

1 **Analysis of geostationary satellite derived cloud parameters associated with high ice water**
2 **content environments .**

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16

17 **Abstract**

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19 We present a newly developed high ice water content mask (High IWC) based on measurements
20 of the cloud physical properties (CPP) algorithm applied to the geostationary Meteosat Second
21 Generation (MSG) Spinning Enhanced Visible and Infrared Imager (SEVIRI). The mask was
22 developed within the European High Altitude Ice Crystals (HAIC) project for detection of upper
23 atmospheric high IWC, which can be a hazard for aviation.

24 Evaluation of the High IWC mask with satellite measurements of active remote sensors of cloud
25 properties (CLOUDSAT/CALIPSO combined in the DARDAR product) shows that the High
26 IWC mask can be fine-tuned for detection of high IWC values $> 1 \text{ g/m}^3$ in the DARDAR
27 profiles. The best CPP predictors of High IWC were the condensed water path, cloud optical
28 thickness, cloud phase, and cloud top height. The evaluation of the High IWC mask against
29 DARDAR provided some indications that the MSG-CPP High IWC mask is more sensitive to
30 cloud ice or cloud water in the upper part of the cloud, which is relevant for aviation purposes.
31 Biases in the CPP results were also identified, in particular a solar zenith angle (SZA)
32 dependence that reduces the performance of the High IWC mask for SZAs $> 60^\circ$. Verification
33 statistics show that for the detection of High IWC a trade-off has to be made between better
34 detection of High IWC scenes and more false detections, *i.e.* scenes identified by the High IWC
35 mask that do not contain IWC $> 1 \text{ g/m}^3$. However, the large majority of these detections still
36 contain IWC values between $0.1\text{-}1 \text{ g/m}^3$.

37 Comparison of the High IEC mask against results from the Rapid Developing Thunderstorm
38 (RDT) algorithm applied to the same geostationary SEVIRI data showed that there are
39 similarities and differences with the High IWC mask: the RDT algorithm is very capable of

40 detection young/new convective cells and areas, whereas the High IWC mask appears to be
41 better capable of detecting more mature and ageing convection as well as cirrus remnants.
42 The lack of detailed understanding what causes aviation hazards related to High IWC hampers
43 further tuning of the High IWC mask. Additional evaluation of the High IWC mask against field
44 campaign data should provide more information on the performance of the MSG-CPP High IWC
45 mask and contribute to a better characterization.

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47 **1. Introduction**

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49 Weather hazards can have a significant impact on aviation via disturbing flight schedules and
50 causing air traffic delays, but also as a cause of accidents, some of them fatal. Among the
51 weather related effects on aviation are changes in visibility like fog, clouds, rain, snow, hail,
52 wind, turbulence, lightning, smoke and volcanic ash [Perkins et al., 1998; Bragg et al., 2002;
53 Mecikalski et al., 2007]. One particular hazardous process is in-flight or in-service icing. Aircraft
54 may penetrate clouds of super-cooled water droplets, or high densities of ice particles. The
55 droplets or particles may deposit on cold aircraft surfaces, affecting aerodynamic properties of
56 the plane, the engine performance, or inlets and nozzles used for onboard monitoring of
57 environmental conditions, the latter resulting in a malfunctioning of for example speed sensors
58 [Mason et al., 2006; Mecikalski et al., 2007].

59 The microphysical conditions under which in-service icing may occur are generally well
60 understood: either large amounts of super-cooled cloud droplets are present, or high
61 concentrations of ice particles. However, what the corresponding general atmospheric conditions
62 are, and how to identify or diagnose them, has been a much more difficult task. This is in part
63 related to the notion that the majority of in-service icing events appear to occur outside of what is
64 called “classic” convection, *i.e.* areas of vigorous updrafts [Grzych and Mason, 2010].
65 Approximately only 20% of in-service icing events are associated with this “classic” convection.
66 The remaining 80% appears to be related to occurrence of ice crystals in anvils, with only weak
67 or moderate convection and turbulence. Such systems are characterized by large concentrations
68 of small particles rather than large particles (hail) and/or super-cooled water droplets.

69 Furthermore, areas of large concentrations of small ice particles are difficult to detect by on-
70 board radar, in contrast to the “classical” convection where the deep convection and vigorous
71 cores can be detected by on-board radar and thus can be avoided. Finally, it appears that the
72 majority of in-service icing events are occurring in tropical and subtropical regions of the world
73 (30N-30S), although potential in-service conditions can occur at higher latitudes [Grzych and
74 Mason, 2010].

75 To address many of the issues related to in-service icing events and in anticipation of regulation
76 changes regarding mixed phase and glaciated icing conditions, the large European High Altitude
77 Ice Crystals project (HAIC) was initiated in 2012 to investigate a wide range of aspects of in-
78 service icing. The HAIC project combines laboratory experiments (wind chambers), field
79 campaigns, numerical modeling and remote sensing techniques to study a variety of aspects of
80 in-service icing.

81 Laboratory measurements focus on the characterization, optimization, enhancement and
82 selection of the most sophisticated cloud microphysics probes in order to measure mixed phase
83 and glaciated icing conditions during flight tests and to calibrate icing wind tunnels.
84 Furthermore, the HAIC project aims at measurement and characterization of the microphysical
85 properties of core or near-core regions of deep convective clouds, including cloud liquid and ice
86 water contents and particle size and shape distributions. Finally, HAIC aims at characterizing the
87 atmospheric conditions for possible in-service icing and the detection of such areas in satellite
88 remote sensing products.

89 An important aspect of the HAIC project is the development of space-borne remote detection and
90 now-casting application of glaciated icing conditions based on imagery of geostationary MSG -
91 SEVIRI (Meteosat Second Generation - Spinning Enhanced Visible and InfraRed Imager)

92 satellite observations. Atmospheric conditions under which in-service icing occurs are not well
93 understood nor well characterized – which is also the prime justification for the HAIC project.
94 However, it is widely accepted that the presence of High Ice Water Content is a crucial condition
95 for the occurrence of in-service icing. Detection of areas of potential High Ice Water Content by
96 satellite remote sensing thus provides important spatio-temporal information for the possible
97 occurrence of in-service icing events.

98 In this paper, we present a new High Ice Water Content mask (High IWC mask) based on the
99 output of the MSG - Cloud Physical Properties (CPP) algorithm [Roebeling et al., 2006; Meirink,
100 2013] that was developed within the Climate Monitoring Satellite Application Facility (CMSAF)
101 of the EUropean METeorological SATellite organization (EUMETSAT), and applied to the
102 geostationary SEVIRI satellite measurements. The CPP algorithm provides a number of cloud
103 physical properties that are of interest in diagnosing possible in-service icing conditions. The
104 high IWC mask will be derived and evaluated against measurements of cloud properties from
105 active remote sensing instruments on board of satellites, and finally the high IWC mask will be
106 compared with the EUMETSAT SEVIRI Rapid Development Thunderstorm (RDT) product that
107 is used to identify rapidly growing thunderstorms and convective systems [Autonès, 2012].

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109 **2. Project description and datasets used.**

110

111 **2.1 HAIC**

112 Within the European FP7 HAIC project, academics and aeronautic industries are collaborating
113 within six main research activities that include dedicated field campaigns, development of new in
114 situ probes, space-based detection and monitoring, upgrade of on-board weather radars,

115 improvement of ground test facilities, and modeling of melting and impingement processes. All
116 activities are designed to enhance aircraft safety when flying in mixed phase and glaciated icing
117 conditions.

