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1 **Impact of mixed-phase cloud parameterization on warm conveyor belts and**
2 **upper-tropospheric dynamics**

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10 ABSTRACT: This study investigates mixed-phase cloud (MPC) processes along the warm con-
11 veyor belts (WCBs) of two extratropical cyclones observed during the North Atlantic Waveguide
12 and Downstream Impact EXperiment (NAWDEX). The aim is to investigate the effect of two
13 radically distinct parameterizations for MPCs on the WCB and the ridge building downstream; the
14 first one (REF) drastically limits the formation of liquid clouds while the second one (T40) forces
15 the liquid clouds to exist. REF exhibits a stronger heating below 6 km height and a more important
16 cooling above 6 km height than T40. The stronger heating at lower levels is due to more important
17 water vapor depositional processes while the larger cooling at upper levels is due to differences in
18 radiative cooling. The consequence is a more efficient potential vorticity destruction in the WCB
19 outflow region and a more rapid ridge building in REF than T40. A comparison with airborne
20 remote sensing measurements is performed. REF does not form any MPCs whereas T40 does, in
21 particular in regions detected by the radar-lidar platform like below the dry intrusion. Comparison
22 of both ice water content and reflectivity shows there may have too much pristine ice and not enough
23 snow in REF and not enough cold hydrometeors in general in T40. The lower ice to snow ratio in
24 T40 likely explains its better distribution of hydrometeors with respect to height compared to REF.
25 These results underline the influence of MPC processes on the upper-tropospheric circulation and
26 the need for more MPC observations in mid-latitudes.

27 SIGNIFICANCE STATEMENT: The diabatic processes occurring in the warm conveyor belt
28 (WCB) of extratropical cyclones impact the jet stream structure at mid-latitudes. This study
29 highlights some sensitivity of upper-level dynamics to mixed-phase cloud related processes. Com-
30 parisons of two different microphysical schemes for mixed-phase clouds shows that the ratio of
31 liquid to solid clouds along the WCB ascents impacts the latent heat release and the radiation.
32 Data from the NAWDEX campaign helps to determine rooms for improvements for both schemes
33 and point out the need of a better understanding of these processes for an improved prediction of
34 upper-level dynamics.

35 **1. Introduction**

36 Mid-latitude atmospheric circulation has been shown to be strongly dependent on diabatic
37 processes occurring in the warm conveyor belts (WCBs) of extratropical cyclones (Pomroy and
38 Thorpe 2000; Grams et al. 2011, among many others). WCBs are ascending coherent warm and
39 moist airstreams rising from the boundary layer to the upper troposphere and forming elongated
40 cloud bands (Harrold 1973; Browning 1986). When these airstreams ascend, liquid, mixed-phase,
41 and ice clouds form and the corresponding latent heat release can warm the air as much as 20 K
42 in 48 h (Madonna et al. 2014; Joos and Forbes 2016). Cloud thermodynamic phase impacts on
43 dynamics can be described through the potential vorticity (PV) framework (Hoskins et al. 1985).
44 PV increases below the maximum of heating in the lower troposphere and decreases above it at
45 the level of the jet stream. Misrepresented diabatic processes may lead to the formation of PV
46 forecast errors that propagate and grow along the jet stream (Dirren et al. 2003; Gray et al. 2014;
47 Martínez-Alvarado et al. 2016) and produce consequences on the downstream predictability of
48 high-impact weather events. This reasoning mainly motivated the international field campaign
49 NAWDEX (North Atlantic Waveguide Downstream and impact EXperiment) that occurred in
50 September-October 2016 (Schäfler et al. 2018).

51 An on-going challenge in Numerical Weather Prediction (NWP) and climate modelling concerns
52 the representation of mixed-phase clouds (MPCs) (Illingworth et al. 2007) that are composed
53 of supercooled cloud droplets (i.e. under 0 °C) and ice crystals. Liquid fraction within MPCs
54 is invariably underestimated in models according to Tremblay et al. (2003) and Morrison et al.
55 (2003). MPCs are thermodynamically unstable because saturation with respect to ice is reached

56 at lower humidity than with respect to liquid. However, according to Shupe et al. (2008) and
57 McFarquhar et al. (2011), supercooled cloud droplets can persist from several hours to several days
58 before the transition to solid phase occurs. MPCs have been extensively studied for their climatic
59 significance through radiation (Sun and Shine 1994), for their impact on precipitation enhancement
60 (Korolev et al. 2017) and because they are responsible of hazardous aircraft icing (Cober et al.
61 2001). Some studies focused on their dynamical impact on convection enhancement (Seifert and
62 Beheng 2006; Kumar et al. 2014), but to our knowledge no studies explored their impact on mid-
63 latitude upper-tropospheric dynamics. MPCs experience the three different water phase changes
64 during their formation and evolution: vapor to liquid, vapor to solid and liquid to solid. Latent heat
65 releases associated with these three different phase transitions differ strongly so that the mixing
66 partition may impact the heating rates by $\sim 10\%$ (Yau and Rogers 1996).

67 High occurrence of supercooled water in the North Atlantic has been reported by Hu et al. (2010)
68 and Mülmenstädt et al. (2015) and evidence of MPCs within WCBs of extratropical cyclones have
69 been observed by Boettcher et al. (2021) and Alexander et al. (2021). MPCs are more likely
70 to occur when vertical velocities are strong enough so that liquid water vapor saturation can be
71 reached (Korolev et al. 2017). In WCBs, embedded convection (Rasp et al. 2016; Oertel et al.
72 2019; Gehring et al. 2020) may allow these conditions to occur. Also, radiation and turbulent
73 mixing with clear air at the top or at the edge of the cloud may favor the occurrence of liquid water
74 supersaturation at temperatures well below $0\text{ }^{\circ}\text{C}$ according to Korolev and Mazin (2003).

75 The present study follows two main objectives: the first one is to document the occurrence
76 of MPCs within the WCBs using the dataset of the NAWDEX campaign and the second one is
77 to investigate how the representation of MPCs in numerical models can impact the jet stream
78 in the WCB outflow region. To achieve the first objective, unique observations of cloud water
79 thermodynamic phases are analysed using the measurements made with both the Doppler radar
80 RASTA (RADAR SysTEM Airborne) and the lidar LNG (Leandre New Generation) (Delanoë et al.
81 2013b) on board the French SAFIRE (Service des Avions Français Instrumentés pour la Recherche
82 en Environnement) Falcon 20. To reach the second objective, numerical simulations of the Meso-
83 NH model (Lac et al. 2018) with two different representations for MPCs have been performed and
84 are hereafter analyzed.

85 Two extratropical cyclones intensively observed during NAWDEX have been analysed and sim-
86 ulated. The first extratropical cyclone is associated with a strong synoptic forcing. It is called the
87 'stalactite' cyclone and corresponds to the Intensive Observation Period (IOP) 6. The second one
88 is associated with a moderate synoptic forcing that led to the formation of the tropopause ridge
89 'Thor' and corresponds to IOP 10. The terms stalactite cyclone and Thor ridge come from specific
90 shapes in the PV field during the formation of these phenomena (Schäfler et al. 2018). It is worth
91 investigating these two events because they are triggered with distinct synoptic forcings and also
92 because the dynamical response to diabatic heating is known to be highly case-dependent (Smith
93 2000). The sensitivity to the pre-existing hydrometeor distribution will also be considered as the
94 results could strongly vary from one initial state to another (Berman and Torn 2019).

95 In a companion paper (Mazoyer et al. 2021, hereafter denoted as MAZ21), simulations of the
96 stalactite cyclone have been already performed using the one-moment microphysical scheme ICE3
97 (Pinty and Jabouille 1998) and compared to a quasi-two-moment microphysical scheme, called
98 LIMA (Vié et al. 2016). Differences between the two schemes on the WCB of the stalactite cyclone
99 and the jet stream aloft were found to be important after 2-day simulations. The study of MAZ21,
100 showed that the ICE-3 microphysics has better skills than the complex two-moment scheme LIMA
101 (Vié et al. 2016) to simulate the WCB and the ridge building downstream.

102 In the present study, the same approach as in MAZ21 is followed but instead we are comparing
103 two different representations of MPCs within ICE3 and analyzing two case studies instead of only
104 one. ICE3 uses a simple saturation adjustment scheme (Lord et al. 1984) based on the assumption
105 that the entire supersaturated water vapor condenses. The saturation mixing ratio is defined as the
106 mass-weighted average of the respective saturation values over liquid and ice. A first possibility in
107 ICE3 is then to adjust water vapor on droplets and pristine ice in proportion to their amount before
108 the adjustment. A second possibility (Tao et al. 1989) is to force the vapor adjustment in a way,
109 that at the end of all the microphysical steps, the sum of water mass due to droplets and pristine
110 ice is distributed between droplets and pristine ice according to a linear function of temperature
111 from 0 to -40 °C. Such a parameterization allows both hydrometeors to coexist at temperatures as
112 low as -40 °C (DeMott and Rogers 1990; Rosenfeld and Woodley 2000; Hu et al. 2010). While the
113 first method is highly dependent on initial conditions (Engdahl et al. 2020), the second one forces
114 the hydrometeor distribution (Boudala et al. 2004). Obviously both methods have advantages and

115 drawbacks, but should proceed to different liquid and solid partitions which rightly allows us to
116 investigate the impact of this partition on large-scale dynamics.

117 The structure of the paper is as follows: section 2 is dedicated to the methodology and the
118 synoptic overview of the two cases. Section 3 describes the microphysical characteristics of the
119 simulations made with the two distinct parameterizations, their differences in latent heat release
120 and their distinct impacts on the upper-level ridge building. Section 4 compares model simulations
121 and airborne radar-lidar observations in terms of thermodynamic phases and microphysics
122 products in an attempt to document the occurrence of MPCs and to assess the skills of the two
123 microphysical schemes. Discussions and conclusions are drawn in section 5.

124

125 **2. Methodology and case description**

126 *a. Model*

127 The French anelastic research model Meso-NH (Mesoscale Non-Hydrostatic) (Lac et al. 2018,
128 <http://mesonh.aero.obs-mip.fr/>) is used in a convection-permitting mode at a 2.5 km horizontal grid
129 spacing with 55 stretched vertical levels. All the parameterizations are the same as in MAZ21. Only
130 the setup of the microphysical scheme ICE3 (Caniaux et al. 1994; Pinty and Jabouille 1998) may
131 differ from MAZ21 in some experiments. ICE3 is a bulk mixed-phase one-moment microphysical
132 scheme with prognostic equations predicting the mass mixing ratios of six water species (water
133 vapor, droplets, rain, pristine ice, snow, and graupel). In cold clouds, snow is only formed by
134 autoconversion and aggregation of pristine ice. As graupel is a MPC hydrometeor, it is first formed
135 by rain or droplets collection by ice or snow and can then grow by vapor deposition. An adjustment
136 to saturation for liquid/solid phase is performed meaning that there is deposition of all the excess
137 vapor on cloud droplets/pristine ice particles in warm/cold clouds. In our reference version (called
138 REF), a barycentric formula based on pristine ice and cloud droplets mass mixing ratio before the
139 adjustment is used to divide the excess vapor between pristine ice particles and cloud droplets,
140 which may lead to artificial distribution between hydrometeors. However, an option, that we call
141 T40, is to distribute the vapor in order to respect a ratio between droplets and pristine ice as a
142 linear function of temperature from 0 to -40 °C at the end of the microphysics (all other source/sink
143 terms computed). Consequently with that option, above 0 °C only liquid is present and under -40

144 °C only pristine ice. While this second option appears even less physical, it gets the advantage of
145 being radically opposite to the REF options as it forces the MPCs to exist.

