

1                   **Characterizing the Mesoscale Cellular Convection in Marine Cold Air**  
2                   **Outbreaks with a Machine Learning Approach**

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9                   **Key Points:**

- 10                   • Cloud cells in marine cold-air outbreaks are objectively identified and classified using a  
11                   profiling mm-wave radar
- 12                   • The classification reveals that open-cellular clouds undergo a lifecycle with distinct  
13                   characteristics at each lifecycle stage
- 14                   • Closed-cellular clouds contain occasional convection but generally have more stratiform  
15                   characteristics  
16

## 17 **Abstract**

18        During marine cold-air outbreaks (MCAOs), when cold polar air moves over warmer  
19 ocean, a well-recognized cloud pattern develops, with open or closed mesoscale cellular  
20 convection (MCC) at larger fetch over open water. The Cold-Air Outbreaks in the Marine  
21 Boundary Layer Experiment (COMBLE) provided a comprehensive set of ground-based in-situ  
22 and remote sensing observations of MCAOs at a coastal location in northern Norway. We  
23 determine MCAO periods that unambiguously exhibit open or closed MCC. Individual cells  
24 observed with a profiling Ka-band radar are identified using a water segmentation method. Using  
25 self-organizing maps (SOMs), these cells are then objectively classified based on the variability in  
26 their vertical structure. The SOM-based classification shows that comparatively intense  
27 convection occurs only in open MCC. This convection undergoes an apparent lifecycle.  
28 Developing cells are associated with stronger updrafts, large spectral width, larger amounts of  
29 liquid water, lower precipitation rates, and lower cloud tops than mature and weakening cells. The  
30 weakening of these cells is associated with the development of precipitation-induced cold pools.  
31 The SOM classification also reveals less intense convection, with a similar lifecycle. Such  
32 convection, when weakening, becomes virtually indistinguishable from the more intense stratiform  
33 precipitation cores in closed MCC. Non-precipitating stratiform cores have weak vertical drafts  
34 and are almost exclusively found during closed MCC periods. Convection is observed only  
35 occasionally in the closed MCC environment.

36

## 37 **Plain Language Summary**

38        During marine cold-air outbreaks (MCAOs) a characteristic cloud field develops over the  
39 open ocean. At large fetch, this cloud field is characterized by open and closed mesoscale cellular  
40 convection (MCC). The Cold-Air Outbreaks in the Marine Boundary Layer Experiment  
41 (COMBLE) in northern Norway provided comprehensive observations of MCC using ground-  
42 based and remote sensing instruments. Distinct open or closed MCC periods are identified using a  
43 vertically scanning cloud radar. Within these periods individual cells are identified. Using a  
44 machine learning algorithm, these cells are objectively classified based on their vertical structure  
45 as observed by the radar. The classification reveals that intense convection primarily occurs in  
46 open MCC, displaying a lifecycle with developing cells characterized by strong updrafts,  
47 substantial liquid water, lower precipitation rates, and lower cloud tops compared to mature and  
48 weakening cells. Weakening cells are associated with precipitation-induced cold pools. Less  
49 intense convection with a similar lifecycle is observed during open and closed MCC. Most  
50 frequently during closed MCC, stratiform cells with weak vertical motions are observed. These  
51 are classified as non-precipitating and precipitating cells. The vertical cloud structure of the  
52 precipitating stratiform cells is very similar to weakening convective cells.

## 53 **1 Introduction**

54        The Arctic is an integral part of the global climate system. It has been observed that the  
55 Arctic is warming at a rate 2-4 times faster than the rest of the globe (e.g., Serreze & Francis, 2006;  
56 Serreze et al., 2009; Rantanen et al., 2022), a trend that models predict will continue in the future  
57 (Davy & Outten, 2020). This well-documented trend is referred to as Arctic amplification. This  
58 amplification is attributed to a variety of feedback processes. Among them are Arctic cloud

59 feedbacks (Taylor et al., 2013), for which the magnitude and sign of the feedback remains  
60 uncertain (IPCC, 2021, p. 974).

61 Here, we examine one specific high-latitude cloud regime, one that occurs in marine cold-  
62 air outbreaks (MCAOs). Such synoptic events produce unique cloud patterns that through vertical  
63 mixing and radiative effects may play an important role in high-latitude cloud feedbacks (Fletcher  
64 et al., 2016). When Arctic air masses move from the sea ice (or boreal continents) over the open  
65 ocean, large surface heat fluxes develop that destabilize the boundary layer (Pithan et al., 2018).  
66 This, combined with intense surface moisture fluxes, leads to shallow moist convection that  
67 deepens with fetch. Initially, as the air moves over the ocean, linear cloud patterns form, referred  
68 to as cloud streets, and at a larger fetch downstream, the cloud streets transition to open or closed  
69 mesoscale cellular convection (MCC) (e.g., Atkinson & Zhang, 1996; Brümmer, 1999; Brümmer  
70 & Pohlmann, 2000). At high latitudes, these clouds are generally mixed-phase (e.g., Geerts et al.  
71 2022).

72 Understanding the differences in the characteristics of open and closed MCC is important  
73 since their differing cloud morphology and microphysical properties impact the radiative  
74 properties of clouds as well as surface fluxes (e.g., Agee, 1987). Open and closed MCC have been  
75 studied extensively in the subtropics and the mid-latitudes (e.g., Eastman et al., 2021, 2022; Jensen  
76 et al., 2021; McCoy et al., 2017, 2023; Mohrmann et al., 2021; Muhlbauer et al., 2014; Wood &  
77 Hartmann, 2006). These studies show that a variety of environmental factors, such as wind,  
78 precipitation, surface forcing, and aerosol can influence the development of open or closed MCC.  
79 McCoy et al. (2017) find that the occurrence of open and closed MCC during MCAOs is correlated  
80 with the MCAO-index  $M$ , a measure of low-level static stability driven by the sea surface ( $M =$   
81  $\theta_{SST} - \theta_{850hPa}$ ). Mesoscale cloud morphology is strongly influenced by surface heat fluxes and  
82 low-level stability: environments with large positive  $M$  values favor open MCC regimes, while  
83 under low  $M$  values, a closed MCC regime prevails, with more stratiform clouds (McCoy et al.,  
84 2017). This has potential implications for the cloud feedbacks in a globally warming climate since  
85 the intensity of MCAOs is predicted to weaken in the future (Kolstad & Bracegirdle, 2008;  
86 Landgren et al., 2019).

87  
88 A comprehensive dataset of ground based observations of MCAO clouds was collected as  
89 part of the Cold-Air Outbreaks in the Marine Boundary Layer Experiment in the 2019/20 cold  
90 season (COMBLE, Geerts et al., 2022). Geerts et al. (2022) and Lackner et al. (2023a) illustrate  
91 MCAOs with episodes of rather deep, intense open-cellular convection observed during  
92 COMBLE. These examples demonstrate a relationship between vertical velocity, supercooled  
93 liquid water path (LWP), and surface temperature anomalies: cells with strong updrafts tend to  
94 have large LWP values, while others have weak vertical motions, low LWP values, and a surface  
95 cold pool. These differences probably can be attributed to different cloud lifecycle stages. Geerts  
96 et al. (2022) and Lackner et al. (2023a) also illustrate closed MCC observed during COMBLE.  
97 The closed MCC periods are characterized by a lower  $M$  value and weaker winds, and clouds  
98 exhibit continuous cloud cover, weaker vertical motions, and lower average cloud top heights  
99 when compared to the open MCC. The objective of this study is to comprehensively characterize  
100 the vertical structure of MCC using the spectrum of MCAOs observed during the 6-month  
101 COMBLE campaign, to better understand the linked MCAO cloud dynamics and microphysics,  
102 i.e. the linkages between cell vertical structure, its lifecycle, and its mesoscale organization.

103

104 This study is structured as follows. Section 2 describes the COMBLE campaign, the  
 105 periods with open and closed MCC, and the methods used to identify and classify individual cells.  
 106 The results of the classification of cells and an analysis of additional measurements is presented in  
 107 Section 3. A discussion of the results is provided in Section 4 and the study is summarized in  
 108 Section 5.

## 109 2 Data Sources and Analysis Methods

### 110 2.1 The COMBLE Campaign

111 The data used in this study were collected as part of COMBLE, which deployed the ARM  
 112 mobile facility 1 (AMF1, Miller et al., 2016) to Nordmela harbor (69.141 °N; 15.684 °E) on the  
 113 Norwegian island Andoya from December 2019 to May 2020. A detailed summary of the  
 114 COMBLE campaign can be found in Geerts et al. (2022), and a description of the datasets can be  
 115 found in Lackner et al. (2023a). The key instrument used for analysis is the Ka-band ARM zenith  
 116 radar (KAZR), providing radar observations of vertical cloud structures. Additionally, the  
 117 *MICROBASEKAPLUS* (Zhao et al., 2014) and the *THERMOCLDPHASE* (Van Weverberg et al.,  
 118 2023) products are utilized. All datasets are summarized in Table 1.

119  
 120 The *MICROBASEKAPLUS* product provides radar retrieved ice water content, which is  
 121 used to calculate ice water path (IWP). We found the IWP values to be exceptionally high for the  
 122 more intense, 4-5 km deep convective cells. Following a recommendation from the ARM  
 123 instrument mentors (S. Giangrande, personal communication, March 28, 2023), we reduced the  
 124 KAZR reflectivity uniformly by 5 dBZ, to achieve more realistic IWP values. The  
 125 *THERMOCLDPHASE* product provides a vertically resolved classification of cloud phase. This  
 126 product uses KAZR and micropulse lidar data, and is based on the algorithm developed in Shupe  
 127 (2007). The micropulse lidar at the AMF1 site was only deployed starting 11 February 2020. Thus,  
 128 *THERMOCLDPHASE* is only available for some of the periods described in Section 2.2.

129

130 **Table 1.** COMBLE AMF1 Data Sets Used in This Study

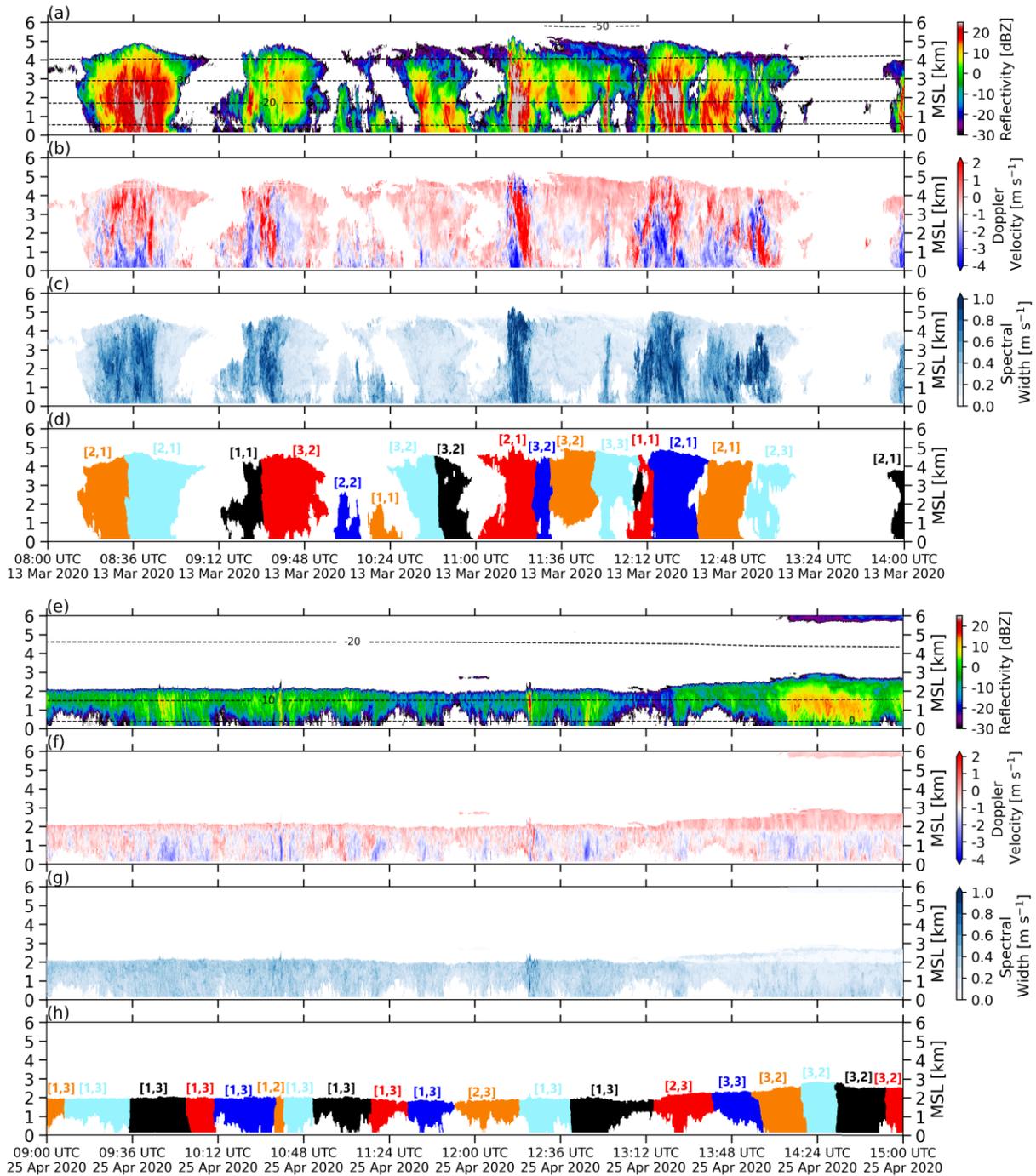
ARM Data Products	Description	Variable(s)	Units
<i>MET</i> (Kyrouac et al., 2019; Ritsche & Prell, 2011)	Surface meteorological instrumentation	Atmospheric temperature Horizontal wind direction Horizontal wind speed Atmospheric pressure Precipitation rate	°C ° m s <sup>-1</sup> hPa mm hr <sup>-1</sup>
<i>MAWS</i> (Keeler et al., 2019)	Vaisala automatic weather station	Atmospheric temperature Horizontal wind direction Horizontal wind speed Atmospheric pressure	°C ° m s <sup>-1</sup> hPa
<i>ARSCLKAZRIKOLLIAS</i> (Clothiaux et al., 2001; Johnson & Jensen, 2019)	KAZR ARSCL.c1: multiple outputs from first Kollias algorithm	Equivalent reflectivity factor Mean Doppler velocity Spectral width	dBZ m s <sup>-1</sup> m s <sup>-1</sup>
<i>ARSCLKAZRBNDIKOLLIAS</i> (Johnson et al., 2019)	Cloud boundaries retrieved from KAZRARSCl	Cloud top height Cloud base height	m m
<i>MWRRETILILJCLOU</i> (Turner et al., 2007; Zhang, 2019)	Microwave radiometer retrievals	Liquid water path	kg m <sup>-2</sup>