118 The HAIC Sub-Project 3 (SP3), entitled Space-borne Observation and Nowcasting of High Ice
119 Water Content Regions, focuses on the development of space-borne remote detection of high Ice
120 Water Content (IWC) and nowcasting techniques to support the second and third HAIC flight
121 campaigns and ultimately provide relevant near real-time weather information through Air
122 Traffic Management (ATM). The SP3 investigations are divided in three interacting Work
123 Packages (WPs): (i) Geostationary space-borne retrievals of high IWC events focusing on the
124 detection of high IWC cloud regions mainly from the SEVIRI imager on MSG in daytime; (ii)
125 Polar orbiting space-borne retrievals of high IWC events investigating the detection of high IWC
126 cloud regions from visible, infrared and microwave passive and active observations of the space-
127 based A-Train mission; (iii) Nowcasting of tropical convection dedicated to the tracking of deep
128 convection over the Tropical Atlantic for operational applications based on the Rapid
129 Development Thunderstorm (RDT) nowcasting tool. Following the HAIC Technology Readiness
130 Level (TRL) strategy, the SP3 activities are required to pass with success three TRL levels:
131 TRL3 (characteristic proof of concept), TRL5 (breadboard validation in relevant environment)
132 and TRL6 (prototype demonstration in a relevant environment).

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134 **2.2 MSG-CPP**

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136 The CPP algorithm [Roebeling et al., 2006; Meirink, 2013] uses SEVIRI's visible (VIS) and
137 near-infrared (NIR) measurements to retrieve cloud optical thickness (τ) and cloud particle

138 effective radius (r_e) by applying the classical Nakajima and King [1990] approach. This approach
139 is based on the basic feature that the reflectance at a for cloud particles non-absorbing
140 wavelength is primarily related to τ , while the reflectance at an absorbing wavelength is mainly
141 related to r_e . For SEVIRI retrievals the VIS 0.64 μm and the NIR 1.63 μm channels have been
142 used here as non-absorbing and absorbing channels, respectively. Around 1.63 μm ice particles
143 are more absorbing than water droplets, which is not the case at 0.64 μm . Hence, together with
144 the use of a thermal infrared (IR) window channel to inform on cloud top temperature, this
145 allows to retrieve cloud thermodynamic phase.

146 CPP is based on look-up tables (LUTs) of top-of-atmosphere (TOA) reflectances for single-
147 layer, plane parallel, water and ice clouds, simulated by the Doubling Adding KNMI (DAK)
148 radiative transfer model [Stammes, 2001]. Single scattering properties have been calculated
149 using Mie theory for spherical water droplets and ray tracing for imperfect hexagonal ice crystals
150 [Hess et al., 1998], respectively. Absorption by atmospheric trace gases is taken into account
151 based on Moderate Resolution Atmospheric Transmission code simulations (MODTRAN4
152 Version 2 [Anderson et al., 2001]). For cloudy pixels (cloud contaminated or cloud filled, as
153 determined by the cloud mask described in Roebeling et al. [2006]) τ and r_e are retrieved by
154 matching the observed reflectance to the LUTs. First the ice cloud LUT is tried. If this leads to a
155 match and if the cloud top temperature – retrieved from the 10.8 μm channel - is below 265 K,
156 the thermodynamic phase is set to ice. Otherwise, the water cloud LUT is used, and the phase is
157 set to liquid. Liquid and ice water path (LWP and IWP) are then calculated following Stephens
158 [1978]:

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$$160 \quad LWP = \frac{4}{3Q_e} \rho_l r_e \tau; \quad IWP = \frac{4}{3Q_e} \rho_i r_e \tau \quad (1)$$

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where Q_e is the extinction efficiency at visible wavelengths (set to 2), and ρ_l and ρ_i are the densities of water and ice, respectively. Eq. (1) assumes a vertically homogeneous distribution of cloud condensate. CPP uses surface albedo at the VIS and NIR channels based on MODIS [Moody et al., 2005], and water vapour path from the ERA-Interim reanalysis project [Dee et al., 2011] of the European Center for Medium range Weather Forecast (ECMWF) as ancillary input data. Cloud property retrievals become very uncertain at high solar zenith angles (θ_0) and viewing zenith angles (θ). Therefore, no retrievals are performed for $\theta_0 > 78^\circ$ or $\theta > 78^\circ$. Earlier versions of CPP have been extensively validated using ground-based observations [Roebeling et al., 2008; Wolters et al., 2008) and used for the evaluation of regional climate models [Roebeling and van Meijgaard, 2009; Greuell et al., 2011]. Note that the CPP parameters associated with reflected solar radiation are mostly representative for the upper parts of clouds, in particular in case of optically thick clouds (*e.g.* deep convection). Because of the reliance of CPP on reflected solar radiation most of the photons are reflected back from the upper parts of optically thick clouds [Platnick, 2000]. Hence, little information from deep within optically thick clouds can be obtained. Also note that unpublished results indicate that CPP R_{eff} does not correlate very well with remote sensing profiles of R_{eff} . Furthermore, the physical interpretation of R_{eff} is rather complicated and care should be taken with interpreting R_{eff} as representative for real-world cloud particles sizes, in particular for ice clouds [*e.g.* McFarquhar and Heymsfield, 1998; Mitchell et al. 2011]. Detailed information on the CPP version used can be found in Meirink [2013].

2.3 DARDAR

184 DARDAR (raDAR/liDAR) [Delanoë and Hogan, 2008, 2010] consists in two synergistic
185 products derived from the combination of the CloudSat radar [Stephens et al., 2002] and
186 CALIPSO lidar [Winker et al., 2009] measurements. These products are distributed through the
187 ICARE centre in Lille (France). The first one, DARDAR-MASK [Delanoë and Hogan, 2010,
188 Ceccaldi et al 2013], is mainly a target classification of the scene observed by both CloudSat and
189 CALIPSO. More precisely the DARDAR-MASK data set employs a combination of the
190 CloudSat, CALIPSO measurements to identify cloud, precipitation and aerosol presences and
191 also retrieve cloud phase properties. The algorithm, based on a decision tree, was originally
192 designed to identify ice clouds on the basis of the synergy of surface-based radar, lidar
193 observations. The DARDAR-MASK returns a range of categories: clear, ground, stratospheric
194 features, insects, aerosols, rain, super-cooled liquid water, liquid warm, mixed-phase and ice.
195 The algorithm also permits an “unknown” classification when it is not possible to determine one
196 of these categories [Delanoë and Hogan, 2010]. This commonly occurs in regions where the
197 radar and lidar signal have been heavily attenuated or are missing. DARDAR-MASK used
198 CALIPSO backscatter and temperature to identify super-cooled water in the 0°C to -40°C range
199 [Ceccaldi et al 2013], while the depolarization is considered too noisy to be used at the
200 CALIPSO resolution [Delanoë and Hogan, 2010].

201 Ice cloud properties are available in the second DARDAR-CLOUD product [Delanoë and
202 Hogan, 2010]. This product uses the “varcloud variational technique” [Delanoë and Hogan,
203 2008] which combines the CloudSat radar and CALIPSO lidar profiles for retrieving the
204 extinction coefficient, IWC and Re of the ice cloud. DARDAR-CLOUD assumes a “unified”
205 PSD given by Delanoë et al. [2005, 2014]. The mass-size and area-size relations of non-spherical

206 particles are considered using in situ measurements [Brown and Francis, 1995; Francis et al.,
207 1998; Delanoë et al., 2014].