146 *b. Synoptic overview and simulation set up*

147 Two extratropical cyclones and associated upper-level ridges that contributed to the onset
148 and persistence of a blocking event over Scandinavia during the period 2–19 October 2016 are
149 hereafter studied. These events are presented in Schäfler et al. (2018, see their Fig.6) and Steinfeld
150 et al. (2020, see their Fig.1) and can be summarized as follows:

151

- 152 • The stalactite cyclone observed during IOP 6 of NAWDEX explosively deepened with a sea
153 level pressure (SLP) decrease of 26 hPa in 24h. The associated upper-level ridge initiated the
154 block onset (Maddison et al. 2019; Steinfeld et al. 2020) and has been already extensively
155 studied using different models and observations (Blanchard et al. 2020, 2021; Flack et al.
156 2021; Mazoyer et al. 2021; Rivière et al. 2021).
- 157
- 158 • The extratropical cyclone associated with the Thor ridge and observed during IOP 10 of
159 NAWDEX was less intense. The Thor ridge is one of the last ridges that contributed to the
160 agglomeration and persistence of the Scandinavian block (Schäfler et al. 2018; Sánchez et al.
161 2020; Steinfeld et al. 2020).

162 The REF and T40 configurations of the model are run for both cases. Because initial conditions
163 may impact the WCB representation (Berman and Torn 2019), sensitivity to the initial state is
164 made for the stalactite cyclone. Overall, six simulations are run, with initial and lateral boundary
165 conditions provided by 6-hourly global operational model ARPEGE analyses:

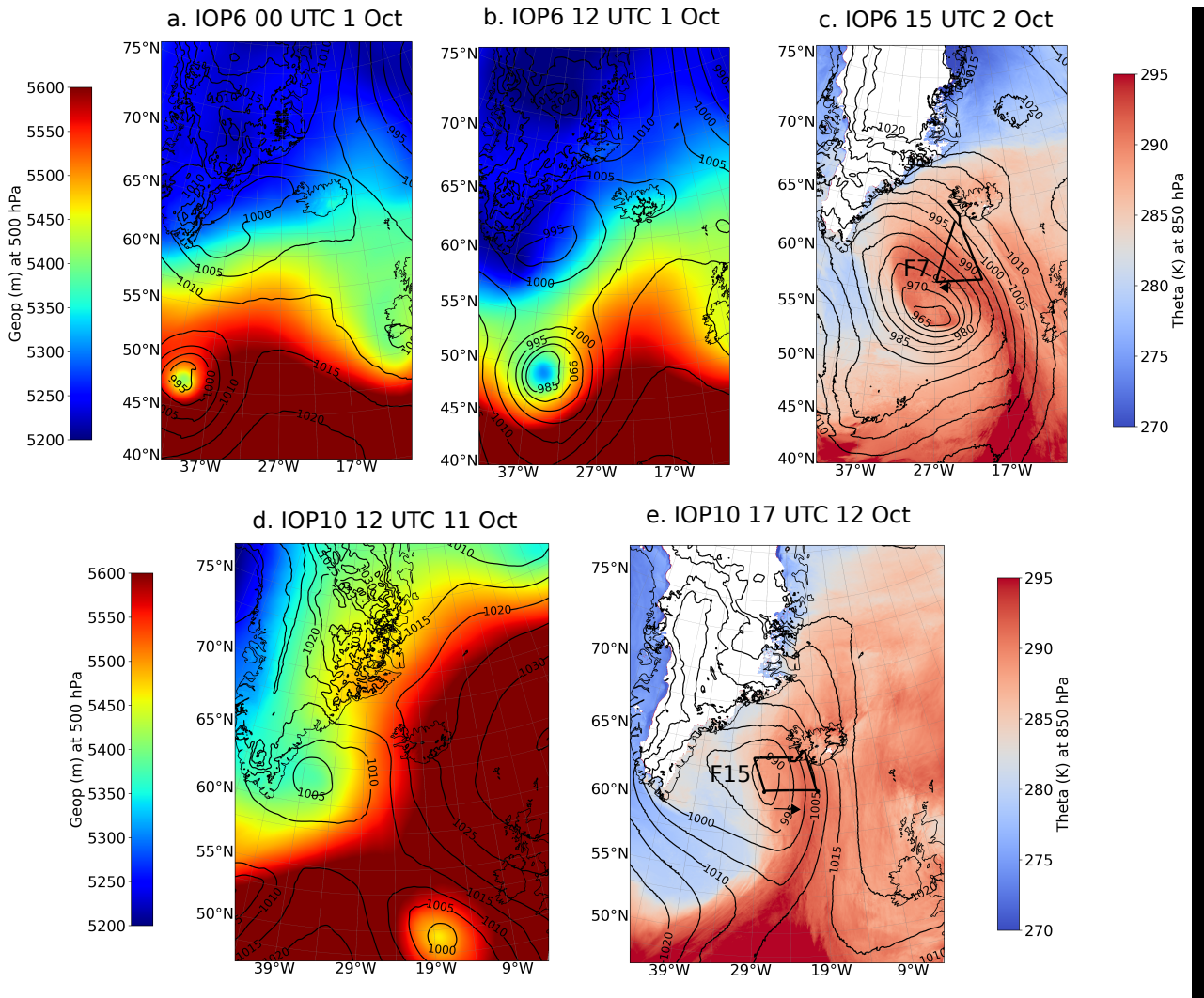
- 166 (i) The stalactite cyclone initialized at 00 UTC 1 October 2016 lasting 48 hours.
- 167 (ii) The stalactite cyclone initialized at 12 UTC 1 October 2016 lasting 36 hours.
- 168 (iii) The Thor ridge initialized at 12 UTC 11 October 2016 lasting 36 hours.

169 The three initial states of the two cyclone events are localized in the southwestern part of the
170 Meso-NH domain at the initial times (Figs. 1a, b and d). The stalactite cyclone is deeper, the
171 circulation is less zonal and the ridge building is more developed in the initial state of (ii) than (i)
172 (see Figs. 1a,b). In (iii), the initial state is composed of a surface low which is only half visible at

173 40°W, 50°N in Fig. 1d, a well-developed Scandinavian block and a decaying cyclone near 37° W,
174 62° N. Flights with the French SAFIRE Falcon 20 were conducted during the deepening phase of
175 both extratropical cyclones in order to sample the ascending branch of the WCB that is associated
176 with intense cloud formation. A good area to examine is located ahead of the surface cold front in
177 the warm sector of the cyclone that corresponds to the ascending part of the WCB. Figs. 1c and e
178 show the surface cold front position in terms of potential temperature at 850 hPa during the time
179 of the selected flights of the NAWDEX campaign. During the stalactite cyclone, the Falcon flight
180 numbered F7 (Fig. 1c) sampled the WCB south of Iceland from 1301 to 1616 UTC on 2 October.
181 During the Thor ridge, the Falcon flight numbered F15 (Fig. 1e) sampled the WCB south of Iceland
182 from 1551 UTC to 1825 UTC on 12 October.

187 *c. Observations*

188 During NAWDEX, the Falcon was equipped with a radar-lidar platform (RALI;
189 (<http://rali.projet.latmos.ipsl.fr/>, Delanoë et al. 2013b). The radar measurements provide re-
190 flectivity and three-dimensional wind components. The combination of the Doppler radar RASTA
191 and the lidar, is unique to get detailed information on clouds (combining the high sensitivity of
192 the lidar and the penetration capability of the radar in thicker clouds). Thanks to the variational
193 algorithm of Delanoë and Hogan (2008) and its further development (Delanoë and Hogan 2010;
194 Cazenave et al. 2019), the radar-lidar measurements allow the retrieval of Ice Water Content (IWC)
195 and provide a cloud classification. The major source of uncertainty comes from the choice of
196 the mass law. More information on the uncertainties of retrievals can be find in Delanoë et al.
197 (2013a) and Cazenave et al. (2019). The cloud thermodynamic phases are categorized in liquid,
198 mixed phase, pristine ice, clear-sky and an 'unknown' category. Note that in our classification,
199 under 0 °C, supercooled liquid water is encompassed in the mixed-phase cloud category. The radar
200 RASTA is very sensitive to large hydrometeors (snow, graupel, rain) and the lidar to smaller ones
201 (pristine ice or liquid cloud droplets). Moreover, the lidar signal is highly attenuated in optically
202 thick clouds and by supercooled layers. The radar signal is less attenuated in the ice levels and is
203 able to provide reflectivity observations at a high vertical resolution in deep cloud systems, as well
204 as around the melting layer.



183 Figure 1. Geopotential height at 500 hPa and SLP (black contours; int: 5 hPa) from ARPEGE operational analysis at: (a) 00
 184 UTC 1 Oct, (b) 12 UTC 1 Oct, (c) 12 UTC 11 Oct. Potential temperature at 850 hPa from the reference simulation and SLP at: (d)
 185 15 UTC 1 Oct, (e) 17 UTC 12 Oct. The flight tracks are shown by the bold lines in c and e. F7 (IOP6) has a clockwise path and
 186 F15 (IOP10) an counter-clockwise path.

205 *d. Model tools*

206 1) RADAR SIMULATOR

207 To evaluate the simulations with respect to the RALI measurements, as in MAZ21, two moments
 208 of the hydrometeor particle size distribution (PSD) are compared: the third order corresponding
 209 to the IWC and the sixth order corresponding to the reflectivity. This double assessment requires a
 210 retrieval of the IWC from the RALI outputs and to derive the reflectivity from the model outputs.
 211 Both derivations have their own assumptions of hydrometeor shape, density, etc. and underlying

212 algorithms. While hydrometeors were assumed to be spherical (using the Mie scattering theory) in
213 MAZ21 to simulate the reflectivity from the model outputs, they are simulated as oblate spheroids
214 in the present study using the T-matrix scattering theory (Mishchenko et al. 1996). The radar
215 forward operator developed by Augros et al. (2016) and adapted to RASTA by Borderies et al.
216 (2018) is used, with the axis ratios recommended by Borderies et al. (2018) for graupel (0.8),
217 snow (0.7) and pristine ice (1). The forward operator accounts for hydrometeor and water vapor
218 attenuation. No mixed-phase hydrometeors are explicitly represented in ICE3. A simple melting
219 or wet growth model is thus used within the radar simulator: graupel particles are considered wet
220 when they coexist with rainwater, and their liquid water fraction is estimated as $F_w = \frac{M_r}{M_r + M_g}$ with
221 M_r and M_g the hydrometeor contents of rain and graupel.

222 2) TRAJECTORIES

223 To identify WCB air masses, backward Lagrangian trajectories are computed using the online
224 algorithm of Gheusi and Stein (2002) as in MAZ21. Information on trajectories is given every 15
225 minutes on a 2.5 km \times 2.5 km horizontal grid but, due to the high computational cost, only one
226 point over eight is considered in the horizontal directions. In the vertical direction all the 22 levels
227 are seeded from 3 600 m to 14 400 m. To identify WCB trajectories, a criterion of ascent of more
228 than 600 hPa in 48 h is applied following Joos and Wernli (2012).

229 3) HEATING AND WATER VAPOR MIXING RATIO BUDGETS

230 The ICE3 microphysics scheme is composed of more than 20 specific processes. Three among
231 them have much more impact than the others on latent heat release in our simulations and are
232 summarized in table 1. They correspond to the vapor condensation/deposition on droplets/pristine
233 ice, snow, and graupel and were already the key processes in MAZ21. Additionally, the radiative
234 heating/cooling rate is also considered as it has an important effect on the heating budget.

235 3. Differences between model simulations in microphysics and upper-tropospheric dynamics

236 Differences between REF and T40 simulations in microphysics and upper-level dynamics are
237 described in the present section and interpreted by analyzing a heating budget.