<i>INTERPOLATEDSONDE</i> (Fairless et al., 2021; Jensen et al., 2019)	Sounding data interpolated to 1 min	Atmospheric temperature Atmospheric pressure Horizontal wind speed	°C hPa m s <sup>-1</sup>
<i>MICROBASEKAPLUS</i> (Dunn et al., 2011; Wang et al., 2019; Zhao et al., 2014)	Improved MICROBASE product with uncertainties	Ice water content	kg m <sup>-3</sup>
<i>THERMOCLDPHASE</i> (Van Weverberg et al., 2023; Zhang & Levin, 2019)	Thermodynamic cloud phase classifications	Classifications: clear sky, liquid, ice, mixed phase, snow, rain, drizzle, liquid + drizzle, unknown	---

131 Note: MICROBASE is the Atmospheric Radiation Measurement (ARM) Climate Research Facility  
132 baseline cloud microphysical properties (MICROBASE) value-added product.

## 133 2.2 Periods with Mesoscale Cellular Convection

134 Periods exhibiting open and closed MCC are determined through visual inspection of  
135 KAZR reflectivity time-height transects (see Figure 1) and satellite imagery. These periods of  
136 MCC are only determined during and shortly before or after the MCAO events at the AMF1 site,  
137 as defined in Geerts et al. (2022) and Lackner et al. (2023a). Short periods of MCC (< 3 hours),  
138 periods with disorganized clouds, periods with polar lows (Lackner et al., 2023b), and periods  
139 during which MCC was connected to mid/upper-tropospheric clouds with a different origin are not  
140 considered in the analysis. An example of the distinct vertical structure of open (closed) MCC in  
141 the KAZR data is shown in Figure 1a-c (1e-g). The closed-cell example appears to be mostly  
142 stratiform, with light precipitation often not reaching the ground (Figure 1e). Consistent with the  
143 literature, we still refer to these cloud patches as mesoscale cellular *convection* (MCC), even  
144 though the convective origin may not be apparent.



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**Figure 1.** KAZR time-height transect for an open MCC period (a-d) and a closed MCC period (e-h) showing (a,e) KAZR reflectivity factor and temperature contours, (b,f) Doppler velocity, (c,g) spectral width, and (d,h) objectively identified cells via the watershed segmentation method (see Section 2.3). Note that the 5 colors in (d,h) merely are recycled and do not indicate any cell grouping. The numbers on top of each cell indicate the best-matched unit, introduced in Section 2.4.

153 Table 2 summarizes all MCC periods used in this study. The distinction between open and  
 154 closed cells is based on KAZR data and satellite imagery and is unambiguous. A total of 13 periods  
 155 with a total of ~249 hours of open MCC were identified at the AMF1 site, compared to 4 periods  
 156 with a total of ~57 hours of closed MCC. In total, this accounts for ~37 % of the MCAO periods  
 157 during COMBLE identified in Geerts et al. (2022) (which themselves cover 19% of the full 6-  
 158 month field phase), mostly because of the previously mentioned reasons for which certain periods  
 159 are not considered in the analysis. A broad spectrum of environmental conditions prevailed during  
 160 these 17 periods. The  $M$  value is above the COMBLE MCAO mean of 4.1 K for most open MCC  
 161 periods (10 of 13), indicating that open MCC tends to occur during more intense cold air outbreaks.  
 162 Closed MCC on the other hand, tends to occur during weaker outbreaks, with mean  $M$  (1.2 K)  
 163 being much lower than for open MCC (6.0 K). This difference in intensity likely explains why  
 164 open MCC is observed more frequently than closed MCC at the AMF1 site: weaker MCAOs often  
 165 lack the synoptic support to cover the large distance between the ice edge and the COMBLE  
 166 observation site (~1000 km). Near-surface temperatures (winds) tend to be warmer (weaker)  
 167 during closed MCC (Table 2). Mean cloud top heights (CTH) are typically higher during open  
 168 MCC ranging from 2.2 – 3.3 km, compared to 1.9 – 2.4 km for closed MCC. However, it should  
 169 be noted that CTHs are much more variable during individual open MCC periods and may exceed  
 170 4 km (see Figure 1).

171

172 **Table 2.** Periods of MCC used in this study, and mean environmental conditions during these  
 173 MCC periods at the AMF1 site during COMBLE (Dec 2019 – May 2020).

Start Time	End Time	Type	Time	$M$	$T$	$U$	$WD$	$CTH$
			[min]	[K]	[°C]	[ m s <sup>-1</sup> ]	[°]	[km]
01 Dec 2100 UTC	02 Dec 0330 UTC	Open	390	4.9	2.3	13.3	323.8	2.7
02 Dec 0700 UTC	02 Dec 1530 UTC	Open	510	4.1	2.2	12.1	323.3	2.5
31 Dec 0000 UTC	31 Dec 1915 UTC	Open	1155	3.7	2.1	10.5	285.6	2.5
04 Jan 0830 UTC	05 Jan 0200 UTC	Open	1050	6.3	0.3	10.6	329.6	2.6
21 Jan 2220 UTC	22 Jan 1830 UTC	Open	1210	3.1	2.3	9.2	328.3	2.4
02 Feb 1330 UTC	03 Feb 0615 UTC	Open	1005	5.0	0.8	10.9	319.8	2.2
03 Feb 1040 UTC	03 Feb 1845 UTC	Open	485	6.3	-1.0	7.3	307.6	2.6
04 Feb 1730 UTC	06 Feb 1545 UTC	Open	2775	7.2	-1.0	11.5	308.3	2.7
13 Mar 0800 UTC	14 Mar 0540 UTC	Open	1300	8.0	-3.0	9.3	336.1	3.3
28 Mar 0320 UTC	30 Mar 0945 UTC	Open	3265	7.1	-2.2	10.2	321.6	3.0
09 Apr 1420 UTC	10 Apr 0200 UTC	Open	700	4.8	-0.3	8.3	289.7	2.7
10 Apr 0810 UTC	10 Apr 1620 UTC	Open	490	5.0	0.3	6.8	303.7	2.8
10 Apr 1940 UTC	11 Apr 0530 UTC	Open	590	4.7	0.2	7.5	277.8	2.5
<i>average</i>		Open	14930	6.0	-0.4	10.1	314.4	2.7
17 Apr 0530 UTC	17 Apr 1630 UTC	Closed	660	1.1	3.3	8.8	290.1	1.9
24 Apr 1700 UTC	26 Apr 0010 UTC	Closed	1870	1.6	3.2	8.5	314.4	2.4
26 Apr 0300 UTC	26 Apr 1050 UTC	Closed	470	0.9	2.5	8.1	27.2	2.3
04 May 1050 UTC	04 May 1730 UTC	Closed	400	0.2	4.6	6.7	287.3	2.3
<i>average</i>		Closed	3400	1.2	3.3	8.3	316.6	2.3

174 Note:  $M$ : MCAO-index;  $T$ : 2-m Temperature;  $U$ : 10-m wind speed;  $WD$ : 10-m wind direction;  $CTH$ :

175 Cloud top height. The time in the summary rows ('average') is the total cumulative time.

176

## 177 2.3 Cell Identification

178 To examine the characteristics of open and closed MCC, individual clouds are identified  
179 by applying a marker-based watershed segmentation to the KAZR reflectivity field (Vincent &  
180 Soille, 1991). This identification is necessary for the classification of the individual clouds  
181 described in Section 2.4. For the rest of the study, these individually identified clouds or cloud  
182 sections will be referred to as cells.

183  
184 Watershed segmentation is a segmentation technique with its origins in image processing  
185 that has also found use in analyzing atmospheric data (e.g., Martini et al., 2014; Wu &  
186 Ovchinnikov, 2022). In the case of a marker-based watershed segmentation, all points in a dataset  
187 that are assigned to a predetermined marker comprise an identified object. Similar to how  
188 geographical locations are part of a water drainage basin (watershed), data points are assigned to  
189 the marker to which they have the steepest downward gradient.

190  
191 For this study, the predetermined markers are local maxima in the smoothed KAZR  
192 reflectivity field. A Gaussian filter with a standard deviation of 1 is used for the smoothing. The  
193 smoothing and each following step use linear units of reflectivity (Z) instead of logarithmic units  
194 (dBZ). The local maxima are determined with two requirements: their value must exceed 2.5 dBZ  
195 (converted to Z) and they must be at least 80 KAZR profiles away in time from a larger value (320  
196 seconds at 4 second time resolution). The corresponding minimum width depends on the advecting  
197 wind speed, e.g. 3.2 km for a 10 m s<sup>-1</sup> layer-mean wind. Other requirements and thresholds were  
198 tested, but this setup was found to achieve the least amount of over- and under-segmentation of  
199 cells in a visual analysis. However, none of the tested setups were able to completely avoid bizarre  
200 segmentation outcomes. Clear segmentation errors are corrected by manually removing  
201 (identifying) specific maxima associated with over (under) segmented cells. After the local  
202 maxima are determined, the watershed segmentation is conducted on the inverted reflectivity field,  
203 since the algorithm determines objects based on downward gradients. Cells are confined to the -  
204 30 dBZ reflectivity threshold, which exceeds the KAZR sensitivity even at a largest relevant range  
205 (~5 km). Each object identified by the watershed segmentation is an individual cell. Lastly, small  
206 cells (< 45 KAZR profiles = 3 minutes) and cells with shallow cloud depth (< 50 KAZR vertical  
207 levels between the lowest and highest echo, or 1500 m) are ignored since they have too few data  
208 points for the method used to classify cells in Section 2.4. Furthermore, cells with high radar echo  
209 bases (> 1500 m above sea level) are ignored since these were typically not MCC but other types  
210 of clouds. In total, 780 cells are identified during the 17 periods, 612 (168) of which are during the  
211 open (closed) MCC periods, i.e. 78%. Examples of identified cells in a vertical transect with open  
212 MCC and closed MCC are shown in Figure 1d, h. Note that continuous cloud structures can be  
213 identified as multiple cells. Specifically, in the case of the closed MCC periods, the cells should  
214 not be seen as distinct clouds but rather as a continuous cloud field that is made up of separate  
215 precipitation cores.