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209 **2.4 Rapid Development Thunderstorm (RDT; v2013)**

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211 RDT tracks clouds, identifies those that are convective, and provides a description of their
212 microphysical, morphological and dynamical properties. In particular, it allows locating the
213 boundaries of the cells and the overshooting tops when present. This last characteristic is of a
214 great importance for aircraft safety as overshooting is associated with strong updrafts. The RDT
215 also estimates the cell vertical extent, its horizontal growth rate and cooling rate necessary for
216 estimating the intensification/decaying of the convective cell. The speed and direction of
217 propagation are also provided. Two other important parameters are available in RDT product for
218 icing issues: the main cloud phase of the convective cell and the highest convective rain rate
219 inside the cell, both coming from other NWCSAF (Satellite Application Facility in Support to
220 Nowcasting and Very Short Range Forecasting) algorithms and integrated into the RDT output.
221 The RDT algorithm is based on four main modules: the detection, the tracking, the
222 discrimination and the advection scheme. The RDT software is developed by Météo-France in
223 the framework of NWCSAF.

224 RDT combines a cloud-tracker and an algorithm to discriminate convective and non-convective
225 cloud objects. The cloud objects defined by the RDT are cloud towers with a significant vertical
226 extension, namely at least 6°C colder than the warmest pixel in the surrounding [Guillou et al.,
227 2009]. For that purpose, the 10.8 μm channel of MSG is used. The tracking algorithm allows
228 linking an object on the previous image. Once the link is identified, some characteristics of the

229 object can be calculated: trends (e.g. cooling rate), motion vector (considering successive
230 positions of the gravity center). Then the third step is a statistical scheme to define if the cell is
231 convective or not. The statistical scheme, called discrimination, depends on the available satellite
232 data as well as historic data. In optimal configuration it requires for the following satellite
233 channels: water vapor channels at 6.2 μm and 7.3 μm , thermal infrared channels at 8.7 μm , 10.8
234 μm , and 12.0 μm . Empirical rules help to classify convective systems. The coordinates of each
235 cell are available as a polygon including associated characteristics. For the comparison with the
236 MSG-CPP High IWC mask we focus on the agreement between the location of RDT objects and
237 the High IWC mask.

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239 **2.5 AIRBUS In-Service event database**

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241 Within the HAIC project, AIRBUS has provided a global database of “In Service” events of
242 icing, *i.e.* reports by pilots of flying conditions where icing apparently has affected flying
243 conditions. Due to AIRBUS regulations the database is not public, but information can be
244 obtained via AIRBUS in case of use for scientific research.

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246 **3. High IWC mask**

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248 **3.1 Analysis of AIRBUS event database and development of a provisional High IWC mask.**

249

250 Within the HAIC project, the AIRBUS “In Service” event database was used to construct a first
251 provisional High IWC mask (v1). Details of its construction can be found in the Supplementary

252 Information (SI). The mask is based on defining thresholds for a set of CPP parameters: only if
253 all criteria are met, *i.e.* the CPP parameter values fall within the pre-defined threshold intervals,
254 the SEVIRI pixel is masked as a High IWC event. The MSG-CPP parameter threshold values
255 used for defining the High IWC mask v1 are listed in table 1. The number of useful events in the
256 database is limited, casting doubts about the usefulness of the database and thereby the
257 provisional High IWC mask v1. Hence, an alternative approach was agreed upon, whereby
258 identification of high IWC values ($> 1 \text{ g/m}^3$) in satellite vertical profile measurement if water
259 content serves as a proxy for in service icing conditions.

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261 **3.2 Evaluation of MSG-CPP with DARDAR**

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263 For comparison between MSG-CPP and cloud profile measurements from radars and lidars on
264 polar satellites we use DARDAR data, which combines vertical information from the
265 CLOUDSAT radar and CALIPSO lidar measurements into one product. A test dataset for the
266 year 2008 was made available containing orbits with sufficient high IWC measurements within
267 one orbit, while orbits were required to fall within the SEVIRI disc during daytime (see
268 supplementary information table S1). A total of 31 orbits were analyzed that cover all months
269 and the entire SEVIRI disc.

270 Figure 1 shows an example of a DARDAR orbit and the corresponding MSG-CPP cloud top
271 heights. Indicated are also the locations where the DARDAR profiles indicate ice clouds. Based
272 on visual inspection there is a clear correspondence between the DARDAR ice identification and
273 the MSG-CPP clouds. Note that because of the time it takes for one DARDAR orbit to circle the
274 earth, and with a MSG-SEVIRI acquisition every 15 minutes, typically three to five MSG-CPP

275 images cover the DARDAR orbit, and thus that for some DARDAR profiles the MSG-CPP
276 image shown in Figure 1 is not the MSG-CPP output data nearest in time to the DARDAR
277 measurement.

278 Figure 2 shows the same DARDAR orbit but now with the vertical ice water content profile and
279 the corresponding MSG-CPP cloud top height (CTH). Also here there is a clear correspondence
280 between mid-latitude DARDAR maximum ice cloud heights and MSG-CPP cloud top heights.
281 However, within the tropics conditions MSG-CPP underestimates of DARDAR maximum ice
282 cloud height frequently occur. This typically occurs for less dense cirrus and is related to the
283 nature of the MSG-CPP cloud top temperature/height algorithm. It is a simple one-channel (10.8
284 micron) approach, which assumes opaque clouds. Top-of-atmosphere IR radiation for semi-
285 transparent cirrus contains a significant contribution from the warm surface, leading to an
286 overestimation of the cloud top temperature and underestimation of the height. Although less
287 severe, such an underestimation of cloud top height and overestimation of cloud top temperature
288 is typical for most SEVIRI-based algorithms, as evaluated in Hamann et al. [2014].

289 Figure 3 shows the probability distribution of DARDAR cloud top height (maximum level with
290 $IWC > 0$) and MSG-CPP cloud top height as function of the MSG-CPP High IWC mask
291 parameter threshold values. The parameters with the largest impact on the probability
292 distribution are the CWP and the cloud top height and/or cloud top temperature, as was already
293 shown before. Obviously the detection is sensitive to choice of height/temperature threshold in
294 this comparison. To provide some background: low clouds and high (optically) thick cirrus
295 clouds typically have a condensed water path of at maximum few hundred g/m^2 . Optically thin
296 cirrus clouds have typically a CWP of less than $100 g/m^2$. Only for very deep and thick
297 convective clouds the CWP exceeds $1000 g/m^2$. When looking at specific CWP values, we see

398 that a given threshold improves the comparison but that it is unclear which of the thresholds is
399 better as the correlation between DARDAR and MSG-CPP cloud top heights hardly differ for
300 different CWP thresholds (not shown).

301 To further investigate the CWP in both MSG-CPP and DARDAR, the DARDAR IWC profiles
302 were converted to total IWP and then compared to the MSG-CPP CWP. Figure 4 shows the
303 probability distribution of MSG-CPP and DARDAR IWP for the same data used for Figure 3.
304 The probability distribution is clearly skewed, with DARDAR IWP being considerably larger
305 than the MSG-CPP CWP. One possible explanation is that for its retrieval, the MSG-CPP
306 algorithm assumes a vertically homogeneous distribution of effective radius and cloud
307 condensate, which may be unrealistic. Because there is less reflected sunlight (information)
308 coming from deeper in the clouds towards the satellite [Platnick, 2000], the satellite
309 measurements will be more representative of the upper part of in particular deep convective
310 clouds. However, the size of ice particles within geometrically thick clouds will generally be
311 larger towards the cloud bottom [Feofilov et al., 2015] due to various processes (*e.g.*
312 sedimentation and the higher water vapor pressure at lower altitudes). Hence, the MSG-CPP
313 algorithm likely underestimates the average effective radius of these optically thick clouds. The
314 parameterization of the MSG-CPP CWP depends linearly on the retrieved effective radius,
315 possibly explaining the MSG-CPP underestimation of CWP.

