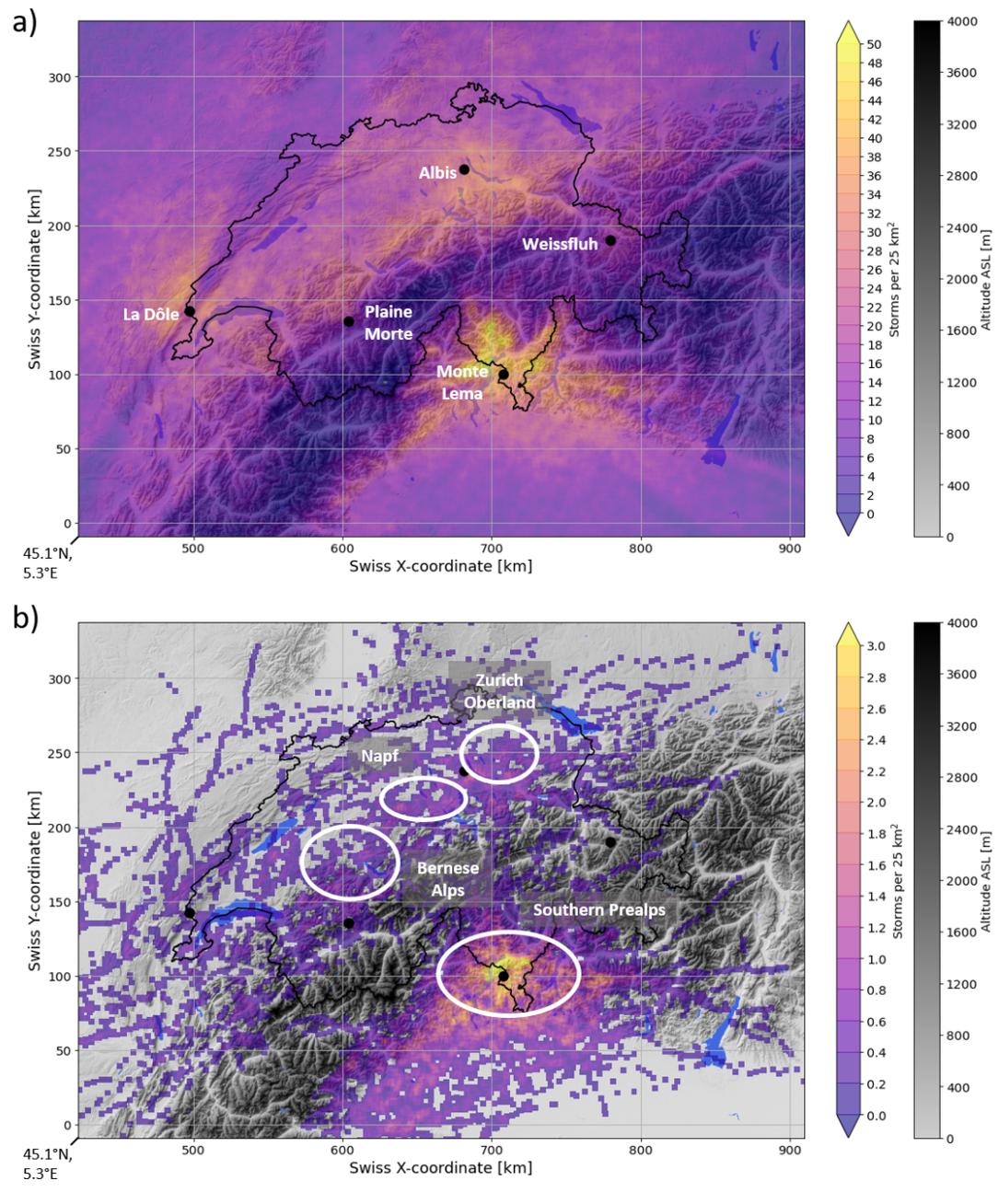


Figure 3. Annual average individual detections of a) ~~Thunderstorm~~-thunderstorms and b) ~~mesocyclone-detections~~-mesocyclones from 2016-2020 per 25 km². Highlighted regions of interest: Zurich Oberland, Napf, Bernese Alps and Southern Prealps.

the capability of La Dôle radar to accurately observe convective events in these areas.

Shifting our focus to the annual average spatial distribution of thunderstorm tracks that contain a mesocyclone in Fig. 3 b), we can see a similar spatial pattern. Most mesocyclonic storms occur to the South of the Alps. In the North, they largely occur
225 in Prealpine areas. A small, but relevant hot spot can be seen in the Napf area to the West of Lake Lucerne. Additionally the Bernese Alps and Zurich Oberland are areas of elevated frequency. Both the global maximum in Ticino and the local maxima in the Northern Prealps correspond to hail occurrence maxima (NCCS, 2021; Nisi et al., 2018; Trefalt et al., 2018). Considering that hail is a known severe weather consequence of mesocyclones, this overlap reinforces the robustness of the obtained spatial distribution. We can see a lesser dependence of detections on the quality index. This may be due to the fact, that mesocyclones
230 generally have a large vertical extent and can be detected in multiple consecutive elevation scans, thus being less dependent on accurate measurements in single elevation scans. ~~By using range-dependent rotation thresholds, the detectable range of mesocyclones exceeds~~ Range-dependent rotation thresholds compensate for decreasing measurement resolution with range and allow mesocyclones to be detected even beyond a range of 100 km per radar. The most issues can still be noted over the Jura, where the beam blockage of La Dôle radar impacts the first 10 elevation scans. The beam blockage in this area is severe
235 enough, that confirmed cases of mesocyclones are missed in this region. This is illustrated by the case study of a tornado near Neuchatel in Grazioli et al. (2019), in which the data from both a mobile, X-band radar that was tracking this storm cell, and the operational C-band data, are analyzed. The rotation is clearly visible in the X-band data, however from La Dôle radar, the rotation is undetectable and the location is at a far range from Albis radar.

240 Figure 4 shows the maximum measured vorticity values of all detected mesocyclones. The values range from $0.6 \cdot 10^{-2} s^{-1}$ to $12 \cdot 10^{-2} s^{-1}$, with a mean of $2 \cdot 10^{-2} s^{-1}$. The typical mesocyclone definition (Stumpf et al., 1998) requires a vorticity of $10^{-2} s^{-1}$, showing that the average event is twice as strong and the extremes exceed this value by an order of magnitude. The lower minimum value stems from the use of range-dependent thresholds, where we lower the vorticity requirement with increasing distance to the radars to compensate for decreasing spatial resolution (see Appendix B).

245 The largest cluster of high vorticity values is located around the Ticino hot spot. But also the Napf area and Zurich Oberland show consistently elevated values of vorticity. This is not the case for the Bernese Alps, where the vorticity values are on the low end of the spectrum and close to the detection threshold. The topography is significantly more complex here, which may impact a storms capability to maintain strong rotation.