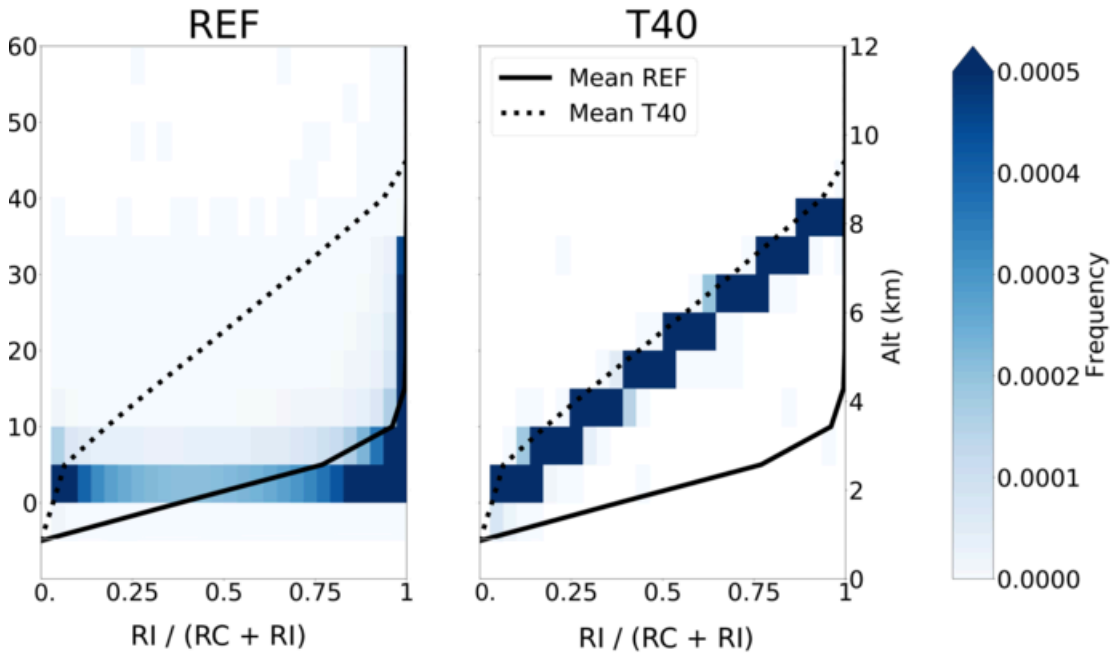
Abbreviation	Description of process
CDEPI	Condensation/Evaporation and Depositional/Sublimation growth of pristine ice ($rv + ri/rc \leftrightarrow ri/rc$)
DEPS	Depositional/Sublimation growth of snow (Deposition, only in MPCs) ($rv + rs \leftrightarrow rs$)
DEPG	Depositional/Sublimation growth of graupel (Deposition, only in MPCs) ($rv + rg \leftrightarrow rg$)
RAD	Radiative heating/cooling rate

Table 1. Abbreviation of the most important diabatic processes involved in the heating budget.

238 *a. Microphysics properties in the simulations*

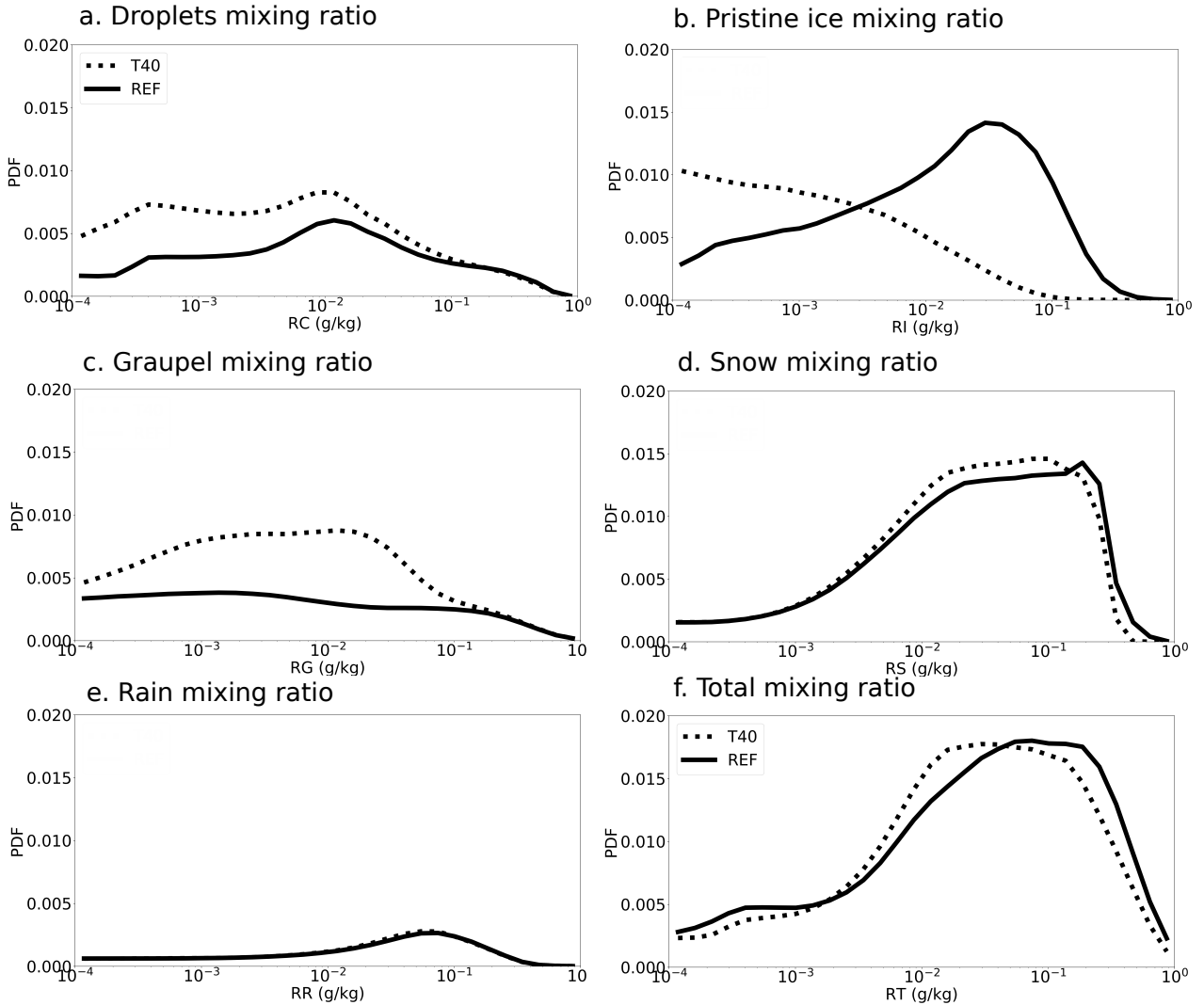
239 To visualize the conceptual difference between REF and T40, Fig. 2 shows the thermodynamic
240 phase partition (pristine ice mixing ratio over the sum of droplet and pristine ice mixing ratios)
241 between REF and T40 as a function of temperature. The ratio varies linearly with temperature
242 in T40 as expected by construction of that simulation (Fig. 2 right). The behavior is radically
243 different in REF with the presence of both droplets and pristine ice above -10°C but almost only
244 pristine ice at temperature below -10°C . Such a partition is consistent with Boudala et al. (2004)
245 observations of mid- and high-latitude stratiform clouds who noticed a minimum for liquid fraction
246 around -15°C associated to a maximum in solid fraction. However, in our model this partition may
247 be due to the fact that REF creates a positive feedback loop. The first stage of the scheme deals
248 with all the processes except the water vapor deposition on droplets and pristine ice: it includes
249 nucleation, vapor deposition on snow and graupel, hydrometeors collision and conversion, the
250 Wegener-Bergeron-Findeisen (WBF) process (Wegener 1926; Bergeron 1935; Findeisen 1938)
251 and sedimentation. It is during the second stage that vapor deposition on droplets/pristine ice
252 occurs. But since vapor deposition within REF depends on the pristine ice and droplets mixing
253 ratios just before the adjustment, and since the droplets mixing ratio is likely to be low at the
254 end of the first stage potentially because of very efficient snow riming processes, vapor will be
255 preferentially transformed in pristine ice. This prevents droplets to grow and has the resulting effect
256 to widen the gap between pristine ice and droplet mixing ratios. Such an issue has already been
257 noticed by Liu et al. (2011) for the same method used in REF and there is room for improvement
258 of this parameterization.

259 Figure 3 shows the PDFs of hydrometeor mixing ratios for values larger than 10^{-4} g/kg. The
260 threshold avoids visualizing all the meshes with very low or near-zero values of mixing ratios.
261 T40 has almost twice as many grid boxes with low amounts of cloud droplets and graupel than



274 Figure 2. Bivariate PDFs as a function of temperature for partition of pristine ice over sum of cloud droplets and pristine ice
 275 over the whole domain using forecast time after 12, 18, 24, 36, 48 hours for the stalactite cyclone simulation initialized at 00 UTC
 276 on 1 Oct. Zero value for mixing ratio is not considered in bivariate PDFs calculation. REF is on the left, T40 is on the right, mean
 277 values of the ratio are plotted in solid lines for REF and dashed lines for T40.

262 REF but the amount is the same for high mixing ratios (Fig. 3a). Fig. 3b shows that REF gets
 263 three times more meshes with high pristine ice mixing ratios than T40, while T40 has twice more
 264 meshes with low pristine ice mixing ratios. The shapes of the PDF distributions for snow (Fig. 3d)
 265 are very similar between the two simulations but slightly right shifted toward higher values (a 0.02
 266 g/kg offset) in REF, consequently REF gets higher snow mixing ratios in total. As REF produces
 267 more pristine ice more auto-conversion to snow should occur and as T40 produces more droplets
 268 more snow conversion into graupel and graupel growth should occur. Finally, the rain PDFs are
 269 very similar (Fig. 3e). The PDFs of the total mixing ratios (Fig. 3f) behave similarly as those of
 270 snow (Fig. 3d) and the difference between the two PDFs is also largely dependent on snow, then on
 271 pristine ice and thirdly on graupel and droplets. To conclude, REF simulates higher mixing ratio
 272 values of cold hydrometeors (excepting graupel) but T40 simulates higher mixing ratio of droplets
 273 (rain is equal).



278 Figure 3. PDFs of mixing ratio of (a) cloud droplets, (b) cloud pristine ice, (c) graupel, (d) snow and (e) total hydrometeor
 279 amount (on a log-scale) over the whole domain using forecast time after 12, 18, 24, 36, 48, 60 and 72 hours. REF is plotted in solid
 280 lines and T40 in dashed lines.