316 To test this idea we further analyzed Figure 4 for its relation with the variability in the effective
317 radius of the DARDAR profile. The root-mean-square (rms) value of the effective radius of the
318 profile for where there is ice provides an indication of how uniform the effective radius
319 distribution is throughout the profile. In Figure 5 the probability distribution of Figure 4 is
320 filtered on the rms value of the DARDAR profile effective radius: the smaller the rms value, the

321 more uniform the vertical distribution of the effective radius is and the more it can be expected
322 that the DARDAR CWP/IWP agrees with MSG-CPP. Figure 5 shows that this indeed is the case.
323 Furthermore, it appears that the vertical effective radius variability acts approximately as an
324 offset: the fit lines through the data are more or less parallel to the 1:1 line.

325 The analysis performed in this section provides a proper characterization of the MSG-CPP data
326 vs. DARDAR measurements, highlighting agreement as well as caveats. With this information,
327 the next step is to investigate to what extent the first High IWC mask is capable of identifying
328 high IWC values in the DARDAR IWC profiles, and whether the mask can be improved.

329 For Figure 6, DARDAR profiles were ranked according to the maximum IWC value in the
330 profile, after which the percentage of DARDAR profiles identified by the High IWC mask was
331 calculated. Clearly, the number of high IWC events identified by the High IWC mask is very
332 limited. The insert shows the same data but for the different thresholds that are used for the High
333 IWC mask. The most important limiting factor here is the CWP, with the CTH and/or CTT being
334 of secondary importance. The latter is not surprising, as the maximum IWC value not necessarily
335 is located higher up in the troposphere (either > 8 km or below 225 K). However, the limiting
336 effect of choosing a high CWP as threshold means that a sensitivity analysis should be
337 performed to see whether a more optimal set of MSG-CPP parameter thresholds can be defined
338 for identification of high IWC events. Hence, similar analyses were performed for the following
339 range of MSG-CPP parameter threshold values:

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- 341 - Cloud water path is > 100 - 1000 g/m^2 with 100 g/m^2 steps
- 342 - Cloud top temperature < 275 - 225 K with 5 K steps.
- 343 - Cloud optical thickness 5 - 20 with steps of 5 units

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345 The effective radius was left out as it is generally not representative for the effective radius at the
346 level of the highest IWC occurrence (see earlier discussion). The cloud top height was left out as
347 it is related to the cloud top temperature.

348 The subsequent statistic of identification of high IWC events by the High IWC mask as function
349 of maximum IWC value in the DARDAR profile as shown in Figure 6 were then analyzed
350 according to the following characteristics: the steepness of the increase in fraction of identified
351 DARDAR profiles by the High IWC mask in the maximum IWC interval in the interval between
352 0.1 g/m^3 and 1 g/m^3 , and the fraction of maximum DARDAR IWC $> 1 \text{ g/m}^3$ identified by the
353 High IWC mask.

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355 **3.3 Optimization of the MSG-CPP High IWC mask.**

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357 The best High IWC mask consists of those combinations of MSG-CPP parameters that identify
358 DARDAR IWC $> 1 \text{ g/m}^3$ while rejecting DARDAR IWC $< 1 \text{ g/m}^3$. This is in essence a binary
359 decision model – also known as a contingency model - as outlined in Table 2, which shows a
360 prototypical contingency table for decision-making. Given that the large majority of MSG-CPP
361 pixels will not be identified as high IWC events (see Figures 3, 5 and 6), we focus on the
362 following three verification statistics: the Hit Rate or Probability Of Detection (POD), the False
363 Alarm Ratio (FAR) and the Threat Score or Critical Success Index (CSI), the latter of which is
364 often being used for low frequency events. These statistics can be used to objectively select the
365 best combination of MSG-CPP parameters thresholds. Based on table 2, these three statistics are
366 calculated as follows (see equation 1):

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$$POD = \frac{A}{A + C} \quad FAR = \frac{B}{A + B} \quad CSI = \frac{A}{A + B + C} \quad (2)$$

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369 Figure 7 shows the probability distribution of the POD (upper panel), FAR (middle panel) and
370 CSI (lower panel) for different MSG-CPP parameter threshold settings (see legend of Fig. 7 for
371 more details). The probability distribution of PODs varies between 0 and 0.9, with a gradual
372 decrease in occurrence of increasing POD. The probability distribution of the FAR starts only at
373 0.3, shows a distinct peak around 0.4 with a long tail up to values of 0.95, showing that to some
374 extent ‘false alarms’ in MSG-CPP cannot be avoided. The CSI shows a broad distribution
375 between 0 and 0.4.

376 If we look at the relation between the POD and FAR as well as between the POD and CSI –
377 shown in Figure 8 - we see that increasing POD also results in increasing FAR, thus better
378 detection of high IWC values in DARDAR IWC profiles by MSG-CPP is accompanied by an
379 increasing number of ‘false alarms’. The relation between the POD and the CSI shows this effect
380 with a maximum around a POD value of 0.6 and a decreasing but also widening distribution of
381 the CSI with increasing POD beyond 0.6, reflective of the problem of more false positives with a
382 better probability of detection.

383 We now proceed to select threshold combination with a CSI close to the maximum CSI
384 encountered in Figure 8 ($CSI > 0.35$). Table 3 shows the fraction of High IWC masks (or pixels)
385 obtained for different MSG-CPP parameter thresholds for which the CSI was larger than 0.35.
386 The CWP threshold is chosen at 100 g/m^2 as a higher value would exclude too many potential
387 high IWC events. The CTT threshold is chosen to be $< 270 \text{ K}$ but not lower for the same reason,
388 and 270 K is close to freezing point of water. The COT threshold is chosen at 20 or larger as we

389 want to avoid too many optically thin clouds. Finally, there does not appear to be much of a
390 relation between the height of the DARDAR high IWC maximum value and the ability of MSG-
391 CPP to detect High IWC events.

392 Summarizing, we define the following MSG-CPP parameter thresholds for version 2 of the High
393 IWC mask.

- 394 - The cloud phase ice
- 395 - The effective radius *no threshold*
- 396 - Condensed water path $> 100 \text{ g/m}^2$
- 397 - Cloud top height *no threshold*
- 398 - Cloud top temperature $< 270 \text{ K}$.
- 399 - Cloud optical thickness > 20

400

401 This combination of thresholds has a POD = 0.59, a FAR of 0.52 and a CSI of 0.36. For the same
402 DARDAR data but with the High IWC mask v1 the numbers were: POD = 0.08, a FAR of 0.34
403 and a CSI of 0.08. Both the POD and CSI are better for v2 compared to High IWC mask v1. The
404 FAR is better for v1 compared to High IWC mask v2, indicative of the trade-off between
405 detection and false alarms as discussed in relation to Figure 8. The better POD and CSI are also
406 reflected in the notion that the number of detections of DARDAR IWC profiles with maximum
407 $\text{IWC} > 1 \text{ g/m}^3$ is in High IWC mask v2 an order of magnitude larger than in High IWC mask v1
408 (see Figure 9).

409 We realize that there is no unique or best set of threshold values, as there are two competing
410 interests: better detection of high IWC events vs. fewer false alarms. Furthermore, it is *a priori*

411 not clear what the defining characteristics of an High IWC mask should be, as the number of real
412 in-service icing events is rather limited. As it is unclear what the exact atmospheric conditions
413 are for the occurrence of in-service icing are to begin with, there are no compelling arguments
414 why to specifically choose for other threshold values as long as the favored statistic (CSI) is
415 close to the maximum CSI found in the sensitivity analysis.

416 We also ran a test accounting for the time difference between the DARDAR measurement and
417 the MSG-CPP measurement (once every 15 minutes). For the verification discussed here the
418 DARDAR measurements were coupled to the nearest MSG-CPP measurement in space and time
419 (which thus can be either before or after the DARDAR measurement). A test with either the
420 nearest MSG-CPP measurement before the DARDAR measurement or the nearest MSG-CPP
421 measurement after the DARDAR measurement did result in very similar verification statistics
422 (change in all verification statistics less than 0.05).