The overlap of the strongest rotation concurring with the largest size hail in the Napf region and Southern Ticino (NCCS, 2021)
250 indicates that stronger rotation ~~may favour larger hail~~ usually favours larger hail (Allen, 2018; Blair et al., 2017; Witt et al., 2018). However the differences in the Bernese Alps, where we have large hail, but low rotation velocities and Zurich Oberland, where we have high rotation velocities, but smaller hail show that there may also be other factors at play and warrants further investigation. The Bernese Alps have a reduced quality index, due to beam blockage to the Northeast of Plaine Morte radar. This may interfere with the ability to reliably detect and estimate the intensity of vortices. Discrepancies may also be owed to the
255 relatively short duration of the 5 year analysis.

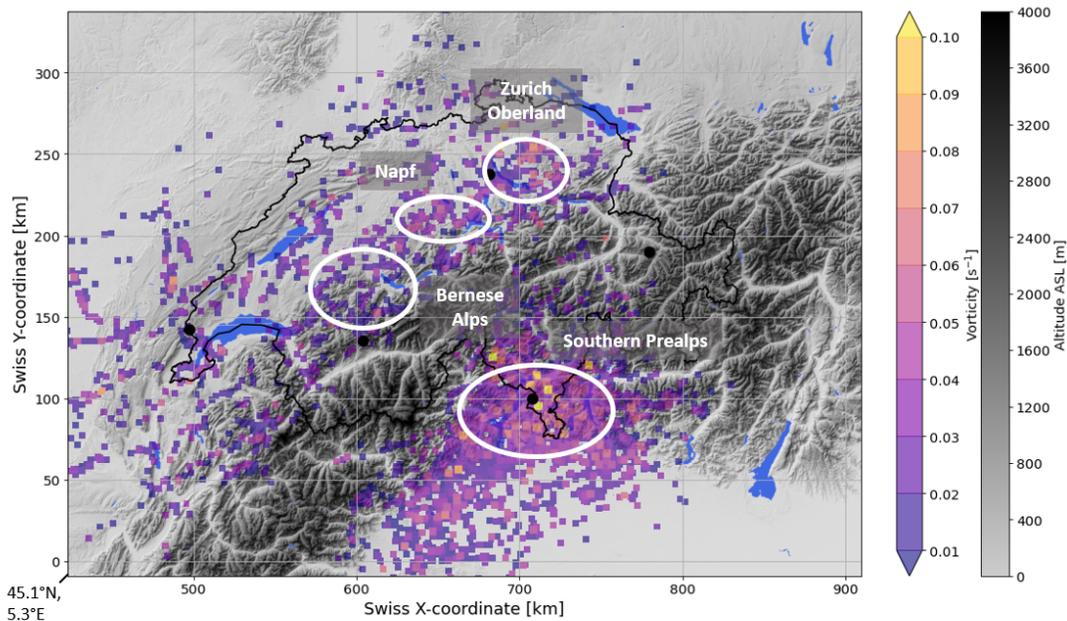


Figure 4. Maximum detected vorticity per 25 km² during five years (2016-2020).

4.1 Dependency on Synoptic Weather Situation

The synoptic weather classification GWT Gross Wetter Types (GWT) provides insight in which synoptical flow situations mesocyclones are likely to occur. Figure 5 ~~shows the location a)~~ shows the complete tracks of all detected mesocyclones (lines) as well as the location of mesocyclone initiation (dots), color coded by the corresponding flow direction. Figure 5 b)
 260 provides a histogram of the overall occurrence of all weather classes during the analyzed period, in comparison to the histogram focusing on the days with mesocyclone activity. Figure 5 c) presents the fraction of days in each weather class that produce a mesocyclone during the analysis period.

Flow from the Southwest is responsible for the majority (55 %) of mesocyclone detections. These situations are ~~often characterized~~ by airmasses generally characterized by air masses originating in the warm, humid Mediterranean area. They hold high amounts
 265 of CAPE convective available potential energy (CAPE) and moisture, thus presenting favorable conditions for severe convection. In the analyzed time period, approximately 25 % of days with a Southwesterly flow produced at least one mesocyclone. Amongst others, Mohr et al. (2020) and Wapler and James (2014) show that a Southwesterly flow induces favourable conditions for deep, moist convection in most of central and Western Europe. A particularly potent synoptic constellation is called the "Spanish plume" (Peyraud, 2013)(Morris, 1986; Peyraud, 2013), where the lowlevel Southwesterly flow is in the
 270 prefrontal zone of an approaching cold front over France, the midlevel flow supplies warm, dry air stemming from the Iberian peninsula and the upper-level flow is Westerly, with cooler, Atlantic air. This leads to high amounts of CAPE in addition to

lifting occurring through the approaching front. The vertical change in flow direction provides directional wind shear, which is beneficial for mesocyclone development (Peyraud, 2013). Depending on the altitude of the transition to the Westerly upper-level flow, a fraction of Spanish plume events may also be classified as Westerly flow in the GWT classification. As shown in

275 Schemm et al. (2016), approaching fronts also play an important role in hail formation, particularly in Swiss regions, where hail falls less frequently.

Westerly flow is the second most frequent flow direction during mesocyclones, contributing to a third of all detections, followed by Southerly flow at $\sim 10\%$. Both have similar characteristics as Southwesterly flow, but less reliably yield the optimal conditions for severe convection (each approximately 12 % of the time). Westerly flow is the most common flow situation in

280 Switzerland (MeteoSwiss, 2018b) and rather brings Atlantic ~~airmasses to Northern Switzerland, however South of the Alps this flow can still advect Mediterranean airmasses~~ air masses to Switzerland. Roughly 10 % of days with Westerly flow produce at least one mesocyclone. Southerly flow is more prevalent to the South of the Alps, but already leads to much less mesocyclone cases. To the North, there are only few cases that are displaced further North, as descending air crossing the Alps does not provide favorable conditions. Other flow directions play a very small role and are only responsible for very few cases ($<5\%$).

285 ~~It also appears that~~ As the track lines in Fig. 5 a) indicate, the synoptic flow steers the main direction of storm tracks, while allowing for the deviation of left- and right-mover storms. Histograms of storm direction per weather class cluster in a Gaussian distribution around the direction of synoptic flow (figures not shown). ~~However~~ Given the synoptic-scale criteria for the weather classification, the mesoscale flow at the steering level ~~may of convection (5000 - 7000 m ASL, Foresti et al., 2018)~~ can also deviate from the synoptic flow classification.