281 *b. Impact on upper-tropospheric circulation.*

282 In all performed experiments, the difference in MSLP minima between T40 and REF does not
 283 exceed 1 hPa. Hence, the surface cyclone is very similar between the two runs. The main purpose
 284 of the study is to focus on noticeable differences at upper-levels and their dynamical interpretation.
 285 Figures 4a-c represent the upper-level PV differences between REF and T40 at the 315-K isentropic
 286 surface for the three types of simulations at 36 h or 48 h valid time depending on the case. The
 287 PV anomaly (T40-REF) is positive and has a narrow crescent shape on the western edge of the
 288 ridge for all three cases but its extension and intensity vary from case to case. Therefore REF

T40 - REF

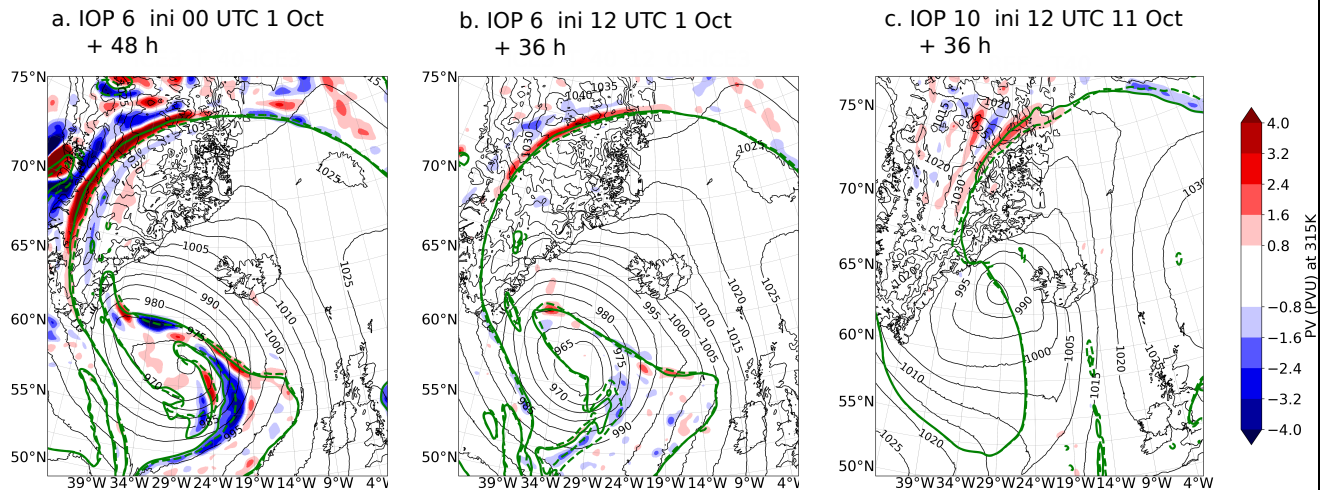


Figure 4. (a)-(c) PV differences between T40 and REF at the 315-K isentropic surface (shading; units: PVU) and SLP at (a-b) 00 UTC 3 Oct and (c) 00 UTC 13 Oct. The initial conditions are (a) 00 UTC 1 Oct, (b) 12 UTC 1 Oct and (c) 12 UTC 11 Oct.

289 produces a slightly larger ridge than T40 for the three sets of simulations with a tropopause shift
 290 varying between 1° and 4° of longitude locally depending on the case. The case with the largest
 291 difference (Fig. 4a) has a PV anomaly of the same order of magnitude as that found in MAZ21
 292 when comparing two distinct microphysical schemes in Meso-NH, and as that shown in Joos and
 293 Forbes (2016) when changing other parameters in the microphysical scheme of the IFS model. The
 294 partition of thermodynamic phases may hence have a significant impact on the upper-tropospheric
 295 circulation.

296 A simulation called T20 (similar to T40 but with the linear function of temperature evolving
 297 between 0°C and -20°C) has been made for the stalactite cyclone case initialized at 00 UTC 1 Oct.
 298 The PV anomaly between REF and T20 was much weaker than that between REF and T40. This
 299 suggests that pristine-ice related processes at upper levels occurring between -20°C and -40°C are
 300 of importance for the ridge building of the stalactite cyclone, consistent with MAZ21's results (see
 301 their Fig. 6). One explanation for the difference between the two initial conditions (Figs. 4a and b)
 302 could be that a large part of the latent heat release along the WCB of the stalactite cyclone occurs
 303 between 00 UTC and 12 UTC on 1 Oct as shown in MAZ21 (see their Fig. 3). Since the case with
 304 initial time at 12 UTC 1 Oct misses that part, it likely explains the smaller impact of mixed-phase
 305 parameterization on the ridge building in that case.

306 *c. Interpretation via heating budget*

307 An interpretation for the PV differences between REF and T40 is now provided by comparing
308 their heating budgets for the case presenting the largest anomaly (Fig. 4a). Figures 5a, b and c
309 show the vertically-averaged total heating rate at 18 UTC 2 Oct for REF, T40 and their difference
310 respectively for that case. This time corresponds to a rapid increase in the PV difference between
311 REF and T40 (not shown). The heating rate is on average higher and covers broader regions along
312 the cold and bent-back warm fronts with REF than T40. Figures 5d, e and f show vertical cross
313 sections of the total heating rate averaged between 60°N and 75°N in the region including the
314 western edge of the upper-level ridge and a significant part of the bent-back warm front (region
315 marked with a black box in Figs. 5a-c). The cross sections show that the strong heating area is
316 larger in REF and the peak values of the heating rate are 40% higher in REF than T40.

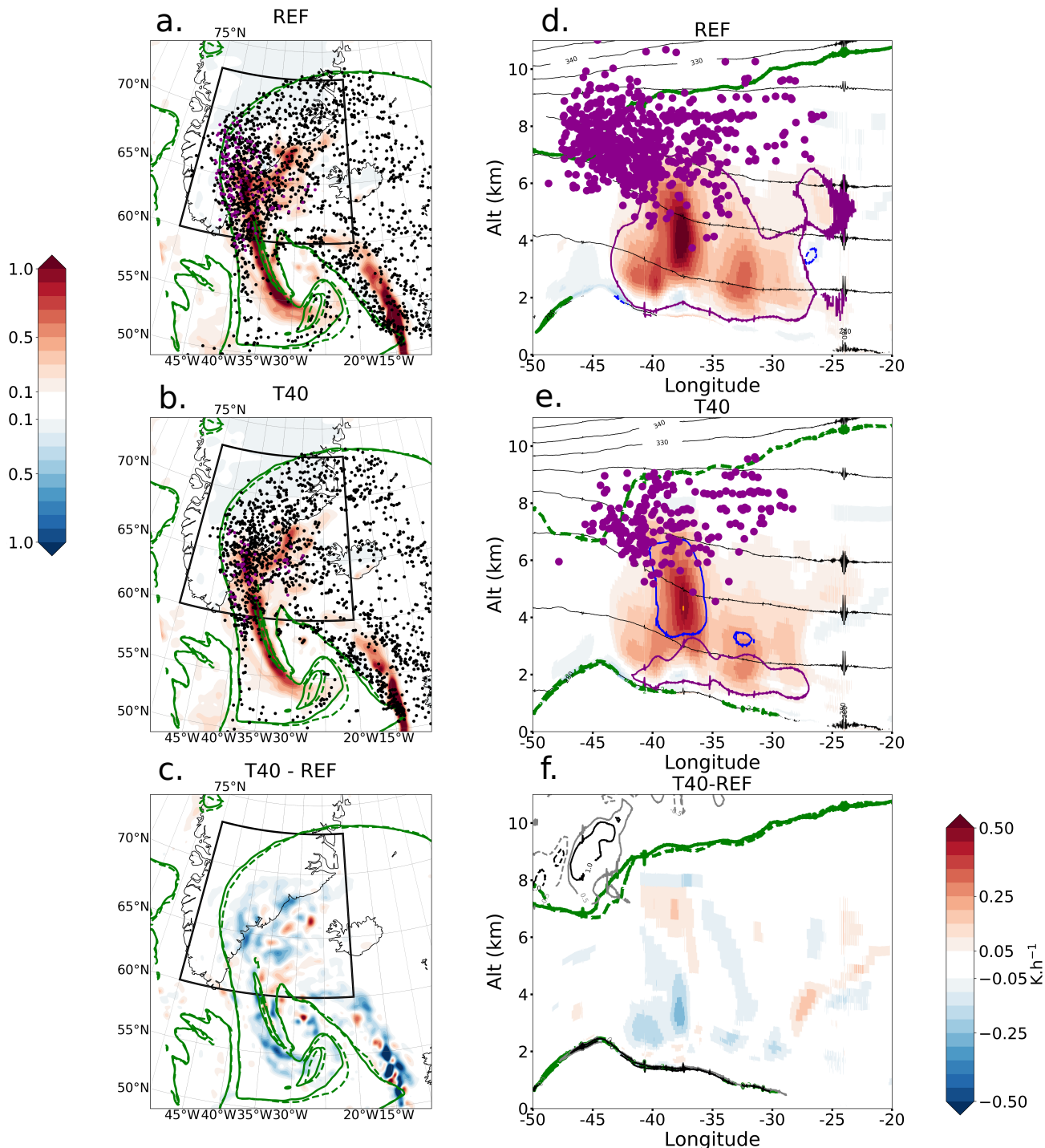
317 Lagrangian trajectories, as defined in section 2d, are also considered. Seeding of backward
318 trajectories is made at 00 UTC 3 Oct and trajectories are computed over the whole domain shown
319 in Fig.1a but only trajectories satisfying the WCB criterion are retained. In total REF gets a bit
320 more WCB trajectories (10860) than T40 (9531), which corresponds to 12% more trajectories
321 (black and purple dots in Fig. 5a,b). But if we focus on trajectories reaching the PV anomaly on
322 the western edge of the ridge the difference increases. These trajectories are shown in purple in
323 Figs. 5a,b,d,e and satisfy the following criteria at 00 UTC 3 Oct: they belong (i) to the troposphere
324 (PV less than 2 PVU), (ii) to the crescent-shaped PV anomaly shown in Fig. 4a (PV anomaly
325 beyond 1 PVU) and (iii) to the black box shown in Fig. 5. For this subsample of WCB trajectories,
326 REF gets many more trajectories (560) than T40 (217). To conclude, REF generates more heating
327 than T40 in average, this generates more WCB trajectories near the western edge of the ridge in
328 particular, which means more diabatically produced negative PV in the upper troposphere and a
329 more rapid ridge building in REF than T40.

330 A more accurate scrutiny of the total heating anomaly shown in Fig. 5f reveals that the general
331 stronger heating in REF is not systematic in all regions. Between 40°W and 35°W, the heating rate
332 anomaly exhibits a vertically-oriented dipole with greater heating below 6 km and smaller heating
333 above 6 km in REF. This heating dipolar anomaly, which will be explained with the detailed
334 heating budget of Fig. 6, reinforces the vertical gradient of the heating, thus the more important

335 PV destruction in REF compared to T40 and therefore participates in the more rapid ridge building
336 in REF.

345 Table 1 describes the main physical processes involved in the heating budget of Fig. 6 and their
346 abbreviations. For both simulations the main latent heating processes are (1) the depositional
347 growth of droplets and pristine ice (CDEPI), snow (DEPS) and graupel (DEPG) and (2) radiation
348 (RAD) as shown in Fig. 6a. Radiative cooling appears to be of primary importance in the upper
349 troposphere, consistent with Chagnon et al. (2013) and Schäfer and Voigt (2018). The total heating
350 rate is a bit higher in REF than in T40 below 6 km but the reverse happens above. This reveals that
351 the dipolar heating anomaly shown in Fig. 5f between 40°W and 35°W prevails. The total heating
352 budgets of the two schemes differ by about 15 % near the peak at 3 km height and can sometimes
353 exceed 0.04 K/h. These differences are not so large but the relative contributions of the various
354 processes participating in the budget are very different. The higher total heating rate in REF below
355 5 km is predominantly due to the greater latent heating associated with all depositional processes
356 and also due to the smaller-amplitude radiative cooling. Above 6 km, the higher-amplitude radiative
357 cooling balances the latent heating differences and makes the total heating in REF smaller than in
358 T40.