423 We finally checked the verification statistics for the sub-MSG-CPP pixel average DARDAR
424 profile and the parallax correction. The MSG-CPP pixel size – typically 5 km – is much larger
425 than the footprint of DARDAR profile - typically 250 m. As a check, we ran the same
426 verification for the MSG-CPP pixel average DARDAR profile. Obviously this results in fewer
427 collocations. However, for only 10% - 2% - 0.1% of the DARDAR profiles with maximum IWC
428 above 1 g/m^3 , the maximum IWC in the corresponding average IWC profile was less than 1 g/m^3
429 - 0.5 g/m^3 - 0.1 g/m^3 , respectively. As a result, the verification statistics were very similar with
430 changes of 0.05 at maximum but generally less. Similar small changes in verification statistics
431 were found when applying the parallax correction.

432 Figure 9 shows the results of the evaluation for the MSG-CPP High IWC mask with DARDAR
433 IWC profile measurements. The higher the maximum IWC value, the larger the chances of

434 detection by the High IWC mask. The results also show that the High IWC mask identifies the
435 majority (50-60%) of the DARDAR profiles that we aim to detect ($IWC > 1 \text{ g/m}^3$), compared to
436 an identification rate of less than 10% with High IWC mask v1. In addition, the higher the
437 altitude of maximum IWC in DARDAR, the higher the percentage of these cases identified by
438 the High IWC mask v2, increasing to almost 80% for DARDAR maximum IWC altitudes > 8
439 km compared to 50-60% for all cases combined. This is consistent with earlier findings
440 indicating that SEVIRI/MSG-CPP is more sensitive to the physical conditions of the upper part
441 of a cloud. On the other hand, for the DARDAR cases with maximum $IWC < 1 \text{ g/m}^3$ yet still
442 identified by the High IWC mask v2 (false detections), the maximum IWC is for the majority of
443 cases still $> 0.1 \text{ g/m}^3$. In other words, for most false detections by the High IWC mask v2 the
444 maximum IWC is still quite high, just not above the threshold value. Most of the false detections
445 are thus not false in the sense that there is no IWC. If IWC values larger than 0.1 g/m^3 are
446 accepted, the FAR drops from 0.51 to 0.14. Finally, and just for reference, in general many more
447 MSG-CPP clouds are identified as ice by the MSG-CPP ice phase than by the High IWC mask,
448 showcasing the effect the different MSG-CPP parameters used in the High IWC mask have.
449 Compared to the High IWC mask v1 the number of DARDAR profiles identified as high IWC
450 events improves with the High IWC mask v2, with most high DARDAR profiles with $IWC > 1$
451 g/m^3 now identified as high IWC events. Figure 9 further suggests the higher in altitude the high
452 IWC value, the more likely it becomes that profiles with high but not extremely high maximum
453 IWC values are identified by the High IWC mask. This is an important result, as it suggests that
454 optically or vertically thick clouds with high IWC values lower in the troposphere are more
455 difficult to identify by the High IWC mask.

456 The sensitivity of MSG-CPP parameter thresholds as presented in Figures 7 and 8 shows that,
457 although the High IWC mask certainly can be improved, there remains some room for choosing
458 parameters. The typical uncertainty ranges we identified are:

459

- 460 - Cloud water path threshold between 100 and 400 g/m²
- 461 - Cloud top temperature threshold between 240 and 270 K
- 462 - Cloud optical thickness threshold between 5 and 20

463

464 These ranges should be kept in mind when using the High IWC mask: there is no optimal choice
465 in MSG-CPP parameter threshold values.

466

467 **3.4 Comparison between the MSG-CPP High IWC mask and RDT.**

468

469 An additional analysis was performed for comparing the High IWC mask and the MF RDT mask
470 in order to evaluate whether both masks identify similar air masses or not, and whether one mask
471 is preferred or the two masks are complementary.

472 Météo France made RDT data available for three AIRBUS events, and provided one complete
473 day of RDT data surrounding each event. Figure 10 shows an example of the comparison
474 between RDT and the High IWC mask. From visual inspection only it appears that for the larger
475 RDT cells there is a considerable overlap between RDT and the High IWC mask. However, the
476 large areas of High IWC mask appear considerably larger than the corresponding RDT area. On
477 the other hand, small RDT cells are generally not identified by the High IWC mask. Figure 11
478 shows the relation between the RDT size and the fraction of pixels identified by the High IWC

479 mask. Clearly, the larger the cell, the larger the fraction of pixels identified. Note that this
480 relation was also found for the other events.

481 Combining these results the following hypothesis emerges. Small RDT cells are young fast
482 growing cells that are not completely iced yet. Only when convection reaches a sufficient mature
483 stage the clouds become fully iced. Once cells mature and become larger, their dynamic
484 development ceases and the corresponding anvils and/or high altitude ice clouds become larger.
485 Ultimately, convective activity ceases and the high altitude cirrus remains, which is more likely
486 to be identified by the High IWC mask than by RDT. This observation appears intuitively
487 consistent with the common conceptual meteorological model of the evolution of convection.

488 In summary, RDT and the High IWC mask are complementary: RDT is very well capable of
489 identifying young, small growing convective cells, whereas the High IWC mask appears better
490 capable of identifying mature and aging convection and/or cirrus.

491

492 **3.5 Solar zenith angle bias.**

493

494 The MSG-CPP High IWC mask v2 has been implemented in an operational stream and made
495 available in near real time on the KNMI MSG-CPP web portal (<http://msgcpp.knmi.nl>). One of
496 the first impressions of the results of the implementation was that there exists solar zenith angle
497 dependence of the High IWC mask v2. It appeared that for high angles the High IWC mask had a
498 tendency to occur at solar facing edges of clouds either associated with frontal zones or
499 convection. This tendency appeared to visually correlate with high cloud optical thicknesses and
500 to cause a displacement of the COT compared to for example cloud top temperature. One
501 possible hypothesis explaining this observation is that for optically thick and/or heterogeneous

502 cloud systems and high solar zenith angles 3D radiative effects (*e.g.* illumination/shadowing of
503 different parts of the cloud top) become very important, and due to the non-linear relation
504 between optical thickness and reflectance, cause larger increase of COT in the more illuminated
505 parts than decrease in the less illuminated parts. An overall positive bias of retrieved COT at
506 high SZA has been observed before in for example MODIS observations [Grosvenor and Wood,
507 2014].

508 To demonstrate that such a bias indeed exists we tracked and analyzed the tropical cyclone
509 Humberto in the Northern Atlantic Ocean on 12 September 2013. Humberto was a hurricane
510 category 1 system on the Saffir-Simpson Hurricane Wind Scale formed in the Cape Verde region
511 west of Africa on 8 September 2013. The system remained over the western Atlantic for
512 approximately 12 days without causing much damage other than heavy rain on the Cape Verde
513 Islands. On 11-12 September 2013 wind speeds reached hurricane strength (source: NOAA,
514 http://www.nhc.noaa.gov/data/tcr/AL092013_Humberto.pdf)

515 Because hurricanes are well defined and consist of fully developed cloud systems whose
516 morphology and physical properties generally do not change very fast during a period of 12
517 hours, they can be used to investigate SZA biases in the MSG-CPP output. Typically clouds of
518 fully developed hurricanes reach up to the tropopause – resulting in fairly small changes in cloud
519 top temperatures, and because of its energetics it is not expected that for example the amount of
520 humidity, cloud water and precipitation will change very fast as hurricanes need a minimum sea
521 surface temperature of 27°C to exist while the maximum SST rarely exceeds 33°C. It is therefore
522 not expected that physical properties change dramatically during a 12 hour period for which
523 MSG-CPP data is available.