290 ~~The response of mesocyclones to the synoptic flow situation is similar to hailstorms (Nisi et al., 2018). The discrepancies lie in hailstorms occurring more frequently in Westerly than Southwesterly flow and rarely in Southerly flow. While Southwesterly flow also plays an important role in hailstorms, it is not the dominant weather class (Nisi et al., 2018). Hailstorms predominantly form in Westerly flow, which is also the most frequent weather class. With hail also occurring much more frequently (Barras et al., 2019; Nisi et al., 2018), it appears that Westerly flow yields conditions that are sufficient for hail production, but not as frequently for mesocyclone formation.~~ Westerly flow also leads to a hail hotspot in the Northern Jura, where the quality of Doppler velocity data is limited and we potentially miss mesocyclones. ~~Moreover, while hailstorms and mesocyclones show considerable overlap, neither necessitates the other.~~

295

4.2 Diurnal Cycle

300 The occurrence of mesocyclones shows a pronounced diurnal cycle that mirrors the cycle of convection in general (see Fig. 6 a)). The majority of storms occur in the afternoon and first half of the night, with the peak of formation at 15 UTC. Mesocyclones, however, show a local, smaller peak, during the second half of the night as well (0-4 UTC) and then a minimum in the early morning at 4 UTC. Thunderstorms in general drop to a lower occurrence from 0-10 UTC, but can initiate at all hours of the day. The base frequency at unfavourable hours in the late night and early morning is almost constant.

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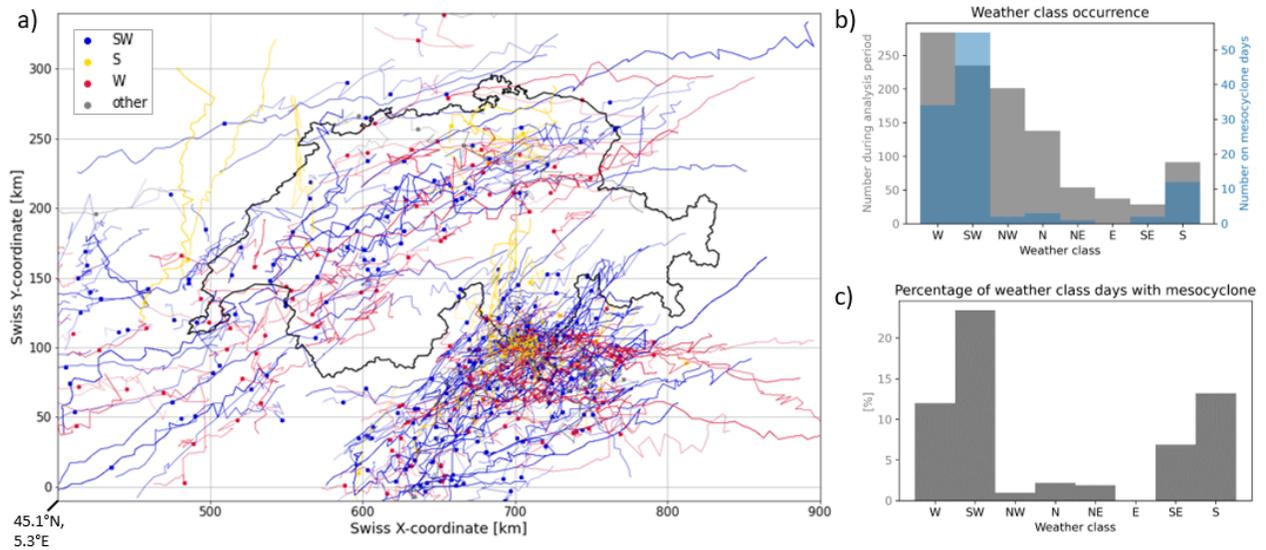


Figure 5. a) Spatial influence dependency of synoptic weather situation based on prevailing flow at 500 hPa, lines show complete tracks of mesocyclones, dots depict mesocyclone initiation; b) histograms of weather class occurrence during entire analysis period and during mesocyclone days; c) Percentage of days per weather class with mesocyclone activity.

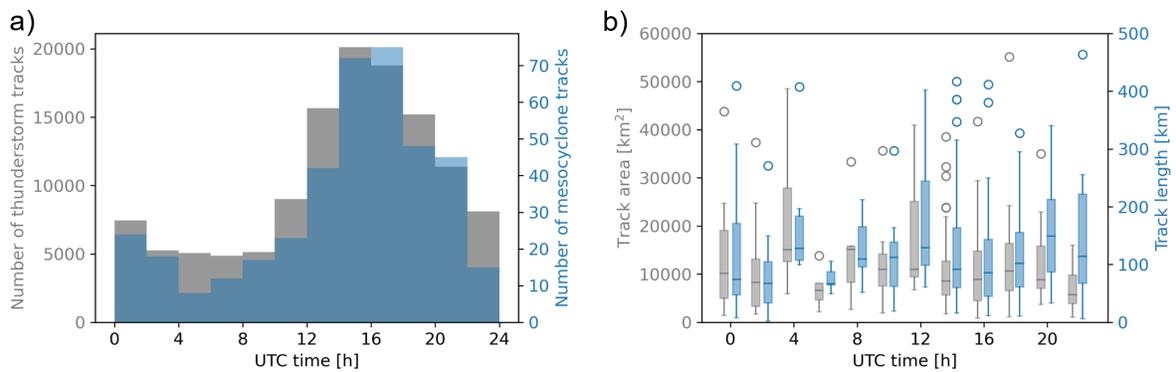


Figure 6. Diurnal cycle of convection (a), and each 2h bin shows the number of tracks beginning at this time; diurnal cycle of mesocyclone track properties (b), each 2h bin shows the cumulative track area and length of tracks beginning at this time.

In comparison to this frequency distribution, there is also a diurnal cycle reflected in cumulated storm area and track length, as shown in Fig. 6 b). The storm area refers to the cumulative area over the entire storm track, whereas the track length refers to the overall distance along the path of the storm track. The behaviour of the track duration mirrors the track length (not shown here). In contrast to the occurrence histogram, the global peak of ~~all three~~ both variables is at 12 UTC, before the peak mesocyclone occurrence time in the day. A local peak is additionally found at 4 UTC during the minimum of mesocyclone occurrence. ~~This~~ Even though the sample size is very small, this shows parallels to research conducted on hailstorms, where the longest and largest storms also occur outside hours of the convective peak. Due to the significant drop in frequency at this time of day, this indicates a significant overlap between ~~these storms.~~ It mesocyclones and hailstorms. In spite of the small sample present, this agreement with severe hailstorm behaviour also reinforces the notion found in Nisi et al. (2018) that convective storms that initiate during unfavourable hours of the day are more likely to be severe, whereas the most active hours of the day contain a ~~large~~ larger fraction of less intense storms (Nisi et al., 2018). As this hypothesis based on the small sample in the mesocyclone data set is rather speculative, it should be revisited, once longer homogeneous data series are available.