359 The sum of latent heating rates due to all depositional processes is higher with REF than T40
360 above 2km height (brown contours in Fig. 6a) because REF exhibits much more vapor depositional
361 growth on pristine ice despite having less depositional growth on droplets, graupel and snow (see
362 DEPS, DEPG and CDEPI in Fig. 6a for the heating rates and DEPS, DEPG, CDEPI RC and CDEPI
363 RI in Fig. 6b for the water vapor budget). Above 3 km, the most important processes are deposition
364 on pristine ice with REF (purple contours in Fig. 5d) and deposition on snow for T40 (blue contours
365 in Fig. 5e). Because T40 has to obey the linear relationship between the ratio of pristine ice and
366 droplet mixing ratios and the temperature, it can not create more deposition of pristine ice. Droplets
367 are lost during the transition to snow and graupel but are continuously replenished via saturation
368 adjustment to the detriment of ice formation. This is why CDEPI RI (deposition on ice) is near
369 zero while CDEPI RC (deposition on droplets) is important in T40 (Fig. 6b). In REF, the heating
370 due to deposition on graupel and snow is negative indicating the dominance of snow and graupel
371 sublimation. In REF, deposition on snow is small because REF produces less MPCs, which are the



337 Figure 5. (Left panels) Vertically averaged heating rate between 2 km and 9 km (shadings) and (right panels) meridionally
 338 averaged heating rate (shadings) in the large black area shown in upper panels at 18 UTC 2 Oct for (a),(d) REF, (b),(e) T40 and
 339 (c),(f) the difference T40-REF. Black dots in (a),(b) correspond to WCB trajectories positions at 18 UTC 2 Oct, while the purple
 340 dots correspond to the trajectories ending in the red PV anomaly shown in Fig. 4a. In the upper panels one trajectory in five are
 341 represented for visibility sake. Green lines represent the position of the dynamic tropopause (full line in REF and dashed line in
 342 T40). The grey and black lines in (f) represent the 1 PVU and 0.5 PVU difference between T40 and REF (solid lines for positive
 343 values and dashed for negative ones). The purple and blue contours in (d),(e) represent the CDEPI and DEPS contributions (see
 344 Table 1 for their definition) respectively when it is greater than 0.3 K.h^{-1} (solid for positive values and dashed for negative ones).

372 only cloudy regions where deposition on snow is possible in ICE3, and has thus less opportunities
373 for vapor deposition on snow.

374 The water vapor budget of Fig. 6b further explains why latent heating due to depositional
375 processes is stronger in REF than in T40. First, there is a slightly larger amount of water vapor
376 deposition in REF in total (black profiles in Fig. 6b). Second, since the deposition on cold
377 hydrometeors is larger in REF than T40 and vice versa for the deposition on warm hydrometeors,
378 latent heat release is larger in REF than T40 for an equivalent amount of transformed water vapor
379 because the specific latent heat of deposition on ice is larger than that of condensation on droplets
380 (about 10% difference at 0° C; Yau and Rogers 1996).

381 Even though heating rates due to liquid to solid transitions are higher in T40 than REF they are
382 negligible (included in other processes) and do not compensate the more important vapor to solid
383 transitions in REF. Diagnostic of WBF impact is surprisingly very low. This can be explained by
384 the fact that the efficiency of dry growth of graupel and snow riming to collect droplets prevent
385 the WBF process to occur as in our ICE3 version it occurs in the second last step of the scheme.
386 Moreover, as the saturation adjustment over droplets and pristine ice is the very last step of the
387 scheme, it mostly wipes off the possible effect of the WBF process.

388 Let us now discuss the difference in radiative cooling in Fig. 6a, which has been checked to be
389 due to longwave cooling (not shown). The radiative transfer code we used does not consider snow,
390 graupel and rain. It is only dependent on pristine ice and cloud droplets. The higher radiative
391 cooling in the upper troposphere in REF is consistent with the higher pristine ice mixing ratio
392 and the larger area covered by the upper clouds. In the lower troposphere, as REF gets more
393 cloud droplets and pristine ice (Fig. 6d) and a broader cloud cover (not shown) it may induce a
394 stronger absorption of surface longwave emission and a less strong cooling maybe restrained by the
395 presence of the broader clouds above. The important impact of radiation on the budget confirms a
396 potential high impact of cloud-radiation interaction and parameterization on upper-level dynamics
397 as already anticipated in Joos (2019).

398 To summarize, the total heating rate is on average higher in REF than T40 when looking at
399 vertically-averaged maps. Vertical profiles of the heating rate show that REF induces a larger
400 heating in the lower half of the troposphere and slightly more cooling in the upper troposphere.
401 The larger heating in the lower troposphere in REF is due to an overall larger amount of water

402 vapor deposition and a preferred transition toward solid phase, which is not compensated by
403 liquid-to-solid transitions in T40. Such a difference explains the higher vertical velocities in REF
404 (Fig. 6c) and the more numerous WCB trajectories in the WCB outflow region. The more important
405 cooling in the upper troposphere in REF is due to the larger amount of pristine ice. Overall, these
406 differences in the vertical profiles of the heating rates will favor more PV destruction in REF than
407 T40 and a more rapid ridge building.

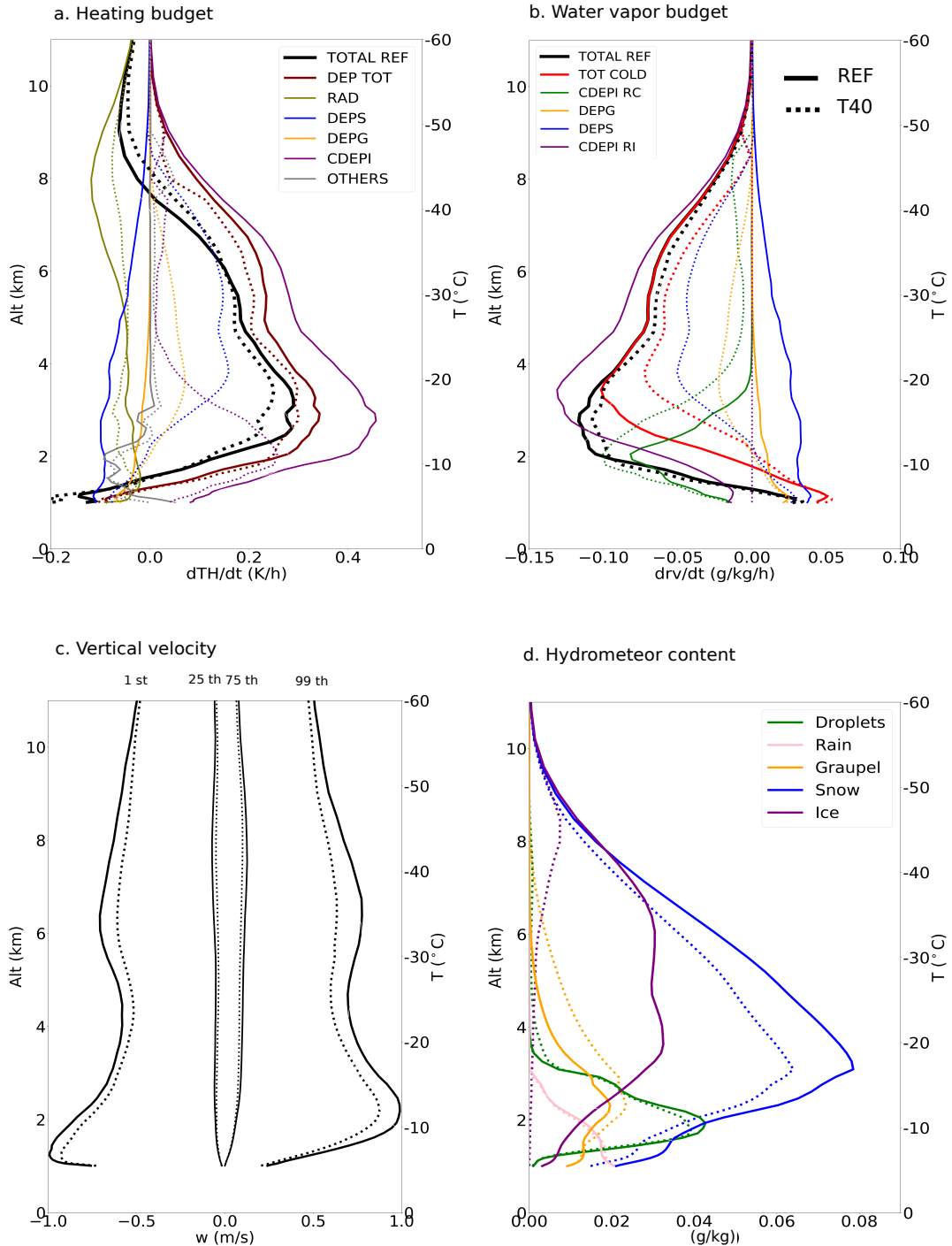
415 **4. Comparison between model simulations and observations**

416 The present section is dedicated to the comparison to observations and pursues two goals: (i)
417 document the locations of the supercooled droplets and the mixed-phase region in extratropical
418 cyclones and how they are represented by Meso-NH and (ii) identify which of the two parameteri-
419 zations for mixed-phase clouds is the closest to the observations.

420 *a. Thermodynamic phases*

421 Figure 7 presents the thermodynamic phase distribution as retrieved by the RALI platform along
422 the flights F7 and F15 and as simulated by REF and T40 for the different sets of simulations along
423 the flight tracks. To compare with the classification made with the observations (Cazenave et al.
424 2019), we need to categorize clouds in the model and to define MPCs. Even though there is no
425 unique way to define MPCs (see discussion in Korolev et al. 2017), we adopt a definition close to
426 Korolev et al. (1998) using a threshold in the ratio between Liquid Water Content (LWC) and total
427 water content. Three categories of clouds are defined as follows: liquid phase ($LWC > 0 \text{ g.m}^{-3}$ and
428 $T > 0 \text{ }^\circ\text{C}$), mixed phase ($LWC/(LWC+IWC) \geq 5\%$ and $T < 0 \text{ }^\circ\text{C}$), ice phase ($LWC/(LWC+IWC) \leq$
429 5%). The choice of the 5% threshold is rather arbitrary and should be taken with caution.

430 Let us first describe the MPCs detected in the observations. As the lidar is not able to detect
431 multiple layers of supercooled droplets and is subject to attenuation (see section 2c), the black line
432 in Figs. 7a and f, represents the lowest level for mixed-phase layer detection. The melting layer
433 located below the black line is detected by the radar only. Between the black line and the melting
434 layers, we have no information on the presence or absence of mixed-phase layer. Observations out
435 of these blind areas show that MPCs occur in few discrete layers of hundreds meters in agreement
436 with Hogan et al. (2003). Their location occur in four kinds of area:



408 Figure 6. (a) Horizontal average of the heating rate over the box defined in Figs. 5a-c at 18 UTC 2 Oct for total absolute values
 409 greater than 0.0 K.h^{-1} . In (b), (c) and (d) statistics are made over the same area and the same time as in (a). Only the main processes
 410 are plotted and explained in Table 1, OTHERS corresponds to the sum of all the other processes. (b) Horizontal average of the vapor
 411 mixing ratio tendencies. CDEPI RC/DEPG/DEPS/CDEPI RI correspond to deposition of vapor on droplets/graupel/snow/pristine
 412 ice respectively. TOT COLD combines all the cold processes. Total is the sum of all the tendencies. (c) 1st, 25th, 75th and 99th
 413 percentiles of the vertical velocity distribution. (d) Horizontal average of hydrometeor mixing ratios: RCT, RRT, RGT, RST and
 414 RIT correspond to droplets, rain, graupel, snow and ice mixing ratios. Full lines stand for REF and dotted ones for T40.

- 437 - at the top of layer of ice crystals (F15 and notably under the dry intrusion between 1630 UTC and
- 438 1715 UTC) consistently with most of the observations from literature (Shupe et al. 2008).
- 439 - embedded within a layer of ice crystals (F7 at 1315 UTC).
- 440 - within a layer of ice crystals with clear air above (F7 at ~ 1405 UTC, ~ 1420 UTC, ~ 1600 UTC
- 441 and F15 at ~ 1720 UTC).
- 442 - at the melting layer.