524 Figure 12 shows the time evolution of a number of MSG-CPP statistics and parameters for a
525 400×400 SEVIRI pixel area centered around 24.86°N, -27.33°E, which covers approximately a
526 20°×20° area. During this time the core of tropical hurricane Humberto was located within this
527 area. Panel [A] shows that the number of CTT below 213 K (-60°C) was fairly constant over the
528 12 hour time period and slowly decreased, consistent with the reported weakening of the system
529 on 12 September 2013. However, panel [B] shows that the occurrence of COT > 100 is strongly
530 peaked at the beginning (09:00-11:00 UTC) and the end (18:00-19:00 UTC) of the period, when
531 the counts double or triple compared to the fairly constant number of occurrences of COT > 100
532 between 11:00 and 18:00 hours UTC. The corresponding area average SZA (panel [C]) and in
533 particular the area average light path (1/cosine(SZA) in panel [D]) shows a similar curvature.
534 Finally, the number of High IWC masked pixels (panel [E]) is also fairly constant over the time
535 period.

536 When comparing the correlation coefficients with the average light path (1/cosine(SZA)), it is
537 clear that the average SZA and in particular the average light path length correlates very well
538 with the occurrence of COT > 100. A typical SZA value for which this starts to become
539 important is 60°. Note that for large SZA the light path could be an order of magnitude larger
540 than for small SZAs. For the hurricane system studied here this does not bias the High IWC
541 mask counts, presumably because the characteristics of clouds associated with a hurricane –
542 cold, optically thick clouds with lots of condensed water - are such that they always qualify for
543 the High IWC mask. Nevertheless, it is obvious that for other types of cloud systems the High
544 IWC mask is likely less reliable for high SZA and/or high viewing angles, and this is consistent
545 with the visual inspection of the data. Even for the well-organized cloud system of hurricane
546 Humberto we could visually identify small misalignments between structures related to CTT and

547 COT for large SZA that we could not identify for small SZA. However, it was difficult to
548 quantify such slight misalignments hence we reverted to the more general extremely high COT's
549 measured in the hurricane for large SZAs. If we exclude CPP measurements for SZAs $> 60^\circ$, the
550 verification statistics of the DARDAR comparison improve slightly with the POD increasing
551 from 0.59 to 0.62, the FAR decreasing from 0.52 to 0.49 and a the CSI increasing from 0.36 to
552 0.39.

553

554 **4. Summary and conclusions.**

555

556 For the detection of potential (high latitude) high ice water content in SEVIRI geostationary
557 satellite measurements a mask was constructed based on the results from the CPP algorithm. The
558 mask is based on defining thresholds for a set of CPP parameters: only if all criteria are met, *i.e.*
559 the CPP parameter values fall within the pre-defined threshold intervals, the SEVIRI pixel is
560 masked as a High IWC event.

561 Evaluation of the High IWC mask with satellite measurements of active remote sensors of cloud
562 properties (CLOUDSAT/CALIPSO combined in the DARDAR product) shows that the mask
563 can be fine-tuned for detection of high IWC values $> 1 \text{ g/m}^3$ in the DARDAR profiles. A detailed
564 sensitivity analysis of SEVIRI thresholds and subsequent statistical analysis shows that a better
565 detection of High IWC events is accompanied by more false negatives. We decided on a
566 combination of thresholds that maximize the Critical Success Index, but readers should be aware
567 that depending on the requirements the parameters thresholds could be changed. Furthermore,
568 the evaluation of results against DARDAR provided some indications that the MSG-CPP High

569 IWC mask is more sensitive to cloud ice or cloud water in the upper part of the cloud, which is
570 relevant for aviation purposes. This will be a focus of future research.

571 Comparison with results from the RDT algorithm applied to the same geostationary SEVIRI data
572 showed that there are similarities and differences with the High IWC mask: the RDT algorithm is
573 very capable of detection young/new convective cells and areas, whereas the High IWC mask
574 appears to be better capable of detecting more mature and ageing convection as well as cirrus
575 remnants. This is likely related to the fact the RDT is developed for detecting fast growing
576 thunderstorms which may not have that much High IWC yet. Once dynamical development of
577 thunderstorms and convective systems ceases, RDT is unable to identify those regions but the
578 High IWC mask still can as there is sufficient ice remaining.

579 Visual inspection of High IWC mask fields suggested that there could be solar zenith angle
580 dependent biases in some of the MSG-CPP products. An analysis of a hurricane system in the
581 tropical Atlantic (Humberto, September 2013) revealed that the MSG-CPP COT can be biased
582 for high solar zenith angles as the light path through high altitude (ice) clouds can become very
583 large and will not be fully representative of the real vertical cloud structure anymore. Under such
584 circumstances, the High IWC mask can be biased, although for the Humberto we did not find
585 evidence of increased High IWC mask occurrences, probably because hurricane systems will
586 always be characterized by generally High IWC throughout the system. Nevertheless, some care
587 has to be taken with the High IWC mask under conditions of extreme solar zenith angles and
588 extreme viewing angles, and a first estimate indicates that excluding MSG-CPP measurements
589 with SZAs $> 60^\circ$ slightly improves the verification statistics of the comparison of the High IWC
590 mask with the DARDAR measurements. Note that it is equally likely that similar errors may

591 occur due to the viewing geometry, something that we believe we could also identify visually but
592 which was difficult to characterize quantitatively.

593 Although the High IWC mask is successful at detecting high IWC values in IWC profiles
594 measured by active remote sensing sensors, it should be noted that it remains unclear what the
595 exact conditions are of In-Service icing. It is well established that high IWC values are likely a
596 condition for the occurrence of In Service icing, but clearly it is not the only condition for these
597 occurrences. The lack of detailed understanding what causes such events precludes further fine-
598 tuning of the High IWC mask.

599 Finally, it has been suggested that apart from icing occurring within the cores of rapidly growing
600 and/or mature convection – with potentially a lot of super-cooled water – the majority of such
601 events occurred in older/aged cirrus with large number densities. However, this is not a settled
602 issue, although hopefully future field campaigns will enable a better characterization of the In-
603 Service icing conditions. The HAIC field campaigns in 2015 and 2016 should provide more and
604 better details of these conditions, and will be used to further evaluate the MSG-CPP High IWC
605 mask.

606

607

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611

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749

750

CPP variable	Threshold value
Cloud Phase	ice
Effective Radius	> 10 μm
Condensed Water Path	> 1000 g/m^2
Cloud Top Height	> 8 km
Cloud Top Temperature	< 225 K

751 **Table 1:** CPP threshold values for the High IWC mask v1.

752

MSG-CPP \ DARDAR	IWC _{MAX} > 1 g/m^3	IWC _{MAX} < 1 g/m^3
High IWC mask = True	[A] True (true positive)	[B] False (false positive)
High IWC mask = False	[C] False (false negative)	[D] True (true negative)