## 216 2.4 Cell Classification

217 The next step is to classify the identified cells based on their vertical structure of KAZR  
218 reflectivity, Doppler velocity (i.e., hydrometeor vertical motion), and spectral width. Since the  
219 freezing level is usually at or very close to sea level, the radar echoes are dominated by snow.  
220 Spectral broadening in snow is generally largely due to atmospheric turbulence (Doviak & Zrnic,  
221 1993). For instance, the red-colored cell around 11:20 UTC (Figure 1a-d) is marked by strong

222 convective updrafts and high spectral width, due to high buoyantly-generated turbulent kinetic  
 223 energy. The four closed MCC periods all occurred in late April – early May with freezing levels a  
 224 few hundreds of meters above the surface, which impacts the profiles of all three radar moments.  
 225

226 For the purpose of classifying the 780 cells, we ignore the horizontal cloud structure (i.e.,  
 227 the time dimension of KAZR profiles, shown in Figure 1). Horizontal structure is highly dependent  
 228 on deep-layer wind shear in the direction of cell motion, which is of little relevance to  
 229 understanding the relation between cell vertical structure and its lifecycle. Instead, the vertical  
 230 distribution of the three radar moments, i.e. the contoured frequency-by-altitude diagrams  
 231 (CFADs) of reflectivity, Doppler velocity, and spectral width, provide a more standardized  
 232 representation of the individual cells.  
 233

234 An unsupervised machine learning algorithm referred to as the self-organizing map (SOM)  
 235 is utilized for this CFAD-based classification (Kohonen, 1982). The main objective of the SOM is  
 236 to represent archetypical patterns in datasets using an interconnected node structure, with the user  
 237 defining the structure arrangement. The basis of the SOM algorithm is the following equation,  
 238 which updates the SOM nodes  $\mathbf{m}_{i,j}$  in each training step  $t$ :

$$239 \quad \mathbf{m}_{i,j}(t+1) = \mathbf{m}_{i,j}(t) + a(t) \times n(t) \times [\mathbf{x}(t) - \mathbf{m}_{i,j}(t)]$$

240 (1)

241 The subscripts  $i$  and  $j$  denote the location of the node in the grid and  $\mathbf{x}(t)$  is the input  
 242 vector. The learning rate  $a(t)$  and neighborhood function  $n(t)$  determine how much a node is  
 243 updated in a training step. Different functions were tested and the ones that minimize the  
 244 quantization (Kohonen, 2001) and topographic errors (Kiviluoto, 1996) of the SOM were selected.  
 245 The learning rate  $a(t)$  at each training step is the following function:

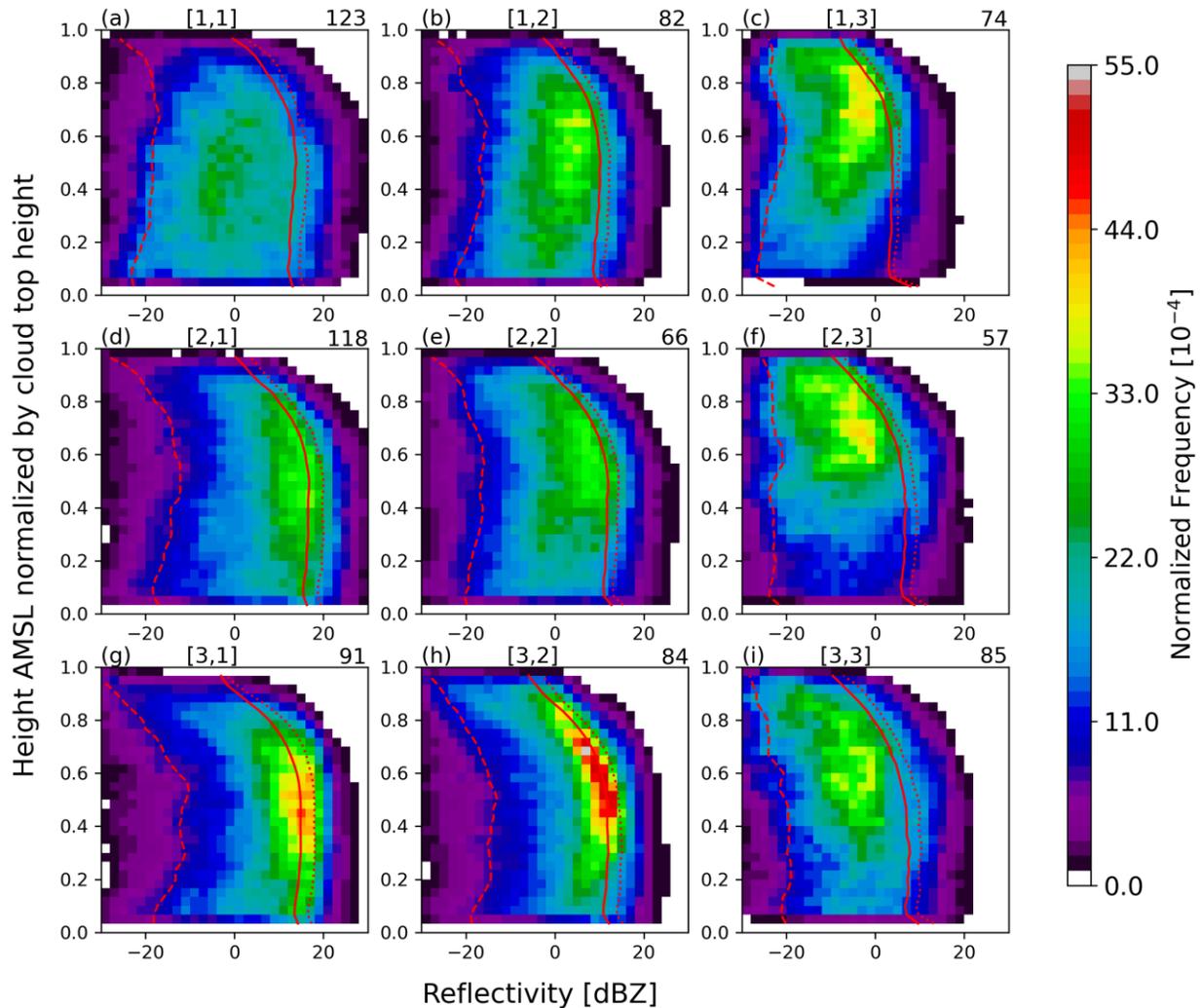
$$246 \quad a(t) = \frac{a(t=0)}{1 + \frac{5t}{t_n}}$$

247 (2)

248 The total number of training steps is denoted by  $t_n$ . The neighborhood function is a  
 249 Gaussian distribution with a standard deviation  $\sigma(t)$ , which follows the same decrease at each  
 250 training step as Equation 2. At the first training step,  $a(t=0) = 0.2$  and  $\sigma(t=0) = 3$ . The center  
 251 of  $n(t)$  is always located on the node that has the smallest Euclidian distance to the input  
 252 vector  $\mathbf{x}(t)$ . This node is referred to as the *best match unit* (BMU). Thus, values of  $n(t)$  decrease  
 253 the further a node is away from the BMU, leading to the arrangement of the SOM nodes by  
 254 similarity. The decrease of  $\sigma(t)$  with each training step continually reduces the value of  $n(t)$  at  
 255 nodes other than the BMU.  
 256

257 The input vector  $\mathbf{x}(t)$  contains the data that is analyzed by the SOM algorithm, in this case  
 258 the CFADs of all three KAZR moments, for a specific cell. The CFAD vertical structure are  
 259 normalized by CTH (a cell's highest echo top), to focus the algorithm's outcome on the distribution  
 260 of the radar variables within cloud, and not the variability of CTHs (which otherwise would  
 261 dominate the SOM nodes). These CFADs provide a standardized and statistically comparable  
 262 representation of each cell. Note that while cell width and CTH do not define the SOM nodes, they  
 263 will be examined as we characterize each node.  
 264

265 Each training step of the SOM consists of calculating Equation 1 for all 780 cells at each  
 266 node. In total, 10,000 training steps are conducted; in each training step, cells are selected in a  
 267 random order. For this study, a grid of 3 by 3 nodes is selected. This setup produced nodes with  
 268 distinct composite CFADs. Setups with more nodes showed little difference between some  
 269 nodes, while setups with fewer nodes merges what we believe are distinct nodes. The final SOM  
 270 resulting from the training process is referred to as the master SOM. The nodes of the master  
 271 SOM are used to classify cells. Each node of the master SOM is characterized, first in terms of  
 272 its composite radar moment vertical structure (e.g., reflectivity, shown in Figure 2) (Section 3.1),  
 273 then in terms of cloud macroscale parameters (Section 3.2), and finally in terms of cloud  
 274 microphysical and dynamical parameters (Section 3.3). Through this analysis, insights into the  
 275 dynamical and microphysical characteristics of each node will be gained, and each node will be  
 276 given a simple identifier. Note that the SOM technique treats each cell independently. It ignores  
 277 the temporal succession of cells or cell nodes as illustrated in Fig. 1d, h, and thus any interaction  
 278 that may occur between cells.  
 279



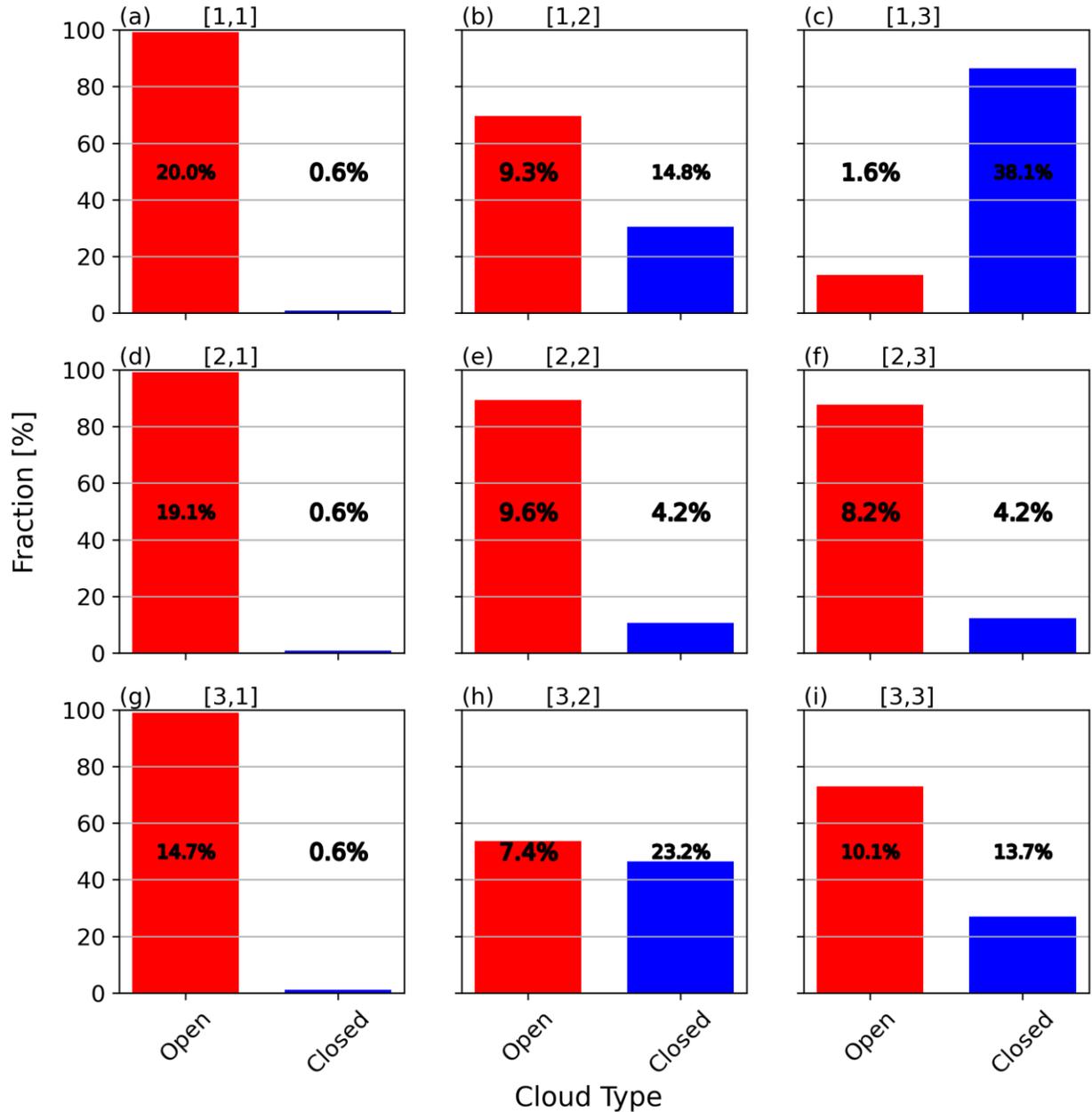
280  
 281 **Figure 2.** Reflectivity part of the master SOM. Each node (labeled as [row #, column #]) shows  
 282 the normalized CFADs of reflectivity composited for all the node's members (cells). The numbers  
 283 on the top right of each node indicate for how many cells (out of a total of 780) each node is the

284 BMU. The red dashed line indicates the 10<sup>th</sup> percentile, the solid line the mean, and the red dotted  
285 line the 90<sup>th</sup> percentile.