4.3 Terrain

Utilizing the data from the digital elevation model, we can see that the majority of rotating storms move uphill during their lifetime. With the majority of storms occurring in Ticino (~ 60 % of mesocyclones are detected from Lema radar) and a South-westerly flow direction dominating here, many storms follow a Northeasterly path towards the main Alpine ridge (see Fig. 5), thus moving uphill. ~~Up~~ As Fig. 7 a) shows, in the South of the Alps, up to an altitude of approximately 1500 m, the storms do not show intensity correlation to the altitude. Beyond that, higher altitude negatively impacts the upper potential of intensity metrics such as rotational velocity ~~, vorticity,~~ and vorticity, here shown by the decreasing trend in the 95th percentile. The same effect can be seen to the North of the Alps, however at a lower altitude. With the storm tracks being more parallel to the Alps (see Fig. 5), less storms move uphill and encounter higher altitudes. In both cases the lowering in intensity is mirrored by a lowering in case numbers with altitude. Similar trends can be observed for vertical extent and maximum reflectivity ~~. Figure 7 shows this relationship for rotational velocity and vorticity. The~~ (not shown). At any given location weaker rotation can occur and dominates the intensity distribution, however with increasing altitude the upper percentiles decrease, indicating a limit to the potential rotational intensity a storm can achieve in this environment. As the number distribution with altitude shows, the majority of storms are detected in lower altitude regions. This concentration in relatively flat areas within the Prealpine region, such as the larger valleys and lakes, ~~as we can see is also shown~~ in Fig. 3. At high altitudes beyond 1500 m ASL the terrain becomes increasingly complex with steep slopes and rapid altitude changes. We hypothesize that this could impact the low-level dynamics of a supercell, disturbing the generation of vorticity at the outflow boundary and its advection back into the storm in the inflow.

As the quality index also decreases over the main Alpine ridge, the probability of underestimating mesocyclone occurrence here also rises. However, as shown in Enno et al. (2020) and MeteoSwiss (2016), the overall thunderstorm frequency, derived

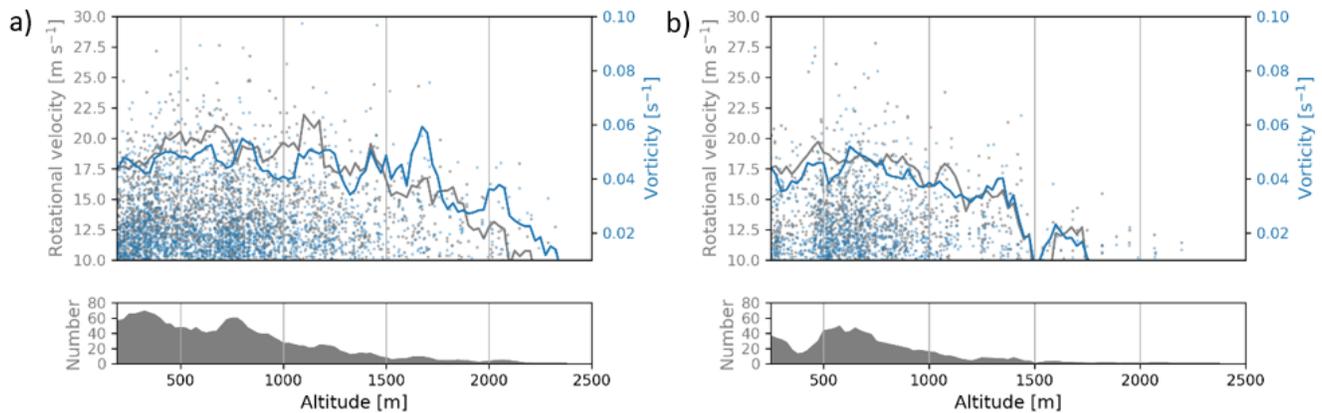


Figure 7. Topographical influence on rotational metrics; scatterplot of rotational velocity and vorticity versus altitude. The grey and blue lines indicate the smoothed 95th percentile, the lower graph shows the number of detection per altitude. a) Cases detected by Lema radar (South), b) cases detected by radars Albis and La Dôle (North).

340 from radar-independent lightning data, also decreases significantly here, indicating that we are observing a true trend and not a limitation of the radar network.

With the majority of storms located in the Prealpine regions, orographic triggers for convective initiation play an important role in Switzerland (Nisi et al., 2016; Linder et al., 1999). The main Alpine ridge poses a strong separation for thunderstorms. The thunderstorm track may occasionally persist across the main Alpine ridge, but no rotation signature is consistently trackable across. This further reinforces the notion With the thunderstorm frequency dropping substantially over the inner Alpine regions in Fig. 3 a), we can see that thunderstorm tracks generally do not persist crossing the Alpine ridge. In Fig. 3 b) we can see the inner Alpine regions devoid of rotation detections. Additionally, Fig. 5 a) shows only one mesocyclone track crossing the Alps, while all other tracks heading towards the main Alpine ridge decay prior. This supports the hypothesis that high altitude mountainous terrain has an inhibiting impact on the rotation dynamics of a thunderstorm.

350 5 Conclusions

Overall, the The implementation of a radar-based mesocyclone detection algorithm and the analysis of the years 2016-2020 allows a first time assessment of the occurrence of mesocyclones in Switzerland. Around 80 thunderstorms per year convective season (April - October) had a mesocyclone, distributed over 22 days per year convective season. It is evident that mesocyclones can be detected and tracked in a large portion of the Swiss radar domain. The While range is usually a limitation, the maximum detectable range for mesocyclones in the Swiss radar network exceeds 100 km per radar. The accompanying relative quality index map helps interpret, where the mesocyclone detection is impeded by the physical limitations of the radar network. The most pronounced limitations are over the Jura in Northwestern Switzerland and over the inner, main Alpine ridge, as well as at

far ranges outside of Switzerland.

360 The 5 year analysis allows a first assessment of the overall frequency and spatial distribution of mesocyclones in the Swiss domain. The absolute maximum of detections lies in the Southern Prealps. Monte Lema radar, situated in this ~~regions~~region, detects approximately ~~50~~60 % of all mesocyclones, with the other half being distributed rather evenly between the other 4 radars. Smaller, local maxima lie in the Prealpine valleys to the North of the Alps, such as in the Bernese Alps, the Napf region and the Zurich Oberland. This spatial distribution parallels that of hailstorms (NCCS, 2021).

365 Clear characteristics emerge and show parallels to other features of convection in Switzerland, such as the importance of the synoptic flow and the pronounced diurnal cycle. Southwesterly flow is the most conducive for mesocyclone occurrence, followed by Westerly and Southerly flow. The diurnal cycle of mesocyclone initiation shows a clear peak in the late afternoon hours and a minimum in the early morning hours, mirroring the diurnal cycle of thunderstorms in general. Size metrics such as area and track length however indicate that the few storms occurring during the minimum tend to be larger and last longer. This tendency can also be observed in hailstorms (Nisi et al., 2018), indicating a probable overlap between the
370 two storm populations. The importance of Southwesterly flow to convection in central and Western Europe is also shown in (Wapler and James, 2014) and (Mohr et al., 2020), which highlights the significance of synoptic flow for large regions.

With mesocyclones being rather rare events, longer timelines are necessary to establish robust assessments of interannual variability and seasonal trends. The spatial distribution can also be evaluated more robustly with a longer analysis period, as low-activity regions are currently dominated by the characteristics of single events. ~~An extension to past data was not made~~
375 Data prior to 2016 was not used in this study, as ~~multiple sources of heterogeneity would need to be introduced~~major changes in the radar network took place at that time.