753

754 **Table 2.** Decision table for MSG-CPP High IWC mask

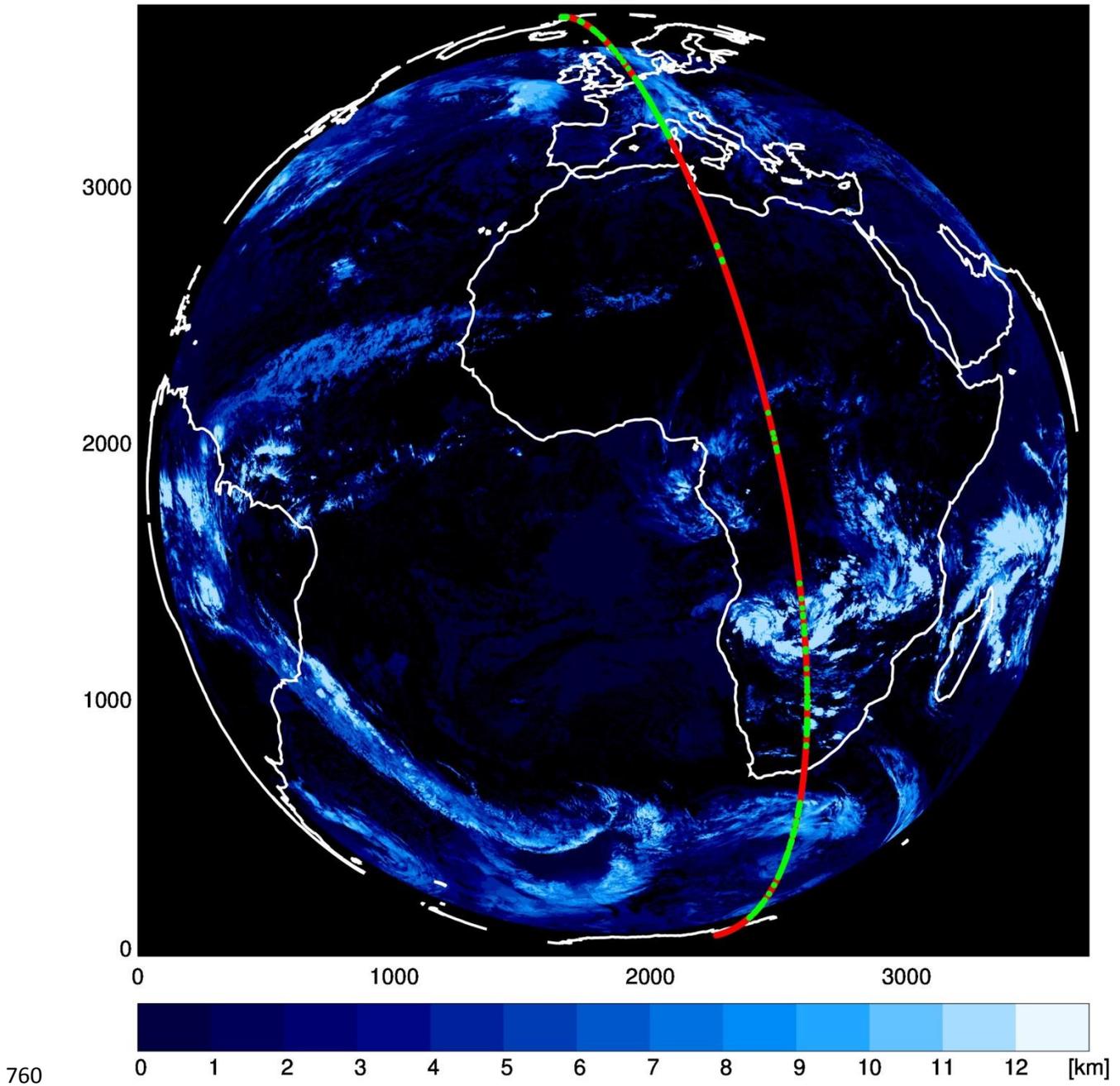
755

CWP [g/m^2]	[%]	CTT [K]	[%]	COT [-]	[%]	H [km]	[%]
100	8	235	2	0	21	0	2
200	10	240	6	10	22	1	7
300	19	245	9	20	32	2	12
400	18	250	10	30	19	3	16
500	21	255	13	40	3	4	21
600	11	260	14	50	0	5	26
700	8	265	14	60	0	6	13
800	0	270	14	70	0	7	0
900	0	275	14	80	0	8	0

756

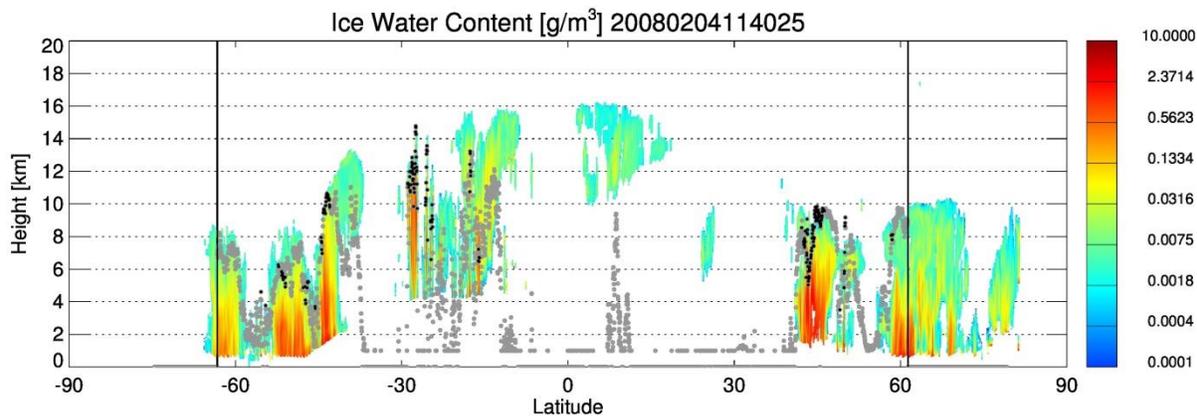
757 **Table 3.** Fraction of High IWC masks with MSG-CPP parameter threshold values larger than the
 758 value given in the table and for which the CSI was larger than 0.35. As an example: H indicates
 759 the height of the maximum IWC value in the DARDAR profile.

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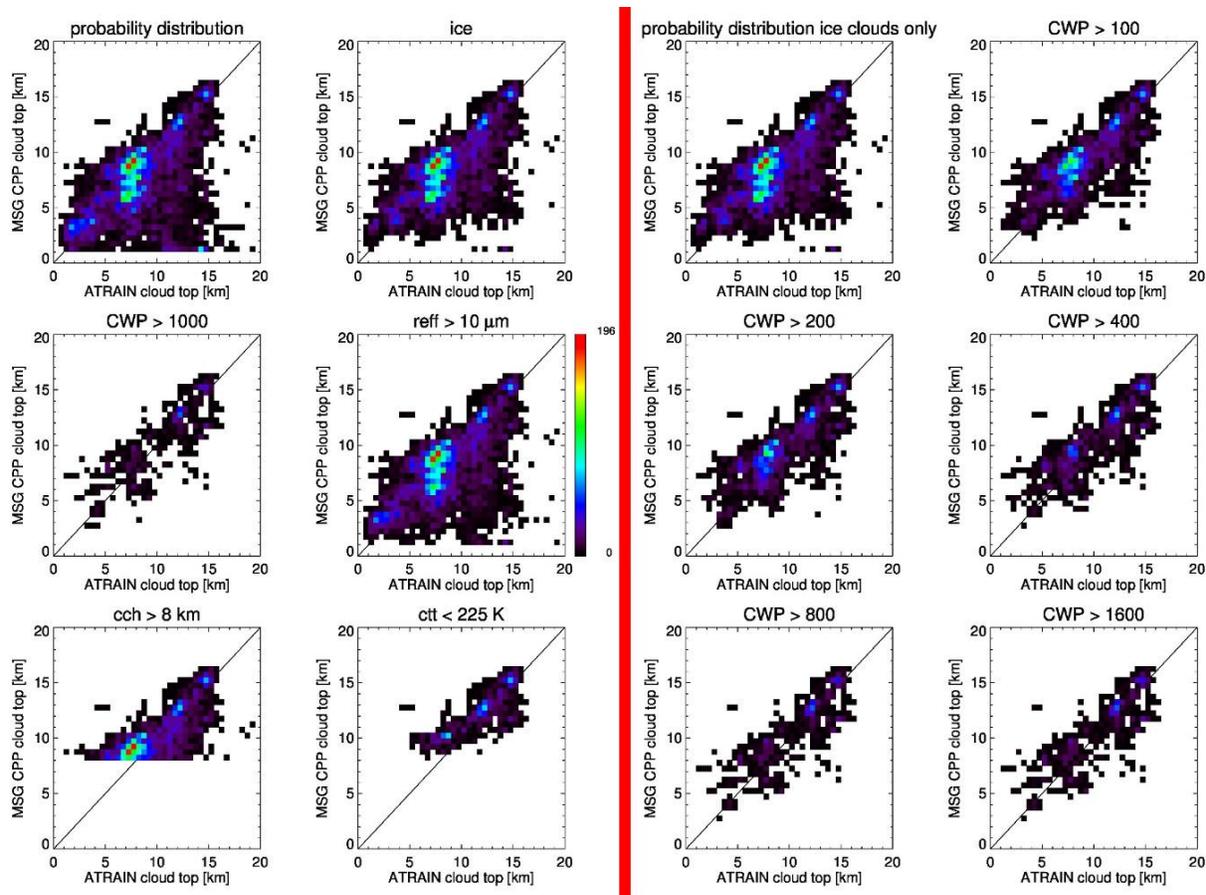
761 **Figure 1.** DARDAR orbit (4 February 2008, 12:29:56 UTC equator crossing time) and
762 corresponding MSG-CPP cloud top height (4 February 2008, 12:30 UTC). The DARDAR orbit
763 is shown by the red or green dots, with the green dots indicating DARDAR profiles with ice in it