### 286 **3 Results**

#### 287 3.1 Cell Classification

288 In this section, the individual nodes of the master SOM are used to classify the MCC cells  
289 observed during the identified periods (Table 2). For a comparison of the differences of the nodes,  
290 Figure 3 displays the fraction of cells in each node, which are from open and closed MCC periods,  
291 and the fraction of all open and closed cells that are in a specific node. For instance, 122 of the 123  
292 cells in node [1,1] are from open MCC periods, accounting for 99.2 % of the cells in this node and  
293 20.0% of all 612 cells during open MCC periods. Additionally, Figures 4 and 5 display the Doppler  
294 velocity and spectral width parts of the master SOM and Figure 6 shows the mean reflectivity  
295 profiles of each node.



296

297 **Figure 3.** Fraction of cells, which are from open (red) and closed (blue) MCC periods at any  
 298 node is displayed by the bars. The sum of the two bars in each node equals 100%. The numbers  
 299 listed in each bar indicate the percentages of the total number of open (left) or closed (right)  
 300 MCC cells that are in each node: the sum of nine numbers equals 100%.

### 301 3.1.1 *Intense convective cells*

302 The nodes shown in the left column ([1,1], [2,1], and [3,1]) contain almost exclusively cells  
 303 found during open MCC periods (Figure 3a,d,g). Since these nodes have a large fraction of  
 304 ascending hydrometeors (Figure 4a,d,g), some rising as fast as  $2 \text{ m s}^{-1}$  in node [1,1], these  
 305 precipitation systems are convective. By definition, convection is characterized by ascending  
 306 hydrometeors during part of the cloud lifecycle or in a cloud region (Houze, 2014). Since these  
 307 nodes have the largest values of mean reflectivity profiles (Figure 6), they can be labelled *intense*

308 *convective cells*. The intense cells undergo a lifecycle which becomes more apparent when cross-  
309 analyzing Figures 2, 4, 5 and 6. Node [1,1] describes rapidly *developing intense cells*, node [2,1]  
310 describes *mature intense cells*, and node [3,1] describes *weakening intense cells*. The developing  
311 intense cells are characterized by the strongest updrafts of any classification (Figure 4a). The  
312 distributions of reflectivity and Doppler velocity values are relatively broad at all levels (Figure  
313 2a, 4a), i.e. clouds are highly heterogeneous with young updrafts and relatively short history of  
314 mixing. Furthermore, the most frequent reflectivity values are in the range of -10 – 0 dBZ (Figure  
315 2a), indicating that hydrometeors in these cells generally are still quite small. The spectral width  
316 on average is the highest in node [1,1] (Figure 5a). When compared to the mature intense cells, the  
317 mean reflectivity profile of the developing intense cells is ~4 – 5 dBZ lower in most of the cloud  
318 (Figure 6).

319

320 The mature intense cells average the largest reflectivity values of all nodes, pointing to  
321 their intensity and maturity (Figure 6). Hydrometeors are mostly of precipitation size, with  
322 reflectivity maxima between 10 – 20 dBZ (Figure 2d). Hydrometeor vertical motions tend to be  
323 only slightly weaker than those of developing intense cells, either due to an increase in  
324 hydrometeor fall speeds, a weakening of the updrafts, or both (Figure 4d). Finally, the variation of  
325 hydrometeor vertical motions of the weakening intense cells is substantially lower (Figure 4g),  
326 and the mean Doppler velocity aloft is closest to zero ( $>-1 \text{ m s}^{-1}$ ), possibly indicating a residual  
327 upper-level mesoscale ascent late in the convective lifecycle, something often observed in more  
328 organized deep convection (Houze, 2014). Reflectivity values are more narrowly distributed  
329 between 10 – 20 dBZ (Figure 2g) indicating weak reflectivity gradients, consistent with more  
330 uniform vertical motions (Figure 4g), and much weaker turbulence (spectral width) than either the  
331 mature or developing intense cells (Figure 5a,d,g). The mean reflectivity profile for these  
332 weakening intense cells is ~2 dBZ lower compared to the mature intense cells (Figure 6). This  
333 indicates that the cells in this node generally contain much precipitation, especially at low levels,  
334 but are weakening. Since the intense cells and their associated lifecycle are found almost  
335 exclusively during open MCC periods (Figure 3), it can be inferred that such intense convection  
336 leads to the development of an open MCC cloud field. The dynamics driving the clearing  
337 (compensating subsidence over the depth of the convective cells) are not observed, since radar  
338 data are only collected in the cloudy sections. This coherent subsidence is at best only indirectly  
339 detected by radar: Figure 1a shows many echo-free regions. The relative lack of such regions in  
340 closed MCC (Figure 1e) suggests lack of coherent subsidence.

341

### 342 3.1.2 Stratiform MCC

343 Node [1,3] has the lowest mean reflectivity profile of any node with values ~3 dBZ in the  
344 lower half of the cloud (Figure 6), showing that precipitation associated with these cells is very  
345 light (also shown in Section 3.3), and, given the scarcity of low-level echoes, frequently evaporates  
346 before reaching the surface (Figure 1e, 2c). The frequent occurrence of (mostly weak) echoes near  
347 normalized cloud top indicates rather uniform cloud tops. Proximity soundings indicate that the  
348 cloud layer generally is capped by a stable layer (not shown). These cells have rather stratiform  
349 characteristics with weak vertical motions and only a small fraction of upward vertical motions,  
350 most of those near cloud top (Figure 4c). Spectral width values are generally low, with higher  
351 values near the surface (on account of high freezing levels and rain for some cells in this node)  
352 and near cloud top (Figure 5c). Cloud top turbulence may be attributed to generating cells (e.g.,  
353 Hobbs & Locatelli, 1978; Rosenow et al., 2014) driven by cloud top radiative cooling (Keeler et

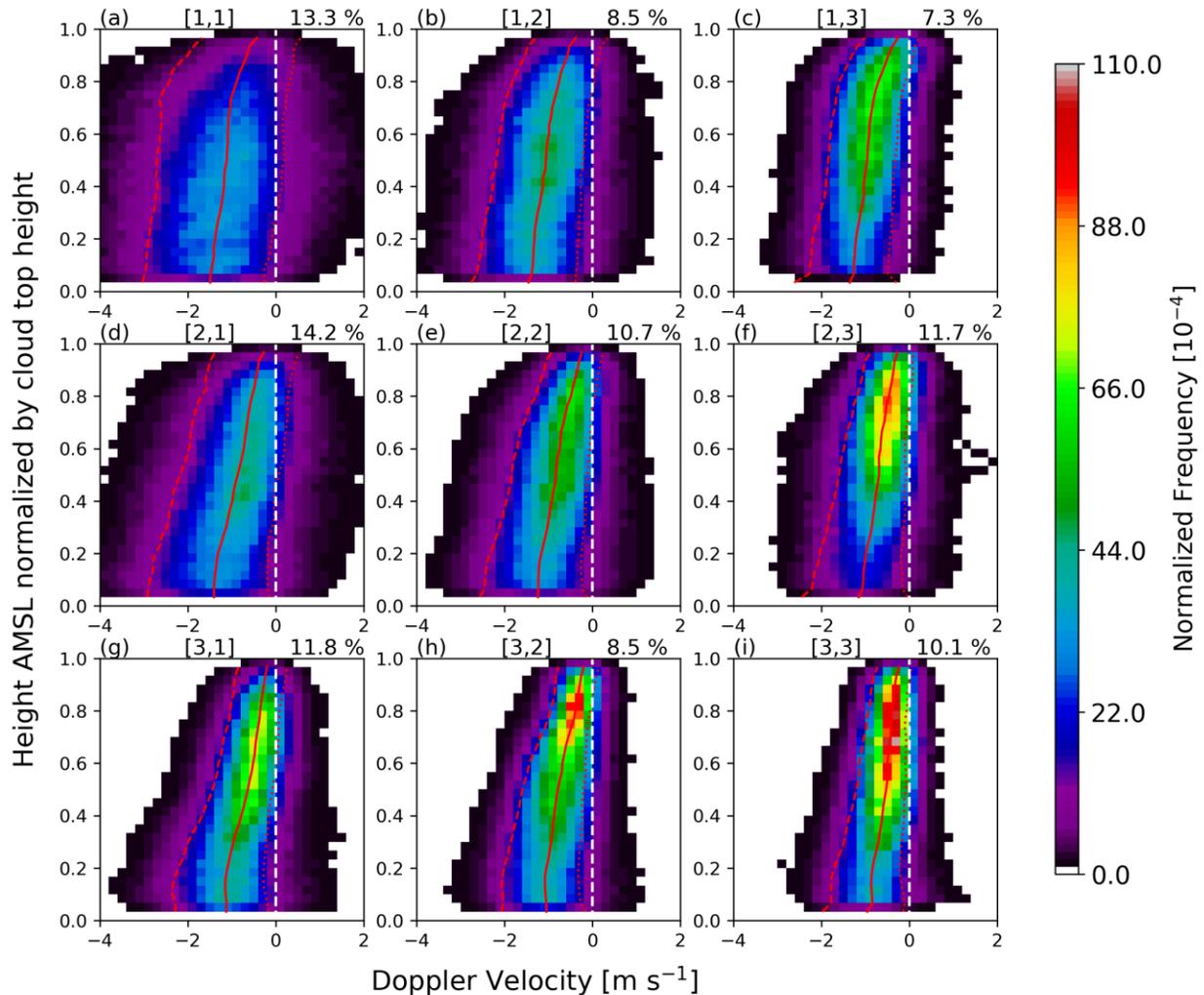
354 al., 2016). Such cells, with a reflectivity and Doppler velocity structure similar that of generating  
355 cells at the top of frontal clouds (e.g., Plummer et al., 2015; Zaremba et al., 2022), become apparent  
356 in a zoom-in of these cells, e.g., around 10:00 UTC in Fig. 1e (not shown). These traits are  
357 indicative of stratiform clouds, with hydrometeors initiated at cloud top and slowly growing as  
358 they fall through the cloud. Thus, these cells can be classified as non- (or barely-) precipitating  
359 stratiform cells. These types of cells are mostly found during closed MCC periods (Figure 3c),  
360 which occurred mostly late in the season (Table 1). The SOM classifies very few cells from open  
361 MCC periods in this node because the relatively high  $M$  values, strong surface heating, and intense  
362 convective development characterizing such periods prevent the development of long-lasting  
363 stratiform clouds. These *non-precipitating stratiform cells* are likely the “base state” in a closed  
364 MCC environment, and they dominate in the closed MCC example in Figure 1h. Yet this cloud  
365 regime exists in a  $M > 0$  environment and contains occasional convective updrafts (Figure 1f), hence  
366 the use of the MCC terminology (consistent with McCoy et al., 2017 and others), even though  
367 stratiform processes may dominate clouds and precipitation.

368

### 369 3.1.3 *Other nodes*

370 Node [1,2] has a relatively broad distribution of hydrometeor vertical motions and spectral  
371 width at most levels of the cloud (Figures 4b, 5b). This indicates the presence of convective  
372 updrafts. The most frequent reflectivity values are relatively low (0 – 5 dBZ) and distributed  
373 throughout the cloud (Figure 2b). Furthermore, the mean reflectivity profile is very similar to the  
374 developing intense cells, except that values are ~4 dBZ lower (Figure 6), i.e., the convection is  
375 weaker. Combined, these characteristics indicate that cells in node [1,2] are developing. These  
376 cells can be labelled *developing moderately intense cells*. Node [2,2] can be labelled *mature*  
377 *moderately intense cells* since the comparison between this node and the developing moderate  
378 cells is very similar to the comparison between the developing and mature intense cells in terms  
379 of the reflectivity (Figure 2b,e), hydrometeor vertical velocity distributions (Figure 4b,e), and  
380 spectral width (Figure 5b,e). Moreover, the mature moderate cells have larger mean reflectivity  
381 values than the developing moderate cells (Figure 6).