~~A first investigation of terrain interactions~~The spatial distribution of both thunderstorms and mesocyclones shows that terrain has a clear influence on the initiation of convection. Similarly, the inner Alpine regions are devoid of mesocyclones, indicating that steep, high altitude environments have a negative influence on rotational dynamics. Rotational metrics show a negative
380 correlation with increasingly high altitudes as well.

After establishing this first time assessment of mesocyclones in Switzerland, future work is required to clarify the severe weather consequences of mesocyclones in Switzerland and further investigate the interactions with the complex terrain.

Code and data availability. The T-DaTing algorithm is available in the pySTEPS package (PySteps developers, 2021). The data set of mesocyclones has been published in Feldmann et al. (2021).

385 Appendix A: Thunderstorm DaTing

The ~~thunderstorm-detection-and-tracking~~[Thunderstorm Detection and Tracking](#) (T-DaTing) algorithm utilizes image processing, computer vision and optical flow techniques to identify thunderstorms and track them in time. The [2-D](#) Cartesian maximum reflectivity field of the Swiss operational radar network is used as input. Its spatial resolution is $1 \times 1 \text{ km}^2$ and it is generated every 5 minutes. All thresholds are tuned to this input data ([Hering et al., 2004](#)), but are adaptable to other [datasets](#)[data sets](#).

390 This algorithm has been published as a part of the pySTEPS package (PySteps developers, 2021).

A1 Thunderstorm Detection

The detection of thunderstorms follows a dynamic, multi-threshold approach. The procedure is modelled after MeteoSwiss's operationally running TRT algorithm ([Hering et al., 2004](#)). [All thresholds are listed in Table A1 and stem from Hering et al. \(2004\)](#)

395 ~~In~~[Utilizing the 2-D maximum reflectivity composite from all five radars, in](#) a first step, all areas below the minimum reflectivity Z_{min} are discarded. All remaining areas need to have a peak reflectivity value exceeding Z_p and be larger than the area A_{min} . We chose a relatively large size limit here, as we are interested in supercellular convection, which generally takes place on larger spatial scales. ~~To avoid arbitrary cell boundaries~~[The next step uses local maxima within the area boundaries to determine whether these should be further split into separate convective cells. To excessive splitting](#) in areas of very high reflectivity values, [where there are many extreme local maxima](#), the data is saturated at the maximum reflectivity Z_{max} . Within these areas exceeding Z_{min} , a local maximum detection algorithm is employed ([van der Walt et al., 2014](#)). Maxima within a consecutive area are counted as separate, if the path of least change between them decreases by at least ΔZ . Maxima within 10 km of each other are merged to avoid excessive cell splitting. The remaining maxima are used as anchors for the cells. To separate cells that lie within the same connected area, an inverted watershed algorithm ([Beucher and Lantuejoul, 1979; van der Walt et al., 2014](#))

400

405 assigns the corresponding areas to each maximum. Thus the boundaries of the inverted watershed algorithm lie along the lowest values of reflectivity in between maxima that are within the same consecutive area, but have a reflectivity drop of at least ΔZ in between them.

This produces the labelled areas for the identified thunderstorm cells. The detection part of the algorithm can be performed on any length of data and does not require temporal continuity. It yields results very similar to [Hering et al. \(2004\)](#), the main

410 deviations are a larger minimum size and the introduction of the minimum distance between maxima. Additionally contours are slightly larger, as they always extent to the boundary of Z_{min} .

A2 Thunderstorm Tracking

After detecting the thunderstorm cells, the tracking part of the algorithm estimates the future path of each cell, propagates it and matches it to the detected cells in the next time step.

415 The movement of the cells is estimated from three consecutive frames of the [2-D](#) input data. The Lucas Kanade optical flow algorithm ([Lucas and Takeo, 1981](#)) applied to the current and previous two time steps of the maximum reflectivity field yields

Table A1. [Thunderstorm detection thresholds.](#)

variable	unit	threshold
min. reflectivity (Z_{min})	dBZ	35
max. reflectivity (Z_{max})	dBZ	51
min. difference in reflectivity (ΔZ)	dBZ	6
peak reflectivity (Z_p)	dBZ	$Z_{min} + \Delta Z = 41$
min. area (A_{min})	km^2	50

Thunderstorm detection thresholds

the projected movement for the next time step (Pulkkinen et al., 2019). Each cell of the previous time step is propagated according to the results from the optical flow. This is then compared to the identified cells of the current time step. If the overlap between two cells is more than 50 %, they are considered as the same cell and assigned the same ID as before. If there is no overlap to a new cell, the cell track ends and this ID is no longer used. If there is no previous cell matching a new cell, a new ID is generated and thus a new track initiated. If a cell splits, the smaller fraction is considered a new cell and obtains a new ID. In case of merging, the smaller ([area](#)) cell is considered decayed, where the track of the larger one continues in the merged cell.

For each step, the x and y coordinates, maximum reflectivity, centroids, area and distance from last detection are recorded. In a final step the detections from each time step are resorted into the tracks assigned to their IDs. Tracks shorter than three detections are rejected.

The tracking procedure follows the same steps as Hering et al. (2004). However where previously the [propagation-cell motion from one detection to the next](#) was estimated by the past track of the cell, we ~~use the extrapolation from~~ [extrapolate the motion from one detection to the next utilizing the output of](#) the optical flow [here algorithm \(PySteps developers, 2021; Pulkkinen et al., 2019\)](#) applied to the three latest time steps.

Appendix B: Mesocyclone Detection

T-DaTing provides the constraints for the mesocyclone detection algorithm. The detected thunderstorm areas are used as a mask to filter out data unrelated to convection. Additionally, all rotation detected within a cell is assigned to this cell.

B1 Data Preparation

To filter the relevant data, the detected thunderstorm areas are dilated with a $5 \times 5 \text{ km}^2$ kernel. Since mesocyclones can be located outside of the area of largest reflectivity ([Kumjian and Ryzhkov, 2008](#)), we consider areas slightly larger than each detected cell. One by one, the algorithm then iterates through the detected cells.

To compute rotation, the dealiased velocity data from all 5 radars and 20 elevations is used. The dealiasing procedure is performed with the novel algorithm R2D2 and COSMO-1 analysis data is used as a first guess. As the velocity data is in polar coordinates, the filter obtained from the Cartesian reflectivity filter is regridded to the polar grid of each radar. Additionally the

first 5 km in range from each radar are excluded from processing, due to excessive noise in the data.