443 MPCs could be formed according to distinct processes. Liquid watersaturation conditions at cloud
444 top may be achieved because of radiative cooling or turbulent mixing with clear air according to
445 Korolev and Mazin (2003). Their potential persistence could be due to low ice freezing nuclei
446 (IFN) inhibiting the pristine ice formation and the WBF process from occurring. MPCs embedded
447 within, or above, a layer of ice crystals, are likely to be due to low IFN concentration (Korolev and
448 Mazin 2003) as well. We assume MPCs exist at the melting layer because melting does not happen
449 all at once.

450 Cloudy areas are very similar between simulations and observations for the Thor ridge and is very
451 close for the stalactite cyclone initialized on 1 Oct 12 UTC. For the stalactite cyclone initialized
452 earlier, that is on 1 Oct 00 UTC, more discrepancies are observed with more dry areas simulated
453 by the model. This is not surprising as the longer the forecasts last, the larger shifts relative to the
454 observations in the dynamical features are expected.

455 The Meso-NH representation of MPCs is quite distinct from the observations. Even though the
456 comparison can be largely influenced by the 5% threshold applied to detect MPCs in the model as
457 mentioned above, some conclusions can be brought out that do not depend much on the threshold.
458 First the melting layer is a region of MPCs seen in the radar observations and in the model even
459 though it is thicker in the model in general. REF produces quasi no MPCs above the melting layer
460 apart from very rare points (Figs. 7b, d, g). At these locations very few solid hydrometeors are
461 present (not shown) which subsequently could favor liquid production and persistence consistently
462 with REF behavior (see section 2a). In contrast, T40 produces MPC areas above the melting layer
463 in all simulations but not necessarily in the same places as in the observations.

464 A significant amount of MPCs are located near ~ 8 km in T40 which precisely corresponds to
465 a temperature of ~ -40 °C (e.g., Figs. 7c and e). At such elevated heights the snow and graupel
466 mixing ratios are very small in such a way that the ratio between liquid and total mixing ratios

467 increases. Therefore, such a layer of MPCs near the -40°C temperature is likely an artefact of the
468 T40 formulation. Nevertheless, two areas of MPCs in T40 are more physically relevant as seen in
469 the stalactite cyclone initialized on 1 Oct 00 UTC and in the Thor ridge:

470 - The upper discrete layers observed between 1630 UTC and 1720 UTC in the Thor ridge. They
471 appear in both the observations and T40 (Figs. 7f, h). This area corresponds to the dry intrusion
472 (Fig. 1e). The residence time of the F7 flight in the dry intrusion is less than for F15 (Fig. 1c),
473 hence equivalent MPCs are not detected along F7. But preliminary results using NASA's LAADS
474 DAAC data (cloud top thermodynamic phases and cloud top temperature, not shown) showed that
475 MPCs are indeed located above that part of the dry intrusion close to the cold front for both the
476 stalactite cyclone and the Thor ridge.

477 - An area of MPCs around 1500 UTC and $\sim 6\text{-}7$ km is simulated in T40 (Fig.7c) even though
478 not detected in the observations (Fig.7a). It actually corresponds to an area where the strongest
479 updrafts of the transect are simulated (not shown). Such a strong updraft allows supersaturation
480 over liquid to be reached as documented by Gehring et al. (2020).

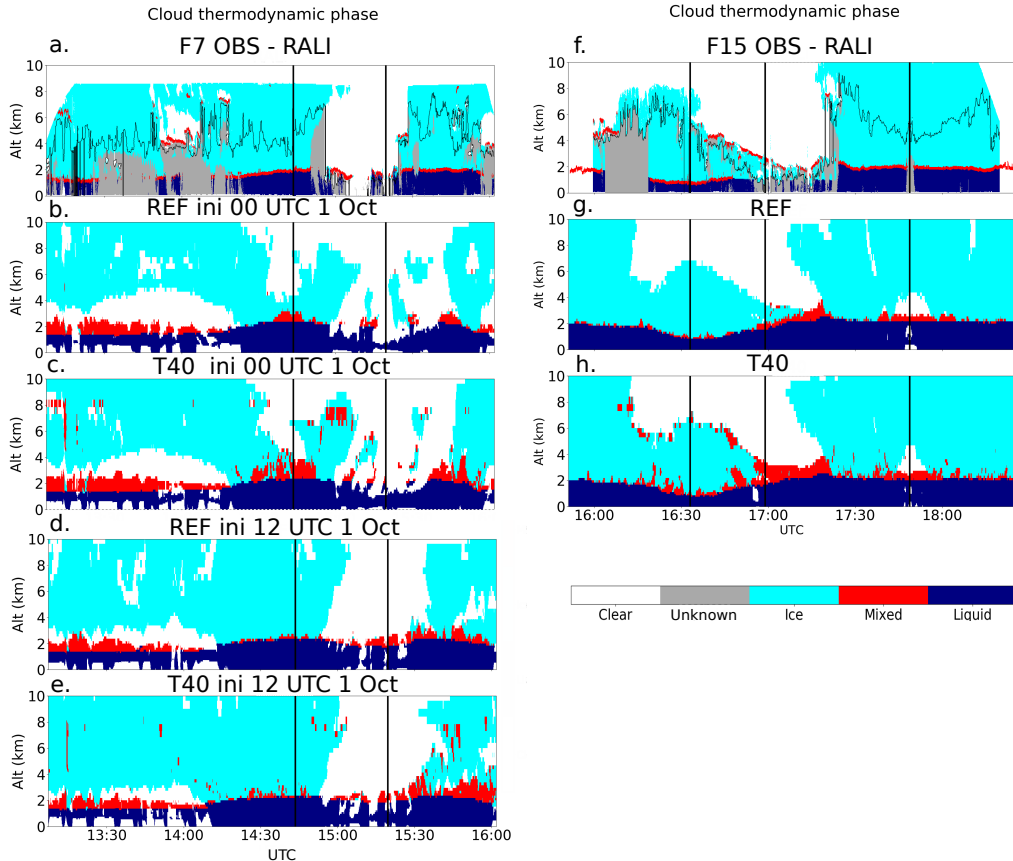
481 To conclude, even though T40 tends to artificially create MPCs in some areas, it also reproduces
482 MPCs in some observed regions and in regions where MPC's are expected, although not observed,
483 whereas REF simply fails to simulate MPCs above the mixing layer. To assess the skills of the
484 simulations more quantitatively with regard to the observations, reflectivity and IWC are hereafter
485 analysed and compared.

491 *b. Reflectivity and IWC*

492 The model-to-radar and radar-to-model complementary approaches are used as in MAZ21. De-
493 spite the fact that IWC and reflectivity represent different moments of hydrometeor size distribution
494 (the third and the sixth ones), this allows one to address the weaknesses associated with the as-
495 sumptions inherent to both approaches. In the following only ranges of simulated reflectivity and
496 IWC values that can be retrieved at each altitude with RALI are used in our comparison.

497 In MAZ21, only the Mie scattering theory was used to compute the model reflectivity while,
498 in the present study, both Mie and T-matrix scattering theories are employed. Figure 8 shows
499 the reflectivity as measured below the aircraft and as simulated by REF and T40 with Mie and
500 T-matrix. All simulated reflectivities are lower than the observed ones but the underestimation

Cloud thermodynamic phase



486 Figure 7. Cloud thermodynamic phase along (a-e): flight F7 (see triangle in Fig. 1d,e), (f-h): flight F15 (see triangle in
 487 Fig. 1f) and for: (a,f) RALI observations, (b,g,d) REF simulation and (c,h,e) T40 simulation. (b-c) correspond to stalactite cyclone
 488 simulations initialized at 12 UTC on 1 Oct and (d-e) to simulations initialized at 00 UTC on 1 Oct. (g-h) correspond to the Thor
 489 ridge simulations. The light dark lines in a and f indicate the bottom attenuation for LIDAR. The vertical bold dark lines stand for
 490 the time where the flight changed direction.

501 is clearly reduced when using T-matrix scattering. For vertically pointing radar, this is because
 502 rain, graupel and snow particles are treated as oblate spheroids and have thus a larger maximum
 503 diameter, which increases the reflectivity, compared to the Mie theory for which particles are
 504 considered spherical. With T-matrix, higher values of reflectivity are thus simulated, bringing the
 505 model closer to the observations, which is in agreement with the study of Borderies et al. (2018).
 506 Some additional aspects can be further investigated to improve the radar simulator. For instance,
 507 the chosen snow axis ratio (0.7) could be lower for higher mixing ratio and could increase the snow
 508 contribution to reflectivity and yield to more realistic snow reflectivities.

509 Figure 9 presents bivariate PDFs of radar reflectivity following the T-matrix theory as a function
 510 of altitude for the stalactite cyclone initialized at 00 UTC 1 Oct. Let us first consider the case

511 where all the hydrometeors are considered in the computation of the simulated reflectivity along the
512 flight tracks (Figs. 9a-c). Below the melting layer, the reflectivity values are rather close between
513 REF and T40 and in agreement with the observations. Above the melting layer, in the middle
514 troposphere between 2 km and 6 km, the reflectivities are also close between REF and T40 but
515 they largely underestimate the observed reflectivity, Root-Mean Square Error (RMSE) are as high
516 as 5 dBz. In the upper troposphere, between 6 km and 8 km, T40 still strongly underestimates
517 the observed reflectivity (RMSE is about 8 dBz) but the REF reflectivity is higher than for T40
518 and is between between T40 and the observations (REF RMSE is about 3 dBz). To isolate the
519 individual hydrometeor contributions to the total reflectivity, Figs.9d-l present successively the
520 reflectivity without the individual contributions of graupel, snow and pristine ice in the model.
521 Graupel contribution is negligible almost everywhere (compare the two upper panels of Fig. 9). In
522 middle troposphere, below 6 km height, reflectivity is mostly due to snow in both REF and T40
523 while in upper troposphere, above 6 km height, reflectivity is mostly due to snow and pristine ice
524 in T40 and predominantly due to pristine ice in REF.

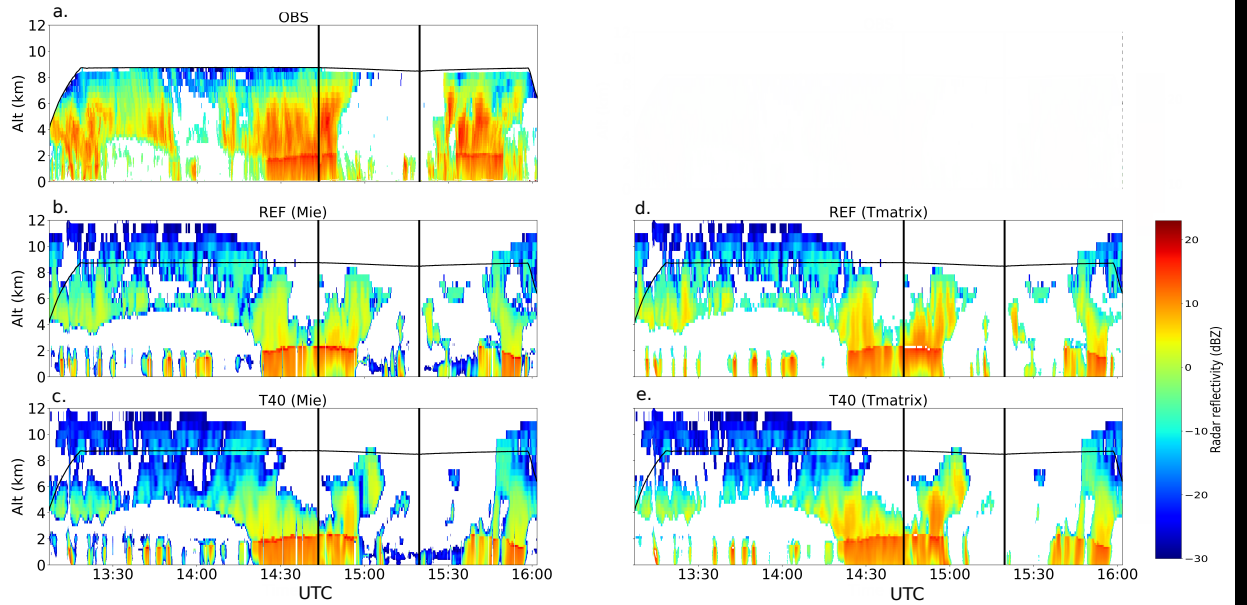
525 Figure 10 presents bivariate PDFs of RALI IWC as a function of altitude for the same simulation
526 along the flight tracks, a log scale is used to have a representation similar to the reflectivity which
527 is shown in decibels. The IWC values are quite distinct between REF and T40 with higher values
528 for REF, especially in the upper troposphere where REF is very close to the observations and T40
529 underestimates the observed IWC (Fig. 10c). As for the reflectivity in Fig. 9, contributions of each
530 hydrometeor to the total IWC are shown in Fig. 10. In middle and upper troposphere, IWC is
531 mostly composed of snow in T40 (compare dotted lines in Figs. 10c, f, i and l) and of both snow
532 and pristine ice in REF (compare thin solid lines in Figs. 10c, f, i and l).