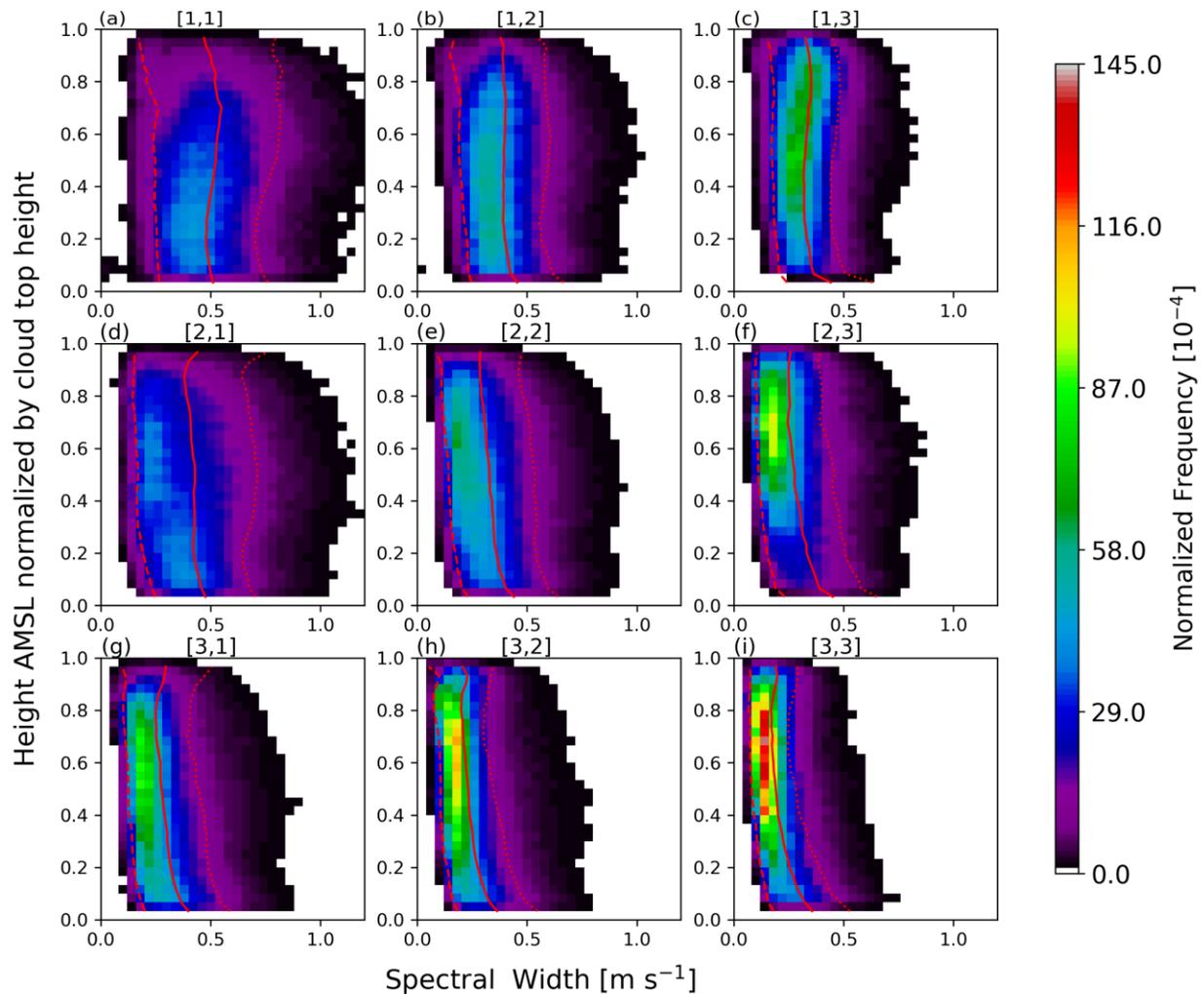
382



383  
 384 **Figure 4.** As Figure 2 but for Doppler velocity (hydrometeor vertical motion). The white vertical  
 385 dashed line indicates  $0 \text{ m s}^{-1}$  Doppler velocity. The percentages on top indicate the percentage of  
 386 positive Doppler velocities in each CFAD.

387 Cells classified as moderate convection (middle column) can be found during open and  
 388 closed MCC periods (middle column in Figure 3), whereas intense cells (left columns) almost  
 389 exclusively occur during open MCC periods. This indicates that moderate convection can  
 390 occasionally occur in the closed MCC environment. Node [3,2] has a rather narrow vertical  
 391 velocity distribution (Figure 4h), very low spectral width values (Figure 5h), and narrowly  
 392 distributed, high reflectivity values, although a few dB lower than the weakening intense cells  
 393 (Figure 2g, h). Therefore, the node is labelled *weakening moderately intense cells*. This node is  
 394 notable because almost half of its cells occur during closed MCC periods, much more than the two  
 395 other moderate intensity nodes. While the cells in node [3,2] from open MCC periods may descend  
 396 from purely convective cells (i.e., weakening moderate cells), the cells from closed MCC periods  
 397 may be relatively intense stratiform cells. For instance, some cells in Figure 1h fall within this  
 398 node but are rather stratiform, while two adjacent cells observed around 13 March 2020 1040 UTC  
 399 are also classified in this node and appear to be the remnants of active convection (Figure 1d). This  
 400 overlap is remarkable: cells with very different development mechanisms (convective vs.

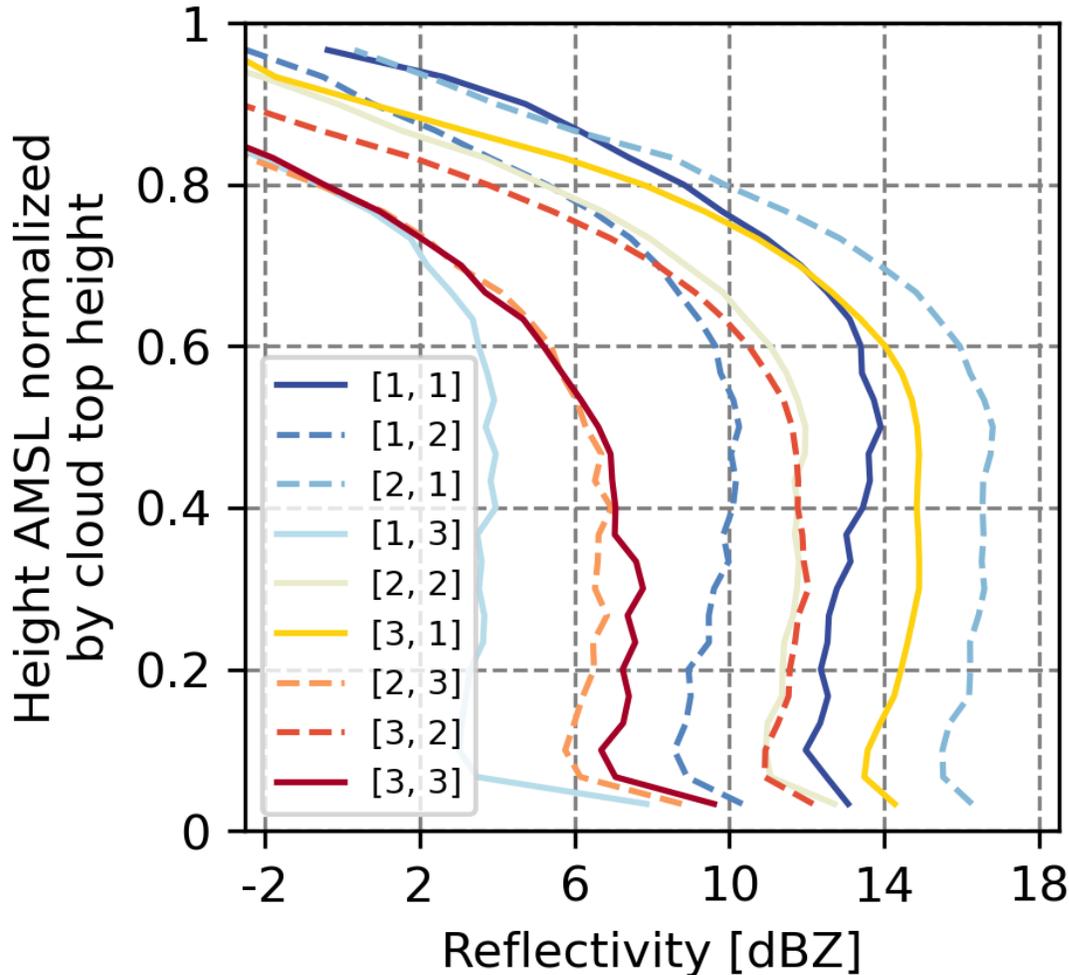
401 stratiform) result in very similar vertical cloud structures (reflectivity, hydrometeor vertical  
 402 velocity, and spectral width) at some point during their development. Thus, we call node [3,2]  
 403 *mixed weakening moderate + stratiform*.  
 404



405  
 406 **Figure 5.** As Figure 2 but for spectral width.  
 407

408 This leaves nodes [2,3] and [3,3] to be analyzed. In terms of the reflectivity distribution  
 409 (Figure 2f,i) and the mean reflectivity profile (Figure 6) these two nodes are very similar. Only the  
 410 non-precipitating stratiform cells (node [1,3]) have lower mean reflectivity values. As in node  
 411 [1,3], reflectivity values in these two nodes are most frequently found in the upper half of the  
 412 clouds, with few low-level echoes, indicating that they are often non-precipitating. The low-level  
 413 echoes are mostly below 0 dBZ for both nodes, indicating light surface precipitation when it  
 414 occurs. Of all nine nodes, node [3,3] has the narrowest distribution of vertical velocity, generally  
 415 slow hydrometeor descent (Figure 4i), and the narrowest distribution of spectral width with  
 416 generally very low values (Figure 5i). An important difference between the non-precipitating  
 417 stratiform cells (node [1,3]) and the cells in nodes [2,3] and [3,3] can be seen in the spectral width  
 418 (Figure 5). While for nodes [2,3] and [3,3] the mean spectral width steadily decreases with height,  
 419 for the stratiform cells node [1,3] it is higher aloft with a maximum near cloud top. This is  
 420 consistent with the observation, in the time-height transects of individual cells, that fine-scale

421 cloud top generating cells with high spectral width, high variability in vertical velocity, and  
 422 reflectivity virga (Figure 1h) are common in node [1,3], and less common in the two other nodes  
 423 on the right, nodes [2,3] and [3,3]. This indicates that the latter two nodes are associated relatively  
 424 more with convection than long-lived stratiform cloud, since the radiative cooling needed for  
 425 generating cells may be a slow process (Keeler et al., 2016). These two nodes occur mostly during  
 426 the open-cellular periods (Figure 3). Node [2,3] has slightly lower mean reflectivity compared to  
 427 node [3,3] (Figure 6), and very few low-level echoes, indicating that it is mostly non-precipitating.



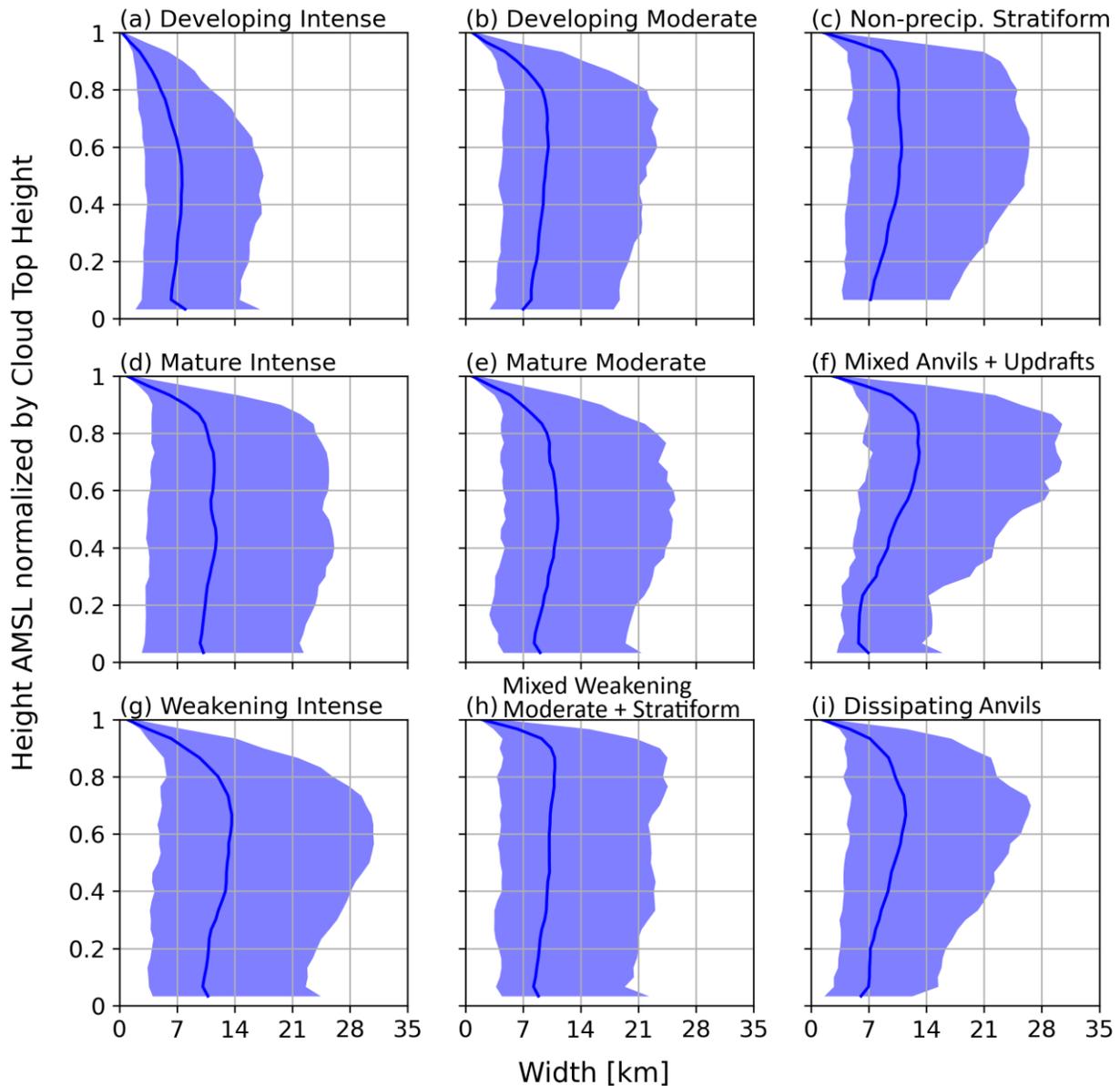
428 **Figure 6.** Mean profiles of reflectivity at each node of the master SOM. Dashed lines are used to  
 429 help differentiate nodes.  
 430

431 Based on our analysis, node [3,3] can be labelled *dissipating anvils*. The cells included in  
 432 this node are at the very end of the convective lifecycle of either intense or moderate cells. Node  
 433 [2,3] has more diverse vertical motions with a rather high fraction of hydrometeors carried upward  
 434 and some localized high spectral width values. This may be explained by the development of new  
 435 updrafts at the outflow boundary of dissipating cells. Thus, we call this node *mixed anvils +*  
 436 *updrafts*.