For each elevation the azimuthal velocity shear is computed using a centered-difference method. In case of residual velocity folds or dealiasing errors, a quality check is in place. If an area of more than three adjacent pixels exceeds the Nyquist velocity (Fabry, 2015) of the corresponding elevation, the Nyquist interval is added or subtracted to reduce the absolute value of the shear in this area. With Nyquist velocities being quite low (Feldmann et al., 2020), particularly in the lower elevations, the azimuthal shear can physically exceed the Nyquist interval. However, usually this will occur in isolated high-shear gates and not in larger areas. Velocity folds and dealiasing errors however produce contiguous lines of erroneous azimuthal shear and can thus be corrected for in this method. The mesocyclone detection presented here is thus less sensitive to dealiasing errors, as long as the edges of folds can be distinguished from physical shear and the estimation of rotational velocity does not cross a fold velocity alias.

B2 Rotation Detection

Within each elevation, the convective cells are evaluated iteratively. From the azimuthal shear $\frac{dv}{d\theta}$, first pattern vectors are constructed. Consecutive areas of shear exceeding a threshold $\frac{dv}{d\theta}$ are conserved, if they exceed 1 km in length and contain at least three gates. All other data is discarded. These pattern vectors are merged over the ranges using 8-bit connectivity. If pattern vectors neighbor each other over a corner, or directly, they are considered one area. These resulting areas are then further evaluated. They each need to exceed a minimum rotational velocity and vorticity threshold Δv (Eq. B1) and ζ (Eq. B2, see Table B1). Additionally, their aspect ratio needs to be less than 1:3, approximating circular objects.

$$\Delta v = \frac{v_{max,inbound} - v_{max,outbound}}{2} \quad (B1)$$

and

$$\zeta = 2 \cdot \frac{v_{max,inbound} - v_{max,outbound}}{\Delta x}, \quad (B2)$$

where Δx is the Cartesian distance between the velocity maxima.

All rotation areas identified in this way are collected. For each area the location of the centroids, size, rotational metrics, elevation and thunderstorm ID are recorded. Within one cell, more than one detection is possible per elevation, as rotational signatures can be fragmented. Positive and negative azimuthal shear are evaluated separately, to differentiate cyclonic and anticyclonic rotation signatures.

B3 Vertical Continuity

After processing all elevations of one radar, the detected rotation objects are merged. All objects of one thunderstorm ID are considered to belong together and are stacked vertically, as the storm structure can be slanted and detections can be discontinuous due to residual aliasing in the velocity data. Additionally, the vertical depth of the lowest and highest detection must exceed a certain depth h .

Fig. Figure B1 shows a schematic overview of the detection process until this point. Figure B1 a) shows the process within a radar elevation. First the data is filtered with the contours identified in T-DaTing, here approximated with the dark grey cloud (1.). Then the velocity data (2.) is evaluated. Here green denotes outbound velocity from the radar and red inbound. From 475 the velocity, the azimuthal derivative is derived (3.), which results in anomalies in the derivative around the velocity couplet. Cyclonic anomalies are shown in light red here and anticyclonic anomalies in light green. Within these anomalies the rotational velocity and vorticity are computed and measured against thresholds, here resulting in one final rotation object shown in blue (4.). In Fig. B1 b) the aggregation of rotation objects within a thunderstorm contour is shown. Detections (blue ovals) from each elevation (dashed slices) within the contour contribute to the overall vertical structure. To these identified objects the vertical 480 continuity constraints on h are applied. After exceeding all criteria, the objects are summarized as one rotation column (light blue column) for the corresponding convective cell. Also here, anticyclonic and cyclonic signatures are considered separately and must each fulfill all criteria to be recorded and are stored as separate columns.

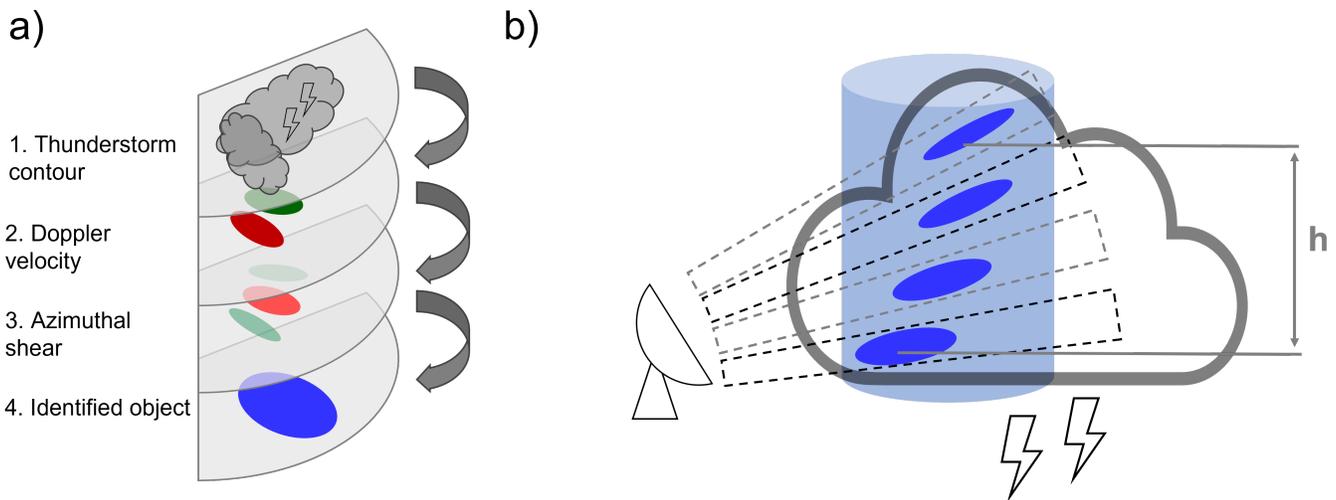


Figure B1. Schematic of mesocyclone detection; a) detection of rotation within radar elevations; b) vertical merging of detections within thunderstorm contour.

B4 Range Dependent Thresholds

485 All detection criteria are range dependent thresholds T (Stumpf et al., 1998). The thresholds are most strict at a range of 20 km at T_m and decrease outwards until 100 km to T_o , from where they remain stationary. Within 20 km they decrease towards the radar to T_i . The decrease of the thresholds with range compensates for the reduction in resolution in the data. Within 20 km,

the decreased thresholds aim to allow for detections in the noisy shear data at small azimuthal distances. The following table depicts the values chosen in the algorithm here.

490

Table B1. [Mesocyclone detection thresholds following Stumpf et al. \(1998\) and Hengstebeck et al. \(2018\).](#)

variable	unit	inner threshold (T_i)	maximum threshold (T_m)	outer threshold (T_o)	
azimuthal shear ($\frac{dv}{d\Theta}$)	s^{-1}	$1 \cdot 10^{-3}$	$3 \cdot 10^{-3}$	$1 \cdot 10^{-3}$	
rotational velocity (Δv)	$m s^{-1}$	6	10	6	Mesocyclone detection
vorticity (ζ)	s^{-1}	$6 \cdot 10^{-3}$	10^{-2}	$6 \cdot 10^{-3}$	
vertical depth (h)	m	0	3000	1000	

thresholds

495

The range dependent thresholds help detecting significant rotation in complex observation situations. Due to the complex nature of the Swiss terrain, there is often no visibility of the lower portion of a storm. Additionally, the environmental conditions allowing for supercellular convection in Switzerland generally show a lower vertical shear than e.g. in the US plains. We tuned the thresholds by investigating visually confirmed cases of supercellular convection and range dependent thresholds that relax at very close and far ranges. While this may detect more storms as supercells, that were merely exhibiting significant rotation but otherwise lack the typical storm structure, we avoid missing detections due to observational issues.