533 When considering the variations with height of the IWC and reflectivity, T40 presents the closest
534 shape to the observations, the correlation coefficient is about 0.37/0.54 for IWC/reflectivity within
535 ICE3 and about 0.37/0.60 within T40. Indeed, the decrease with height of both IWC and reflectivity
536 values from 3 km and 8 km are more similar to the observations in T40 than REF (Figs. 9c and 10c).
537 The less important decrease with height in REF is attributed to differences in the distribution of
538 hydrometeors as the decrease with height is much smaller without snow contribution than without
539 ice contribution (compare Figs. 9i and 9l and Figs. 10i and 10l). Therefore it suggests that REF
540 may have too much pristine ice relative to snow and the better vertical profile in T40 than REF

541 reveals a better hydrometeor distribution in the former than the latter. This consideration is done
542 realizing that model categorization of pristine ice and snow is somehow arbitrary as they very often
543 have significant overlap where they coexist in terms of particle sizes.

544 Figure 11 presents the same panels as Figs.9a-c and 10a-c but for the Thor ridge. As for the
545 stalactite cyclone, T40 presents the closest variations with height of the IWC and reflectivity to
546 observations (the correlation coefficient is about 0.32/0.51 for IWC/reflectivity within ICE3 and
547 about 0.4/0.58 within T40) but generally underestimates both quantities between 3 km and 8 km
548 (RMSE is about 2.2 dBz for reflectivity and 0.13 g/m³ for IWC). In contrast, REF exhibits higher
549 quantities than T40 but the decrease with height is further away from the observations than in T40.
550 In the upper troposphere, IWC in REF, and to a lesser extent the reflectivity, are overestimated
551 (RMSE for reflectivity is about 2.8 dBz and 0.02 g/m³ for IWC) whereas in the middle troposphere
552 the IWC in REF has realistic mixing ratios but the mean reflectivity is strongly underestimated
553 (RMSE is about 0.8 dBz) (Figs. 11c,f). Since the highest values of snow are found in mid and
554 low troposphere and the highest values of pristine ice in the upper troposphere, it indicates there is
555 maybe too much ice compared to snow in REF as already seen in the stalactite cyclone simulation.
556 Another result based on the sensitivity of the reflectivity to the different hydrometeors supports
557 these findings: between 2 km and 6 km, the reflectivity is largely underestimated but not the IWC.
558 In the range of mixing ratio encountered in middle troposphere, the snow reflectivity is higher than
559 for pristine ice for an equal mass (not shown). So an increase in snow and a decrease in ice would
560 help to make the REF curves closer to the observations.

561 To conclude, the common results of the Thor Ridge and Stalactite cyclone cases are the following:
562 there is maybe too much pristine ice and not enough snow in REF and not enough cold hydrometeors
563 in general in T40. Two additional sensitivity numerical simulations have been performed to confirm
564 this conclusion for REF (see supplementary material). A first sensitivity test was performed by
565 increasing the ice to snow autoconversion in REF for the stalactite cyclone case. It improved the
566 shapes of the distributions for the IWC and reflectivity (Fig. S2) while it decreased their absolute
567 values because of more sedimentation due to more precipitating hydrometeors. It also impacted
568 notably the ridge building and the PV values along the dynamical tropopause through radiative
569 impact (Fig. S1). As snow is not taken into account in the radiation code, a higher ice to snow
570 autoconversion causes a lower cooling at cloud top and a higher cooling at cloud base due to

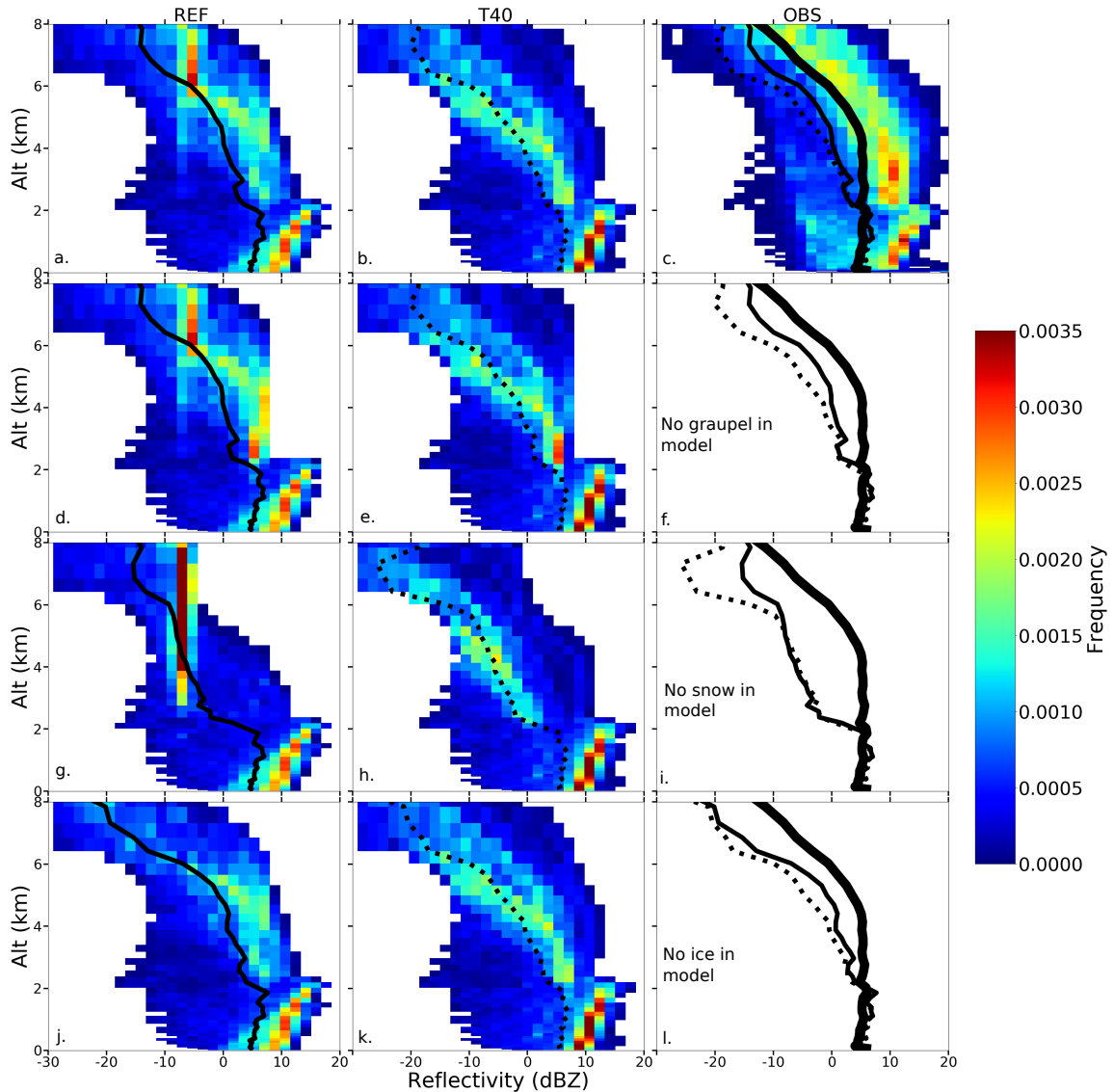


576 Figure 8. Along F7 (stalactite cyclone), reflectivity for (a) RASTA observations regridded onto the model grid, as calculated
 577 with the Mie scattering theory for (b) REF and (c) T40, as calculated with the T-matrix scattering theory for (d) REF and (e) T40.
 578 The vertical dark lines stand for the time where the flight changed direction. The simulations are initialized at 00 UTC 1 Oct.

571 less cloud cover (based only on pristine ice and cloud water). While further investigation should
 572 undeniably deepen this aspect, this sensitivity test confirms the potential importance of considering
 573 snow in radiation code. Last, but not least, a second sensitivity test was performed by reducing the
 574 snow fall speed. It has the effect to increase the atmospheric amount of snow and to improve the
 575 distributions with respect to the observations (Fig. S2).

592 5. Conclusion and discussion

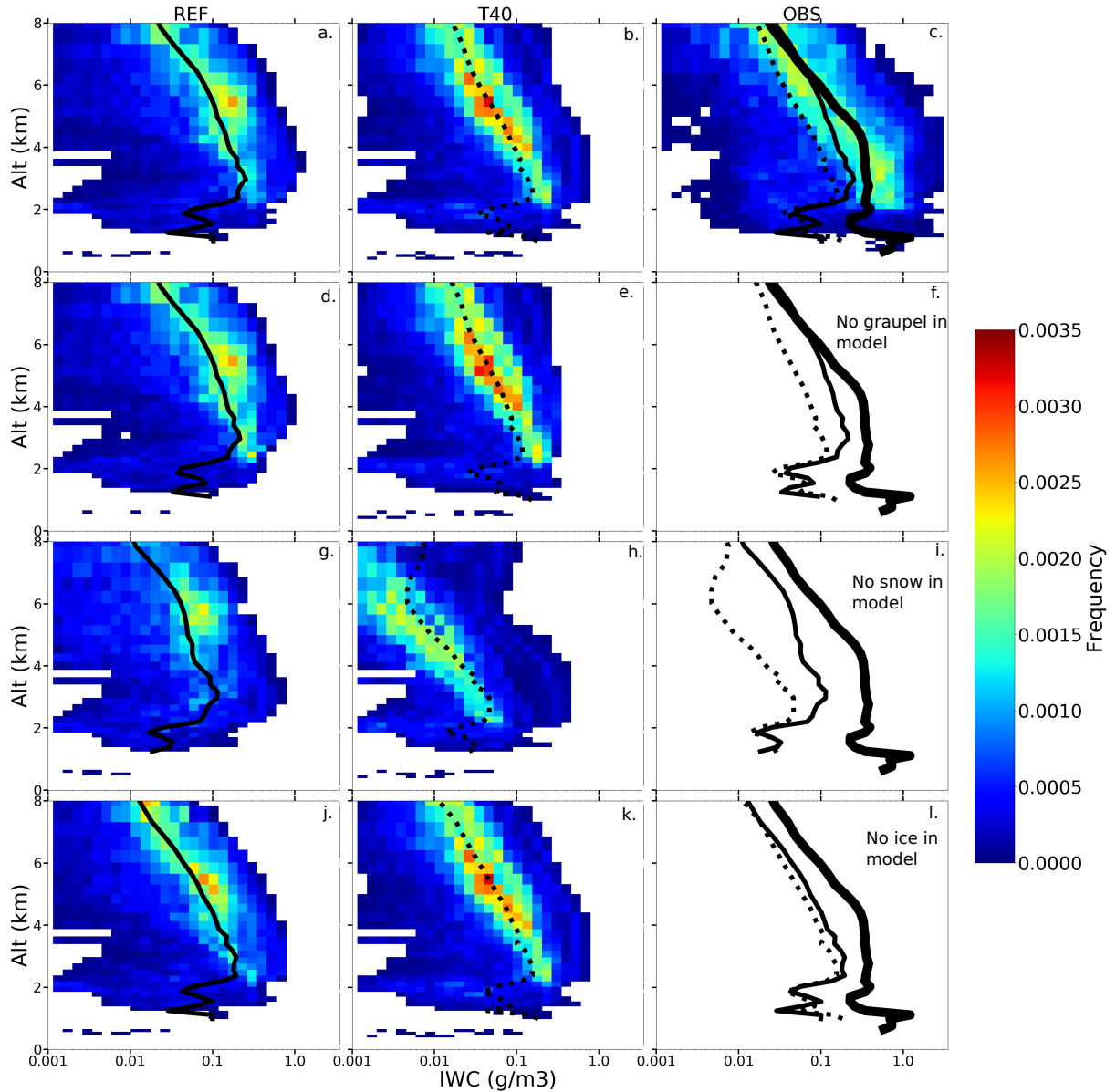
593 The present study investigates the impact of two mixed-phase cloud parameterizations (REF and
 594 T40) developed within the microphysical scheme ICE3 of the Meso-NH model on warm conveyor
 595 belts and upper-tropospheric circulation. Three-day hindcast simulations of two extratropical
 596 cyclones that developed during IOP 6 and IOP 10 of NAWDEX, and corresponding to the stalactite
 597 cyclone and the Thor ridge cases respectively, are performed at a resolution of 2.5-km grid spacing.
 598 The differences between the two parameterizations are as follows: in REF deposition of water vapor
 599 on droplets and pristine ice is made in proportion to their amount before the saturation adjustment
 600 while, in T40, deposition is made in such a way that at the end of all the microphysical steps, the