437 In summary, seven nodes are purely convective or of convective origin, i.e., the three nodes  
 438 on the left (intense convection), 2 in the middle (moderate convection), and two on the right: node

439 [3,3] as dissipating anvil, and node [2,3] as mixed anvils + new convective updrafts. One node (the  
 440 upper right, [1, 3]) is purely stratiform, occurring during weak MCAOs. And one node, [3,2], is  
 441 mixed convective-stratiform, combining the weakening moderate convective cells with more  
 442 intense stratiform cells.

443 3.2 Cloud Morphological Characteristics



444 **Figure 7.** Width of the identified cells at each node of the master SOM. The solid line indicates  
 445 the mean and the shaded area the interquartile range. The titles indicate the node nomenclature.  
 446

447 To examine the characteristics of the cell classifications, other observations collected  
 448 during the identified cells are collectively analyzed for each classification. In this section, cell  
 449 morphological characteristics such as the cloud width and CTH are analyzed. The horizontal width  
 450 of the cells is determined by multiplying the temporal width of the cells at normalized height levels

451 with the closest available *INTERPOLATEDSONDE* wind speed (Figure 7), i.e., it is the along-  
452 wind width only. Note that this width is not fully independent from the classification as it is  
453 determined using the same radar data. Due to the standardized CFADs, the classification contains  
454 only height-relative information about the cloud width, e.g., upper vs lower levels. The absolute  
455 cloud width matters less, it depend in part on a choice in the watershed segmentation method.  
456 What matters more is the vertical structure of the cell width.  
457

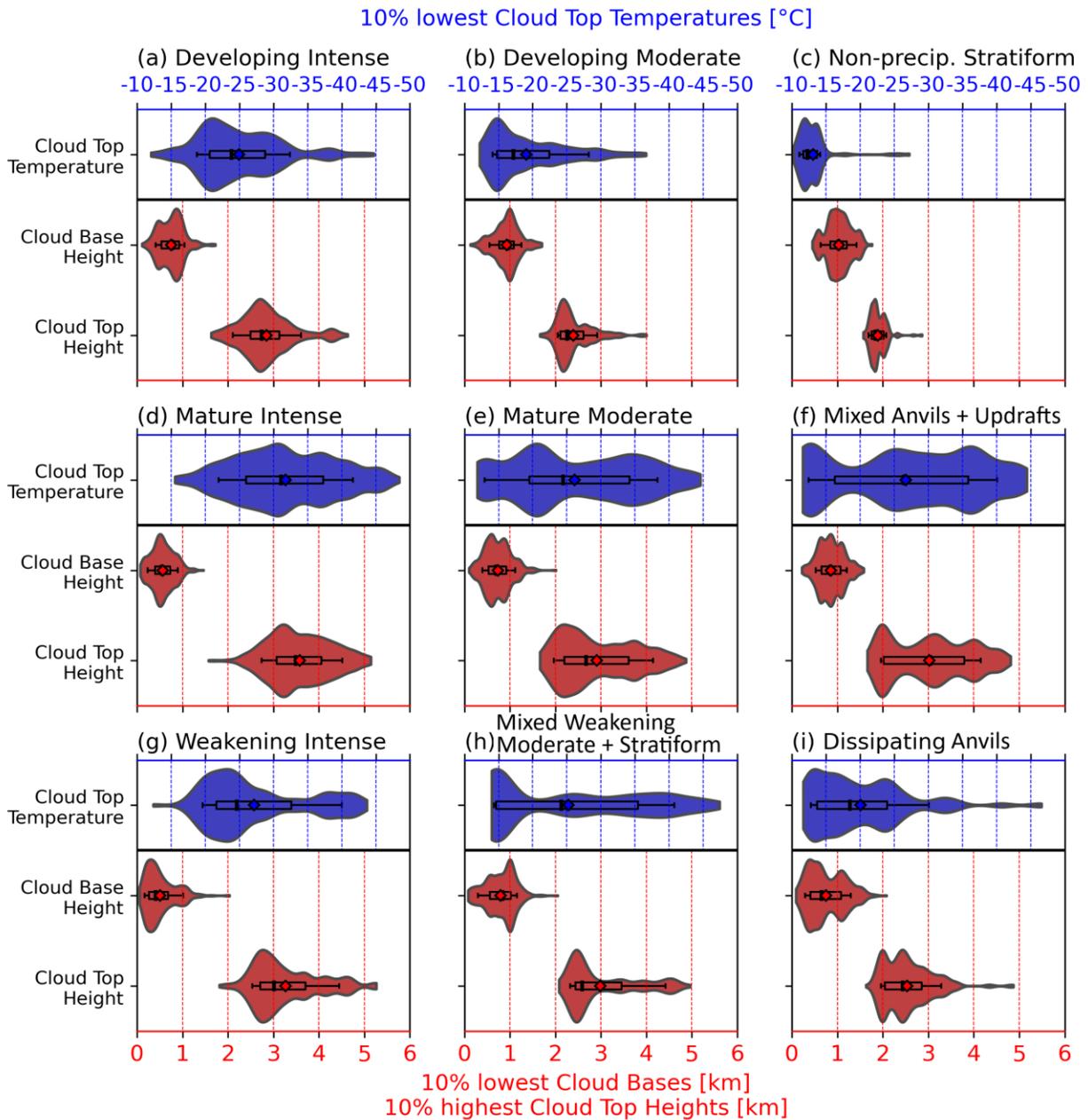
458 There are substantial differences between the cell classifications in terms of the vertical  
459 structure of their width. The intense cells (left column) show a widening as they develop. On  
460 average, developing intense cells are narrower than any other classification and are narrow-peaked,  
461 since the cells are in an upward development. At the mature stage, cells are wider than at the  
462 developing stage and the width of cells is relatively similar throughout the cloud except very close  
463 to cloud top (Figure 7d). The weakening intense cells are wider in the upper half, the result of  
464 divergent flow aloft (Figure 7g). Anvil formation is typical for capped deep convection, but anvils  
465 are not well-developed in the weakening intense cells.  
466

467 This same pattern is not as clear for the moderate cells (middle column, Figure 7). This is  
468 likely due to some of these cells occurring during closed MCC periods. The moderate convection  
469 during closed MCC periods are generally surrounded by preexisting clouds, namely those that are  
470 classified as stratiform cells (Figure 7c,h). Therefore, the average width of moderate cells shows  
471 similarities to the stratiform cells. The non-precipitating stratiform cells have a constant width in  
472 the upper half of the cloud, but they become narrower in the lower parts of the cloud, indicating  
473 their frequent lack of surface precipitation. If Figures 7b,e,h are created for the open MCC periods  
474 only, these moderately-intense cells show a widening as they mature, comparable to the intense  
475 cells with a similar indication of cloud top divergence for the weakening cells (node [3,2]) (not  
476 shown). The dissipating anvils (Figure 7f,i), have an especially large contrast between width near  
477 cloud base (narrow) and cloud top (wide). This is likely related to the cells dissipating from the  
478 base upwards, leaving behind anvils.  
479

480 Next, CTH, cloud top temperature (CTT), and cloud base height (CBH) are analyzed  
481 (Figure 8). A distribution of CTHs, CBHs and CTTs is available for each cell. Here, we use the  
482 10% highest CTHs (10% lowest CBHs and CTTs) of each cell to avoid cells being represented by  
483 outliers of these variables. The CTH of a cell is determined based on the cell mask from the  
484 watershed segmentation (see Figure 1d,h). The CTT is the *INTERPOLATEDSONDE* temperature  
485 at this height at the matching time. CBH estimates are from the *ARSCLKAZRBND1KOLLIAS*  
486 product, which is derived from ceilometer and lidar data. Since cells can overlap in time, cloud  
487 base heights are assigned to the cell that is the closest to the surface in any given KAZR profile.  
488

489 The distributions of CTH and CTT show a large spread within individual nodes (Figure 8),  
490 which can be explained by the variability of the mean CTHs of the MCC periods (see Table 2).  
491 However, the distributions also reveal differences between the nodes. For the intense cells, the  
492 mean CTH is the shallowest (2.8 km) for the developing node (Figure 8a). This can be explained  
493 with the cells developing upwards and not having reached the maximum CTH of their lifecycle.  
494 This maximum CTH (3.6 km) is reached at the mature stage (Figure 8d). At the weakening stage,  
495 CTHs are slightly lower on average (3.3 km) (Figure 8g). As a result, very few developing  
496 intense cells (5 %) have CTTs at which homogeneous freezing can occur [-38 °C (Ickes et al.,  
497 2015)], while many more mature intense cells (25 %) reach such cold temperatures (Figure 8a,d).

498 This indicates that primary nucleation may contribute to an abundance of ice crystals in the cells,  
 499 which may play a role in the lifecycle of these intense cells. Cloud phase will be examined in  
 500 more detail later (Section 3.3). CBHs are not very different between the lifecycle stages, nor  
 501 between MCC periods; they are almost always between 300-1000 m above sea level, consistent  
 502 with the surface-based lifting condensation level.  
 503



504 **Figure 8.** Distributions of cloud top temperature, cloud top height, and cloud base height of the  
 505 identified cells at each node of the master SOM. The box plots inside the violin plots indicate mean  
 506 (diamond), median (solid black line), interquartile range (box), and 10<sup>th</sup> and 90<sup>th</sup> percentile  
 507 (whiskers).  
 508

509 The distributions of CTH, CTT, and CBH for the moderate cells do not directly resemble  
 510 the same pattern as the intense cells. The closed MCC periods within these moderate cells generally  
 511 have rather shallow cloud tops (CTH between 2 – 2.5 km) and high cloud bases (CBH ~1 km) (not  
 512 shown). The mean CTH increases steadily with the development stages from 2.4 km (developing),  
 513 to 2.9 km (mature), to 3.0 km (mixed weakening moderate + stratiform) (Figure 8b,e,h). This  
 514 deepening is more pronounced when analyzing only moderate cells from open MCC periods (2.5  
 515 km, 3.2 km, and 3.5 km; not shown). The reasons for the continued deepening in the late-  
 516 convective stage are not clear. It might be related to the node [3,2] also containing some cells of a  
 517 more intense convective origin (left column in Figures 2, 4, and 5) that have further weakened  
 518 compared to the weakening intense classification. Such cells tend to have a high cloud top,  
 519 explaining the tail of CTH values around 4-5 km in this node (Figure 8h).