B5 Temporal Continuity

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Within a valid thunderstorm track, rotation of the same sign must have been detected at least 3 times within 10 minutes of each other. Additionally the rotation track must leave the range of 20 km around a radar. In strong linear wind situations, the geometric nature of the radial velocity produces artificial rotation signatures at opposing sides of the radar that remain stationary. These can produce false detections, but are easily removable considering that thunderstorms generally propagate.

Appendix C: Relative Quality Index

The relative quality index combines multiple physical constraints of the Swiss radar network and combines them to a single, summarizing quality index. The characteristics we include are: the vertical sum of theoretical visibility V (dimensionless, ranging from 0-1 for each elevation, in total ranging from 0-20), minimum altitude of observation h_{min} [m], maximum altitude of observation h_{max} [m], azimuthal resolution $\Delta\Theta$ [m] and discretisation in velocity shear ϵ [s^{-1}].

The theoretical visibility corresponds to the unblocked fraction of a radar beam at each location. It is derived combining the [effective earth radius model \(AMS Glossary of Meteorology, 2012\) with a refractive index of 5/4 atmospheric refraction model](#) and a digital elevation model to estimate beam blockage. The vertical sum over all 20 elevations is computed on a 2-D polar grid for each radar. In a similar fashion, the minimum and maximum altitudes of measurements are obtained from the altitude of the lowest and highest radar beam with 100 % visibility, yielding each a 2-D polar grid per radar. The resolution corresponds to the distance of each radar bin to its azimuthal neighbours. As we here work with the azimuthal derivative of Doppler velocity, we additionally introduce the quantization noise. The numeric resolution at which the Doppler velocity is stored introduces a small level of noise. The azimuthal derivative is strongly range-dependent, as it utilizes the azimuthal resolution. In the vicinity of the radars this noise reaches high levels and thus impacts the data quality. We here compute the noise level by dividing the numerical resolution by the azimuthal resolution.

After obtaining the radar-based grids for each variable, these are regridded to a 1 km resolution Cartesian grid, where the highest-quality index at each location of overlap is retained. [An overview of the variables-The contribution of each variable](#) is shown in Fig. C1.

520

To constrain the fields to values that correspond to strong quality degradations, some fields are saturated at threshold values. The minimum altitude field's upper bound is saturated at 5 km ASL, corresponding to an inability to observe the lower atmosphere. The maximum altitude field's lower bound is saturated at 11 km, indicating a lack of convective top observations. The noise field's upper bound is saturated at $3 \cdot 10^{-3} s^{-1}$, which is a critical threshold for rotation detection.

Each Cartesian field of a characteristic is then rescaled between 0 and 1, utilizing the highest and lowest values present in the domain, so that 0 represents the lowest quality value and 1 the highest quality value. The normalization for the positively (Eq. C1), as well as negatively (Eq. C2) correlating variables is given in the following:

$$var_{p_norm} = \frac{var - var_{min}}{var_{max} - var_{min}} \quad (C1)$$

530 [and](#)

$$var_{n_norm} = \frac{var_{max} - var}{var_{max} - var_{min}}. \quad (C2)$$

[Positively correlating variables are visibility and maximum altitude of measurements, where high values correspond to a high quality index. Negatively correlating variables are resolution, minimum altitude of measurements and noise, where a low value](#)

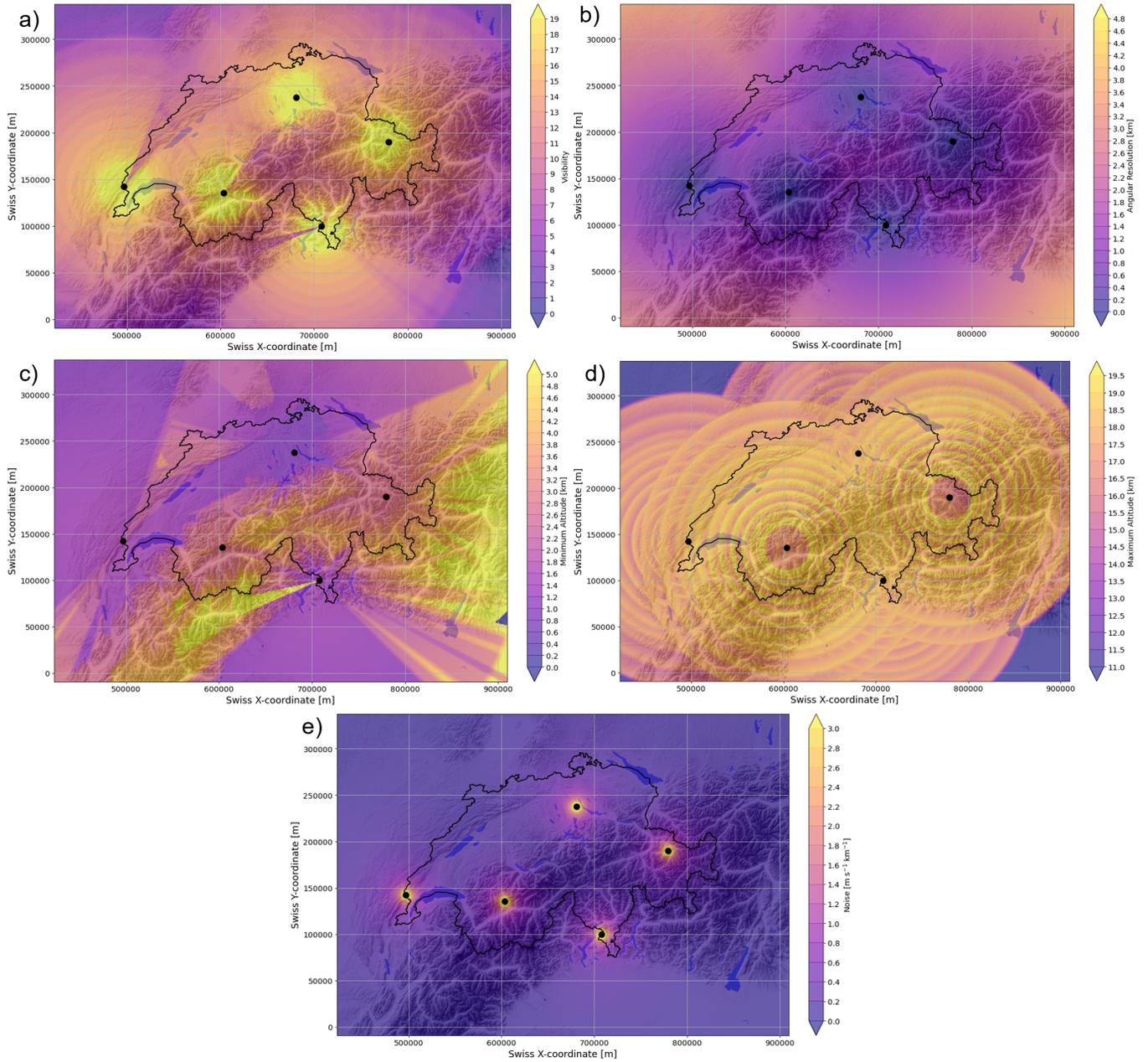


Figure C1. Components contributing to the relative quality index for mesocyclone detection in the Swiss radar network; a) vertical sum of visibility; b) azimuthal resolution; c) minimum altitude of observations; d) maximum altitude of observations; e) numerical noise in azimuthal velocity derivative.