579 Figure 9. During F7 (stalactite cyclone), bivariate PDFs as a function of altitude of radar reflectivity (a)-(c) total hydrometeors,
 580 (d)-(f) without graupel in model, (g)-(i) without snow in model, (j)-(l) without ice in model, (a),(d),(g),(j) REF, T40 and (c),(f),(i),(l)
 581 the observations regridded onto the model grid, mean vertical profiles are indicated for REF (solid line), T40 (dashed line), and
 582 observations (thick solid line). The measurements and observations are normalized with the total number of points. The simulations
 583 are initialized at 00 UTC 1 Oct.

601 ratio between droplets and pristine ice mixing ratios is a linear function of temperature from 0 to
 602 -40°C .

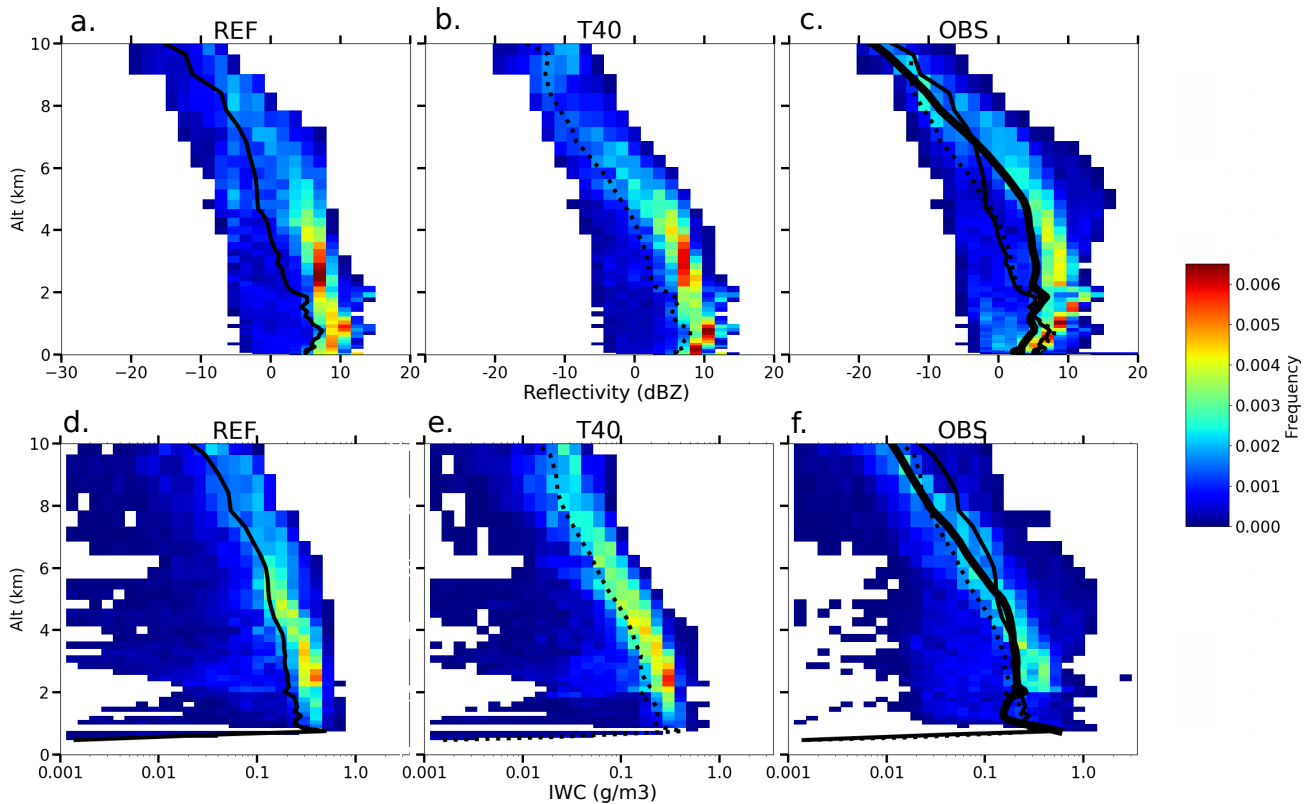
603 The first part of the results concerns the impact on the upper-level ridge building in the WCB
 604 outflow. REF is found to amplify the ridge more rapidly than T40 even though the amplitude of



584 Figure 10. During F7 (stalactite cyclone), bivariate PDFs as a function of altitude of IWC (a)-(c) total hydrometeors, (d)-(f)
 585 without graupel in model, (g)-(i) without snow in model, (j)-(l) without ice in model, (a),(d),(g),(j) REF, (b),(e),(h),(k) T40 and
 586 (c),(f),(i),(l) the observations regridded onto the model grid, mean vertical profiles are indicated for REF (solid line), T40 (dashed
 587 line), and observations (thick solid line). The measurements and observations are normalized with the total number of points.

605 the PV anomalies between REF and T40 varies from case to case and with the choice of the initial
 606 time.

607 The second part of the results provides an interpretation of the PV differences between REF and
 608 T40 based on the simulations of the stalactite cyclone initialized at 00 UTC 1 Oct. It also relies on



588 Figure 11. During F15 Thor ridge, Bivariate PDFs as a function of altitude of (a)-(c) radar reflectivity and (d)-(f) Ice Water
 589 Content for (a),(d) REF, (b),(e) T40 and (c),(f) the observations regridded onto the model grid, mean vertical profiles are indicated
 590 for REF (solid line), T40 (dashed line), and observations (thick solid line). The measurements and observations are normalized
 591 with the total number of points.

609 the computation of Lagrangian trajectories and budgets of hydrometeor mixing ratios and heating
 610 rates. The following results were found:

- 611 • The vertically-averaged total heating rate is higher in REF than T40 in most regions along
 612 the cold and bent-back warm fronts. This explains the higher vertical velocities and the more
 613 numerous WCB trajectories found at the leading edge of the ridge building in REF.
- 614 • REF exhibits a stronger heating below 6 km height and a more important cooling above 6 km
 615 height than T40. The stronger heating in the lower troposphere is due to more important
 616 water vapor depositional processes while the larger cooling in the upper troposphere is due to
 617 differences in radiative cooling.
- 618 • The above differences lead to a stronger vertical gradient of the heating rate in REF that
 619 explains the more important PV destruction and more rapid ridge building in REF.

- 620 • While differences in horizontal averages of heating rates do not exceed 10 to 20 %, the different
621 processes contributing to the heating rates drastically differ between the two simulations.
- 622 • The greater heating rate in REF is due to more water vapor deposition onto ice hydrometeors,
623 which is not compensated by the liquid to solid transitions in T40.
- 624 • REF simulates far more pristine ice than T40 but less cloud droplets and graupel. Also, REF
625 simulates more snow that could be due to its higher pristine ice content.
- 626 • The larger pristine ice content in REF induces a larger cloud cover and thicker clouds in the
627 upper troposphere that explains the more important radiative cooling at those heights. The
628 difference is well marked because the radiation code does not consider snow. A sensitivity
629 test with an increased autoconversion from ice to snow confirms this result.

630 The third part of the study is dedicated to the comparison with airborne observations collected
631 during two flights of the SAFIRE Falcon-20 and led to the following results:

- 632 • Four main layers of hundred meters of MPCs were detected by the RALI platform at altitude
633 as high as 7 000 m: at the top of pristine ice clouds, embedded within layer of ice crystals, in
634 between a layer of ice crystals below and a layer of clear air above as under the dry intrusion
635 and at the melting layer.
- 636 • Both parameterizations reproduce the mixed-phase cloud associated to the melting layer seen
637 in the observations. Well above the melting layer, REF does not form any MPCs whereas T40
638 does, in particular in regions detected by the radar-lidar platform like below the dry intrusion.
- 639 • Comparison of both IWC and reflectivity shows there is maybe too much pristine ice and not
640 enough snow in REF and not enough cold hydrometeors in general in T40. The lower ice to
641 snow ratio in T40 likely explains its better distribution of hydrometeors with respect to height
642 compared to REF.
- 643 • Changing the snow fall speed or ice-to-snow conversion are two ways to improve the hydrome-
644 teor vertical distribution in REF as confirmed by performing sensitivity numerical experiments
645 (supplementary material).

646 The present study showed that two different parameterizations of MPC processes have an impact
647 on upper-tropospheric dynamics because they have different latent heat release and radiative cooling

648 within the WCB region. The two parameterizations used in this study have inherent limitations
649 that need to be recalled: in T40 because it forces the MPCs to exist; in REF because it is strongly
650 dependent on ice initiation processes according to Bengtsson et al. (2017); Engdahl et al. (2020)
651 . Indeed if REF first produces a larger ratio of pristine ice compared to cloud droplets, then
652 more vapor deposition will be made on pristine ice limiting the growth of cloud droplets. One
653 way to overcome this limitation is to delay ice formation that should offer larger possibility to
654 droplets to grow and interact with other hydrometeors as done in OCND2 scheme (Bengtsson
655 et al. 2017; Engdahl et al. 2020). The present study shows that to get closer to reality, one would
656 need to better assess distribution of ice, snow, graupel and droplets in mid and upper levels. It
657 could be done by taking advantages of the A-train merged products (CloudSat/CALIPSO/MODIS)
658 which provide thermodynamic phases at cloud top and along vertical transect using DARDAR
659 product (Delanoë and Hogan 2010). In-situ observations (Wurtz et al. 2021; Bernstein et al.
660 2021) or polarimetric radar would be also very useful to achieve this objective (Gehring et al.
661 2020). Furthermore, radiative observations may indirectly help to get a better representation of
662 the spatial distribution of hydrometeors. Eventually, an improved representation of hydrometeors
663 in the models is an important issue for climate studies as the distribution of hydrometeors within
664 WCBs has a strong impact on the radiative budget in the mid-latitude as shown in Joos (2019).

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669 **Data Availability Statement**

670 Data available on request from the authors.

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