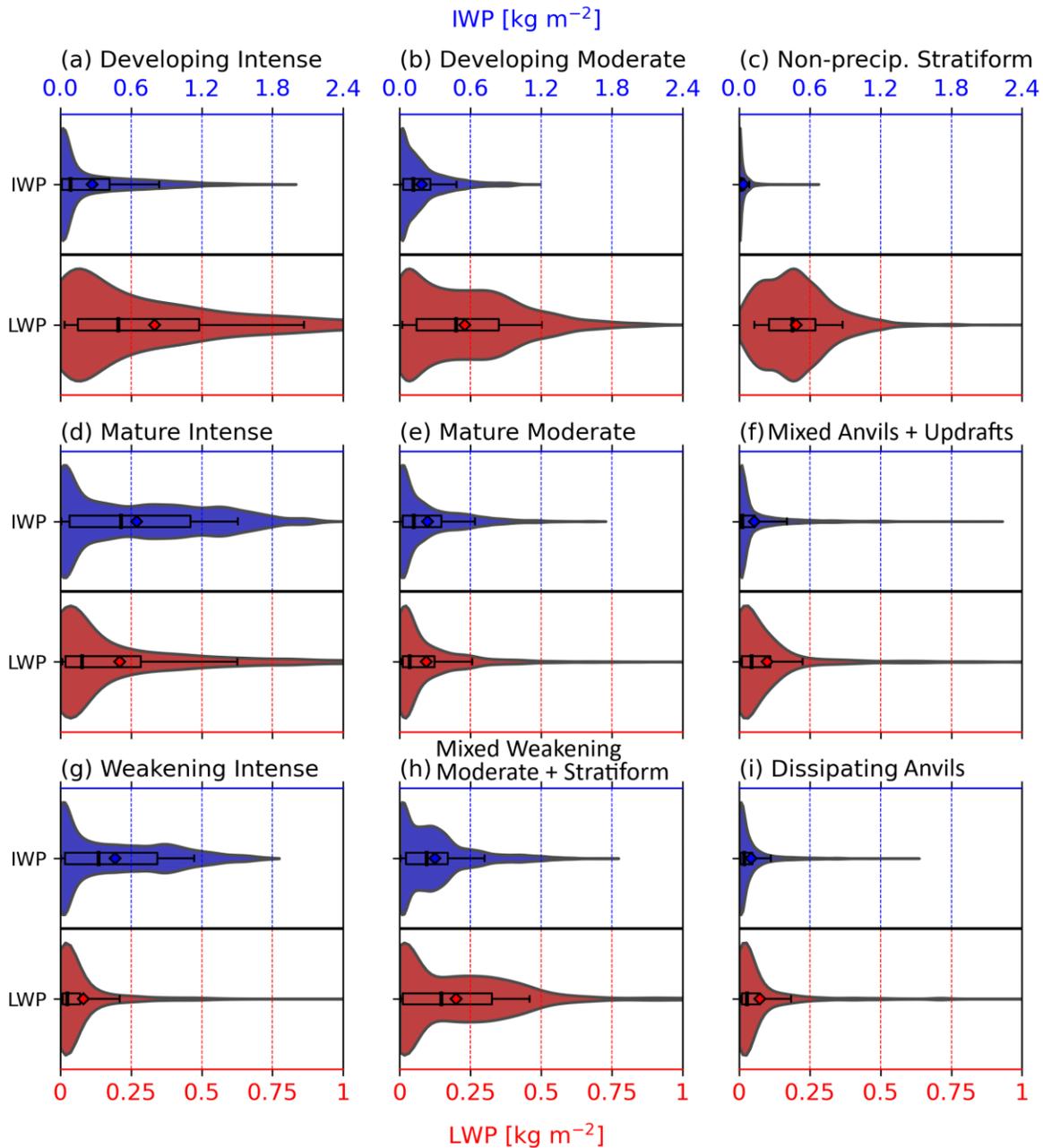
520  
 521 The non-precipitating stratiform cells have comparatively warm CTT ( $> -15$  °C), and a  
 522 narrow distribution of CTH with ~80 % of cloud tops between 1.7 – 2.1 km, indicating their  
 523 homogeneous cloud top, and a CBH around 1 km. This highlights the shallow depth of the closed  
 524 cells, and explains the lack of surface precipitation. The two other nodes in the right column  
 525 (dissipating anvils) also have a large fraction of CBHs above 1.0 km. The mixed node (dissipating  
 526 anvils + updrafts) has a broad range of CTHs, with new updrafts on the shallow side and dissipating  
 527 anvils on the deep side.

### 528 3.3 Cloud Microphysical and Dynamical Characteristics

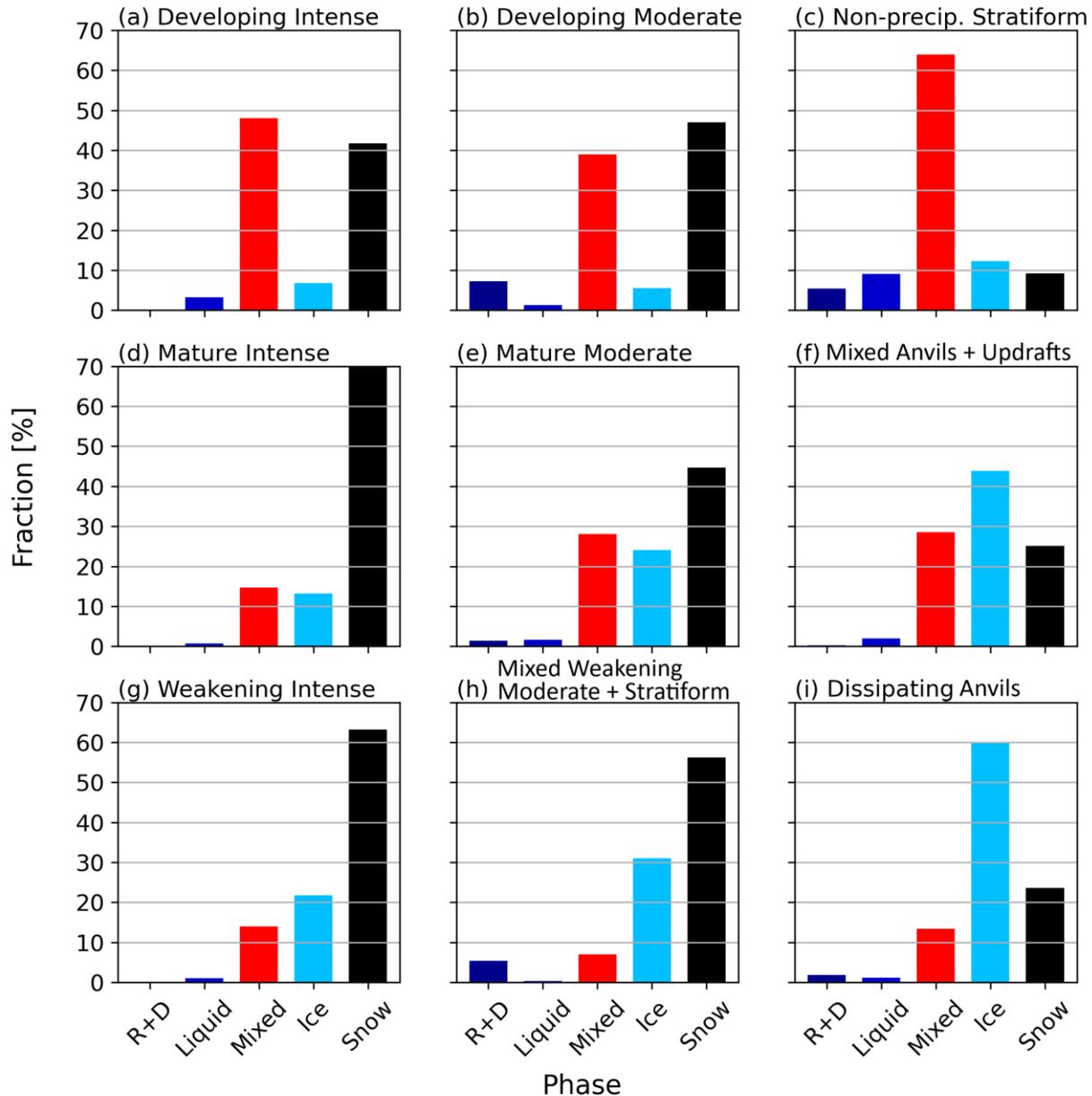
529 In this section, microphysical and dynamical characteristics of the cells are analyzed,  
 530 specifically five variables: microwave radiometer liquid water path (LWP) (Figure 9), radar-  
 531 retrieved ice water path (IWP) from the *MICROBASEKAPLUS* product (Figure 9), cloud phase  
 532 classification from the *THERMOCLDPHASE* product (Figure 10), surface precipitation rate, and  
 533 surface temperature anomaly (cold pools) (Figure 11). Since multiple cells can be identified in a  
 534 single vertical column, it is not always possible to unambiguously assign a LWP measurement (a  
 535 vertically integrated quantity) to a single cell. Therefore, LWP are only assigned to a cell if that  
 536 cell makes up more than 80 % of cloud in a vertical profile and is the closest cell to the surface.  
 537 The *MICROBASEKAPLUS* product has the same time-height resolution as the ARSCL product  
 538 (see Table 1) used to identify individual cells. Ice water content retrievals from this product can  
 539 be directly used to calculate the IWP associated with a specific cell, using the 2D watershed  
 540 segmentation. Data points from the 2D *THERMOCLDPHASE* product are assigned to the cell they  
 541 cover. Precipitation measurements and the surface temperature anomaly are assigned to the cell  
 542 closest to the surface. The minimum (including negative values) difference between the  
 543 instantaneous and the six-hour mean surface virtual potential temperature (centered on the  
 544 instantaneous value) during each cell is used as a measure for cold pool strength.

545  
 546 The cell classifications show strong contrasts in terms of presence of liquid water (Figure  
 547 9). For the intense cells, LWP is much larger in the developing stage with a mean value (90<sup>th</sup>  
 548 percentile) of  $0.33 \text{ kg m}^{-2}$  ( $0.86 \text{ kg m}^{-2}$ ) (Figure 9a). As the convection matures, LWP values  
 549 decrease substantially: the mean value (90<sup>th</sup> percentile) for the mature intense cells is  $0.21 \text{ kg m}^{-2}$   
 550 ( $0.62 \text{ kg m}^{-2}$ ) and for the weakening intense cells  $0.08 \text{ kg m}^{-2}$  ( $0.20 \text{ kg m}^{-2}$ ) (Figure 9d,g).  
 551 Furthermore, the LWP distributions of the intense cells have their mode at relatively low values  
 552 ( $< 0.1 \text{ kg m}^{-2}$ ), indicating that the presence of larger amounts of liquid is confined to small pockets,  
 553 often coincident with deep updrafts (not shown).

554 IWP increases with the development of the intense cells reaching the maximum at the  
 555 mature stage and is only slightly lower in the weakening stage, but still substantially larger than at  
 556 the developing stage (Figure 9a,d,g). This shift in phase with the lifecycle of the intense cells is  
 557 also present in the *THERMOCLDPHASE* product. Slightly over 50 % of the phase identified in  
 558 developing intense cells is mixed-phase or even pure liquid (Figure 10a). In contrast, mixed-phase  
 559 makes up just ~15 % of the phase identified in the mature and weakening intense cells, the rest  
 560 being classified as snow (or ice) (Figure 10d,g). These findings indicate that the conversion of  
 561 liquid to ice is a key component in the evolution of the intense convection.  
 562