corresponds to a high quality index. All characteristics are then combined by the following formula:

535

$$index = V_{p_norm} \cdot \frac{(h_{min,p_norm} + h_{max,n_norm} + \epsilon_{n_norm} + \Delta\Theta_{n_norm}^2)}{4}$$

As visibility can degrade the quality to zero in absolute terms, it is used as a multiplicative factor. The other variables do not directly influence each other and are thus averaged at equal weights. To account for both horizontal and vertical azimuthal resolution, it is squared. ~~The resulting quality index map for the Swiss domain is shown in the main manuscript in Fig. 1.~~

540 **Appendix D: Case studies**

Case B, as indicated in the map of Fig. 2, is located in the Valais Alps and was observed from Plaine Morte radar. It shows a case in complex, high-altitude terrain, observed at ~ 4800 m ASL. Figure D1 shows the supercell at 10-30 km range and 200-240° azimuth, in the Doppler velocity panel the location and direction of rotation is indicated with arrows. The hook shape in the reflectivity is less evident here compared to the event presented in Fig.2, but we can see a clear indentation in the high reflectivity values at the location of outgoing (blue) Doppler velocities, showing the perturbation from the rotation. ~~We additionally show vertically integrated liquid (VIL) and probability of hail (POH) here to provide more context about the thunderstorm intensity~~ The high values of VIL also indicate the large moisture content in the atmospheric column. This storm was associated with multiple extreme precipitation and wind gust measurements (MeteoSwiss, 2019).

545

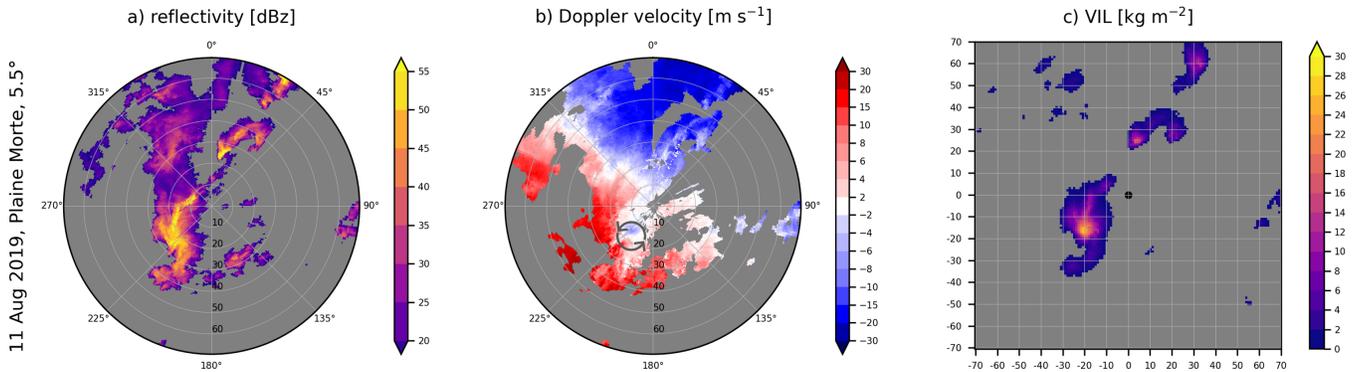


Figure D1. Supercell in Valais; August 11, ~~2019~~2019.

550

The second case (Fig. D2) stems from the Rhine valley and comes closest to convection without orography in Switzerland and is shown in the radar imagery at an altitude of approximately 2000 m ASL. Nonetheless the proximity of the Black Forest to the Northwest and Jura in the Southwest indicate that topography is a relevant factor for thunderstorm initiation and development everywhere in Switzerland. The supercell is at a further range than the previous cases (30-50 km, 330-30°), but nonetheless well observed. We can see a clear perturbation in the high reflectivity signature. The rotation in the Doppler

555 velocity fields is quite strong, averaging around 20 m s^{-1} . The main region of the thunderstorm shows high values VIL, as well as POH between 90 and 100 %. We can see that VIL is elevated and POH values are. This storm was responsible for a new precipitation record in Switzerland (36.1 mm in 10 minutes) at the time (MeteoSwiss, 2017). During the evolution of the storm, the reflectivity data also shows significant attenuation behind the storm core. Probability of hail is also estimated to be close to 100 % in a large portion of the storm throughout large parts of the track, however no hail was reported on the ground, possibly due to the storm taking place at night

560

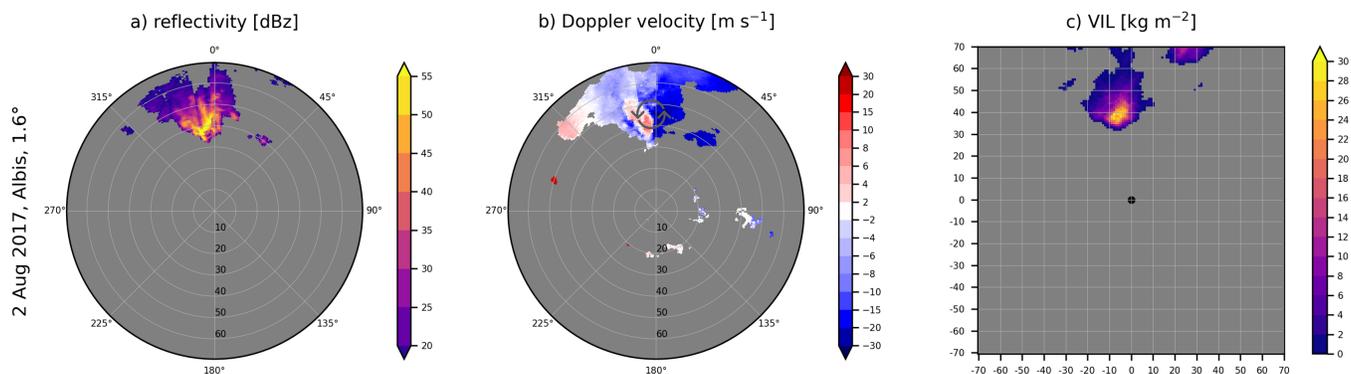


Figure D2. Supercell along the Rhine valley; August 2nd, 2017.

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