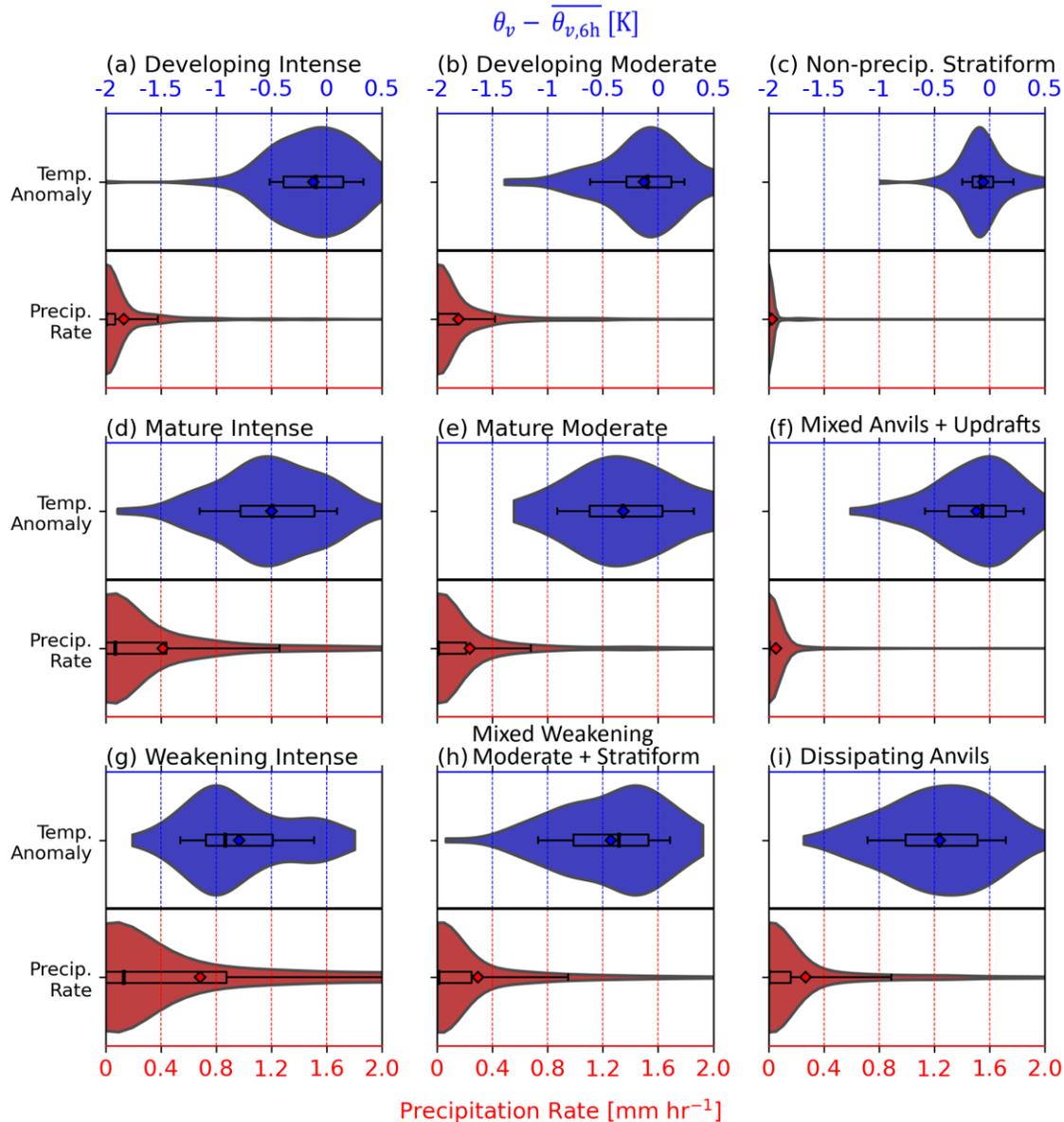
563  
 564 **Figure 9.** Distributions of liquid water path (LWP) and radar retrieved ice water path (IWP) of the  
 565 identified cells at each node of the master SOM. Box plots are as in Figure 8.



566  
 567 **Figure 10.** Fraction of retrieved cloud phase of the identified cells at each node of the master SOM.  
 568 Note that R+D refers to rain and drizzle combining the rain, drizzle, and liquid + drizzle  
 569 classification of the *THERMOCLDPHASE* product (see Table 1).

570 The moderate cells follow the same pattern, with comparatively more liquid and mixed-  
 571 phase during the developing stage and more ice during the mature stage (Figures 9b,e; 10b,e). If  
 572 only the contributions from open MCC periods to the mixed node [3,2] (weakening moderate +  
 573 stratiform) are considered, this pattern continues and there is even less liquid (i.e., LWP mode  
 574 close to  $0 \text{ kg m}^{-2}$  in Figure 9h) (not shown). However, this mixed node includes cells with rather  
 575 large LWP values with a mean of  $0.2 \text{ kg m}^{-2}$ . This can be mostly attributed to a high freezing level  
 576 and rain, associated with the closed stratiform cells. Above the freezing level these stratiform cells  
 577 are mostly ice phase, with very little mixed-phase (Figure 10h). In contrast, the non-precipitating  
 578 stratiform cells consist mostly ( $\sim 75\%$ ) of either mixed-phase or pure liquid cloud (Figure 10c).

579 Liquid is rather normally distributed in this node. This can be inferred from the median, mean, and  
 580 mode of LWP being almost the same ( $\sim 0.19 \text{ kg m}^{-2}$ ) for this node. The dissipating anvils consist  
 581 mostly of ice particles smaller than snow and have very low LWP values (Figures 9f,i; 10f,i). The  
 582 mixed node with dissipating anvils + updrafts has a larger spike of high LWP values and more  
 583 liquid and mixed-phase cloud pixels than the dissipating anvil node (Figures 9f,i; 10f,i). This is  
 584 likely due to the new updrafts and associated supercooled liquid water.  
 585



586  
 587 **Figure 11.** Distribution of precipitation rate and virtual potential temperature anomaly of the  
 588 identified cells at each node of the master SOM. Box plots are as in Figure 8.

589 Lastly, surface precipitation rates and cold pools are analyzed. Precipitation rates and  
 590 (cold) temperature anomalies increase steadily in the lifecycle of the intense cells (Figure 11a,d,g).  
 591 Maxima are reached at the weakening stage, confirming the convective nature of the cold pools,  
 592 i.e. driven by precipitation. For the moderate cells, the same pattern is observed with overall

593 weaker precipitation rates (Figure 11b,e,h). The mixed weakening moderate + stratiform category  
594 shows little difference in precipitation rate between open and closed MCC periods (not shown).  
595 The non-precipitating stratiform node has the lowest precipitation rates confirming this  
596 nomenclature, which was based on the low reflectivity values (Figures 2c, 11c). Furthermore, these  
597 cells display no significant temperature anomalies at the surface, indicating that the precipitation  
598 cores are driven not by cold pool dynamics, but by dynamical or microphysical processes in the  
599 cloud layer. For the dissipating anvil nodes, there is a contrast in precipitation rate and temperature  
600 anomaly (Figure 11f,i). While both nodes have low precipitation rates, the mixed dissipating anvils  
601 + updrafts node has even less precipitation and are not associated with cold pools. This is consistent  
602 with the development of new updrafts outside (or at the edges of) cold pools.

#### 603 **4 Discussion**

604 Our analysis shows that a SOM-based classification can determine distinct characteristics  
605 of open and closed MCC clouds observed during MCAOs. This classification reveals a lifecycle  
606 of convection in which cells rapidly develop (with strong updrafts, high spectral width, growing  
607 cloud tops, high LWP but low IWP, no cold pool) and then weaken through mixed-phase  
608 precipitation processes, which in turn produce a cold pool. This study does not explicitly observe  
609 the coupled microphysical-dynamical process that results in the open-cellular cloud morphology,  
610 but the existence of objectively defined nodes corresponding to lifecycle stages strongly suggest  
611 it. This cycling contributes to the short residence times of water vapor (~1 day) described for  
612 MCAOs (Papritz & Sodemann, 2018).

613  
614 A few things need to be considered when interpreting the results of the cloud classification.  
615 While discrete classifications are determined, it should be remembered that these clouds are found  
616 on a continuous spectrum in terms of their development stage, the intensity of convection, or  
617 stratiform precipitation growth. For instance, the transition of cells from developing to mature is  
618 fluid. Also, an individual cell defined objectively (watershed segmentation method) may consist  
619 of multiple smaller convective turrets at different life stages, e.g., the blue cell around 12:20 UTC  
620 in Figure 1a-d. Furthermore, the analysis is limited to a two-dimensional snapshot of each cell in  
621 time and height. The large number of different cells that were observed enables the classification,  
622 but it is not possible to determine how the characteristics relate to the three-dimensional structure  
623 of individual cells. For instance, it is not possible to determine through which parts of a cell the  
624 vertical scans of the KAZR were made (center vs. edge of cell). Another limitation of this study is  
625 that it does not examine cell interaction, e.g., does a cold pool associated with a dissipating cell  
626 trigger a new cell?

627  
628 Nevertheless, the approach to objectively classify clouds helps to conceptualize the  
629 defining characteristics of convective cells during MCAOs, and to elucidate the driving dynamical-  
630 microphysical processes. While buoyant ascent (possibly forced by outflow boundary  
631 convergence) clearly is the driving mechanism during relatively intense MCAOs with strong  
632 surface heating, stratiform cloud and precipitation processes play a role as well, especially under  
633 low  $M$  value conditions. This may result in a closed MCC organization, which was less common  
634 during COMBLE, and observed only late in the season (April-May). Remarkably, the cloud  
635 vertical structure of late-stage moderately-intense convective cells, as probed by the KAZR, is  
636 very similar to that of more intense stratiform precipitation cores, resulting in a single SOM node  
637 that combines both.

638

639 Our analysis is limited to the comparatively short data record of COMBLE. While a certain  
640 range of MCAO intensities is captured, it is not necessarily representative of the long-term  
641 climatological conditions over the high-latitude oceans, and certainly not elsewhere. The approach  
642 presented here, using the COMBLE dataset, could be used to analyze MCC clouds at observational  
643 sites with a much longer data record such as ARM's North Slope of Alaska and Eastern North  
644 Atlantic (ENA) sites. On average,  $M$  values are lower in the area of the ENA site during MCAOs  
645 (or post-frontal periods) (Fletcher et al., 2016), and the amount of time during which open and  
646 closed MCC occurs is much more equal (Jensen et al., 2021). A comparison with the ENA site  
647 allows examination of the importance of the ice phase in MCAO convection dynamics: the ENA  
648 site is considerably warmer, resulting in less common mixed-phase MCC.

649

650 In future work, we will analyze the MCAOs listed in Table 2 using a large-eddy simulation  
651 (LES), starting with the 13 March 2020 case (Kosović et al., 2023), and a similar approach as  
652 presented in this study. A radar simulator such as the Cloud Resolving Model Radar Simulator  
653 (Oue et al., 2020) will be used to create synthetic radar data from the LES that is comparable to  
654 KAZR observations. A comparison of the observational SOM classification to an LES-output  
655 based SOM classification may reveal whether the model reproduces MCC with the characteristics  
656 observed in this study. Another benefit of conducting this analysis with LES is that the three-  
657 dimensional spatial structure and the temporal evolution of the variables presented in this study  
658 could be analyzed. The LES further allows analysis of a large number of cells given that the  
659 simulation covers a large domain, stretching from north of the ice edge to south of the COMBLE  
660 observation site (~1,200 km distance).

661

## 662 **5 Conclusions**

663 In this study, the characteristics of open and closed mesoscale cellular convection (MCC)  
664 during marine cold-air outbreaks (MCAO) are investigated. The data were collected as part of the  
665 COMBLE field campaign at a coastal site in northern Norway. Unambiguous periods of open and  
666 closed MCC are determined within MCAOs, based on radar and satellite data. Periods of open and  
667 closed MCC are associated with MCAO intensity and display distinct cloud top height differences.  
668 Watershed segmentation and self-organizing map (SOM) algorithms are used to objectively  
669 identify and classify individual cells observed during these periods. The identification and  
670 classification of cells are based on the vertical structure of the cells as observed by a vertically  
671 scanning Ka-band radar. The main findings from the classification of individual cells are as  
672 follows:

- 673 • The SOM algorithm yields nine nodes with distinct vertical distributions of the three radar  
674 moments, i.e., reflectivity, Doppler velocity, and spectral width. These nine nodes are given  
675 descriptive identifiers that refer to the intensity of their convection, their lifecycle stage, and  
676 whether they have stratiform characteristics. The nine classifications are: developing, mature  
677 and weakening intense cells, developing and mature moderate cells, mixed weakening moderate  
678 cells and precipitating stratiform cells, non-precipitating stratiform cells, anvils with updrafts,  
679 and dissipating anvils.
- 680 • Cells classified as intense convection have the largest reflectivity values of any classification,  
681 and only occur during open MCC periods. They are separated into developing, mature, and

682 weakening intense cells. Developing cells are associated with strong updrafts, high spectral  
 683 width, shallower cloud depth, pockets of large liquid water path, and minimal precipitation. As  
 684 the convection matures and then decays, updrafts decrease in strength, cloud tops are higher  
 685 and colder, the amount of liquid decreases while the amount of ice increases, surface  
 686 precipitation intensifies and cold pools develop below the cells. At the very end of the lifecycle  
 687 dissipating anvils remain. New updrafts can develop below these anvils if they are not located  
 688 over cold pools.

- 689 • Cells with more moderate convection compared to the intense cells are observed during open  
 690 MCC and occasionally during closed MCC. This moderate convection shows a similar lifecycle  
 691 as the intense cells.
- 692 • During closed MCC periods, cells with stratiform characteristics are observed most frequently.  
 693 These stratiform cells are separated into non-precipitating and precipitating cells. Non-  
 694 precipitating stratiform cells are relatively shallow with cloud tops mostly  $>-15^{\circ}\text{C}$ , have weak  
 695 vertical drafts, somewhat enhanced spectral width near cloud top, and mostly mixed-phase  
 696 cloud. The precipitating stratiform cells are dominated by ice, and are structurally very similar  
 697 to late-phase (weakening) moderately intense convective cells. Neither reveal distinct cold  
 698 pools.

699

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706

707 **Open Research:** COMBLE campaign data at the Andenes site (ANX) used in this study are  
 708 available through the references found in Table 1. The watershed segmentation was implemented  
 709 in python code using the sci-kit image package (<https://scikit-image.org/>) and the self-organizing  
 710 map algorithm was implemented with the minisom package  
 711 (<https://github.com/JustGlowing/minisom>).

712

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