764 and the red dots indicating DARDAR profiles without ice in it. Note that the time of MSG-CPP
765 image is nearest to the DARDAR equator crossing time.



766
767 **Figure 2.** Cross section of DARDAR ice water content and corresponding MSG-CPP cloud
768 top height (grey/black dots) as shown in Figure 1. The black dots denote the MSG-CPP pixels
769 for which the High IWC mask was identified. The vertical bars indicate the geographical
770 range for which MSG-CPP measurements are available due to the need of MSG-CPP for
771 daytime observations.

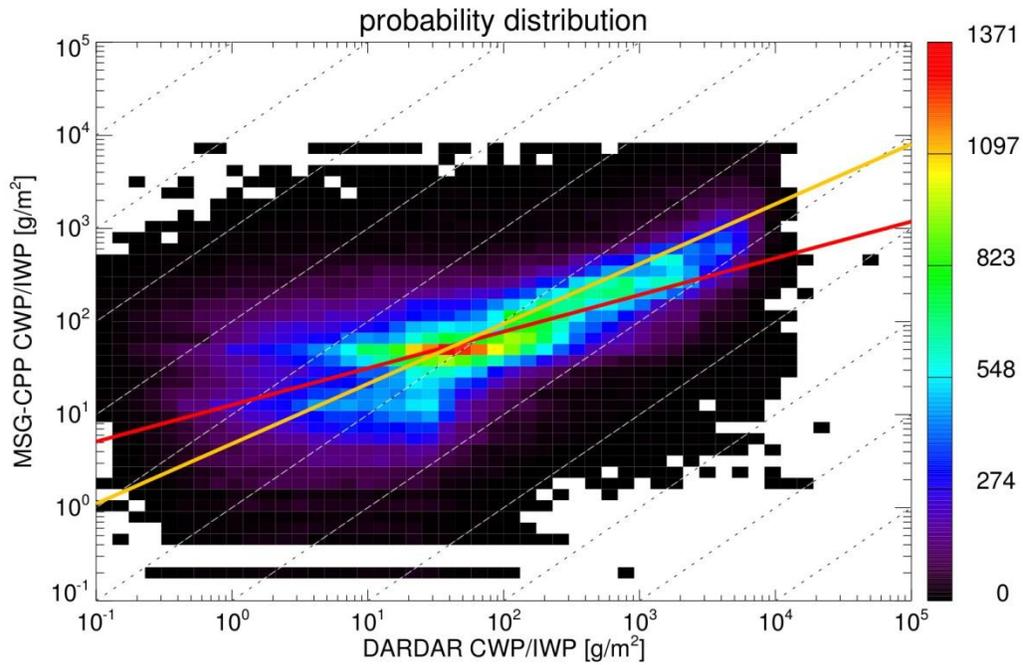
772



773

774 **Figure 3.** Probability distribution of cloud top heights estimated from MSG-CPP and A-
 775 Train/DARDAR data (highest level with IWC > 0) as function of MSG-CPP parameter
 776 values for approximately 160,000 DARDAR profile measurements obtained from 31
 777 DARDAR orbits. The left section shows the effect of the different High IWC mask
 778 thresholds, the right section shows the effect of different CWP thresholds.

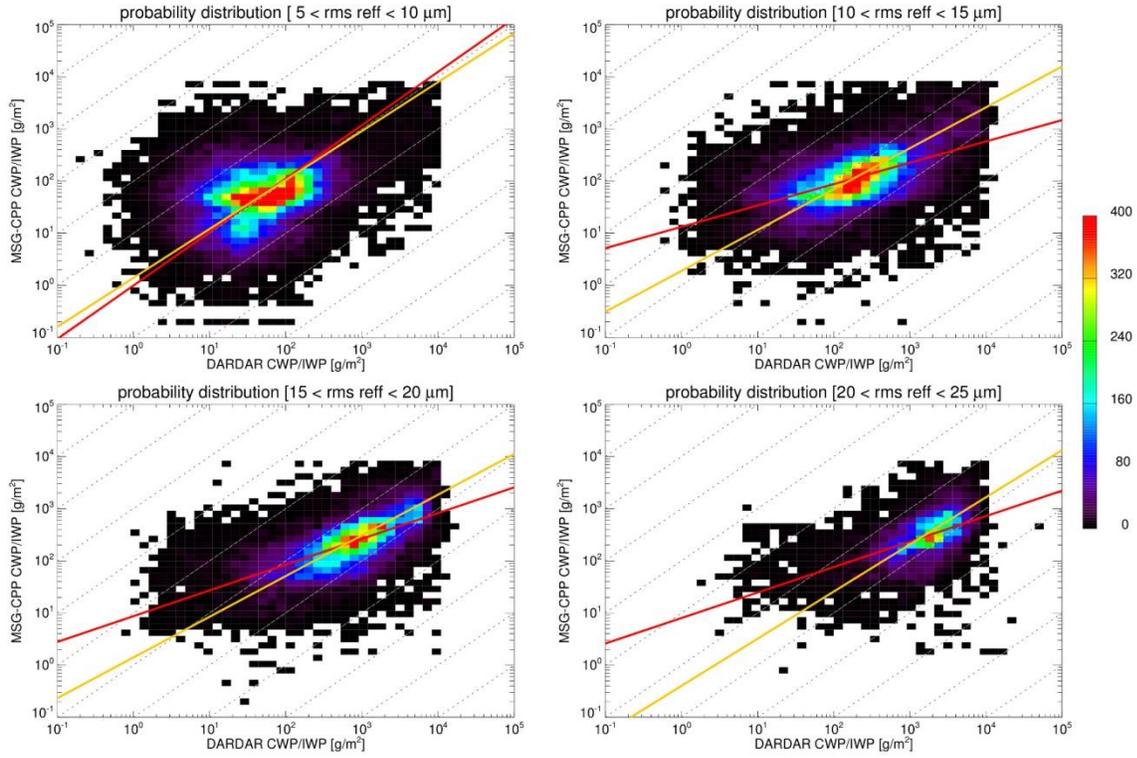
779



780

781 **Figure 4.** Probability distribution of CWP or IWP from MSG-CPP vs DARDAR for the orbits in
 782 table 2 combined. Two different linear fits are indicated with (orange) and without (red) forcing
 783 intercept of zero, but are for visualization purposes only.

784

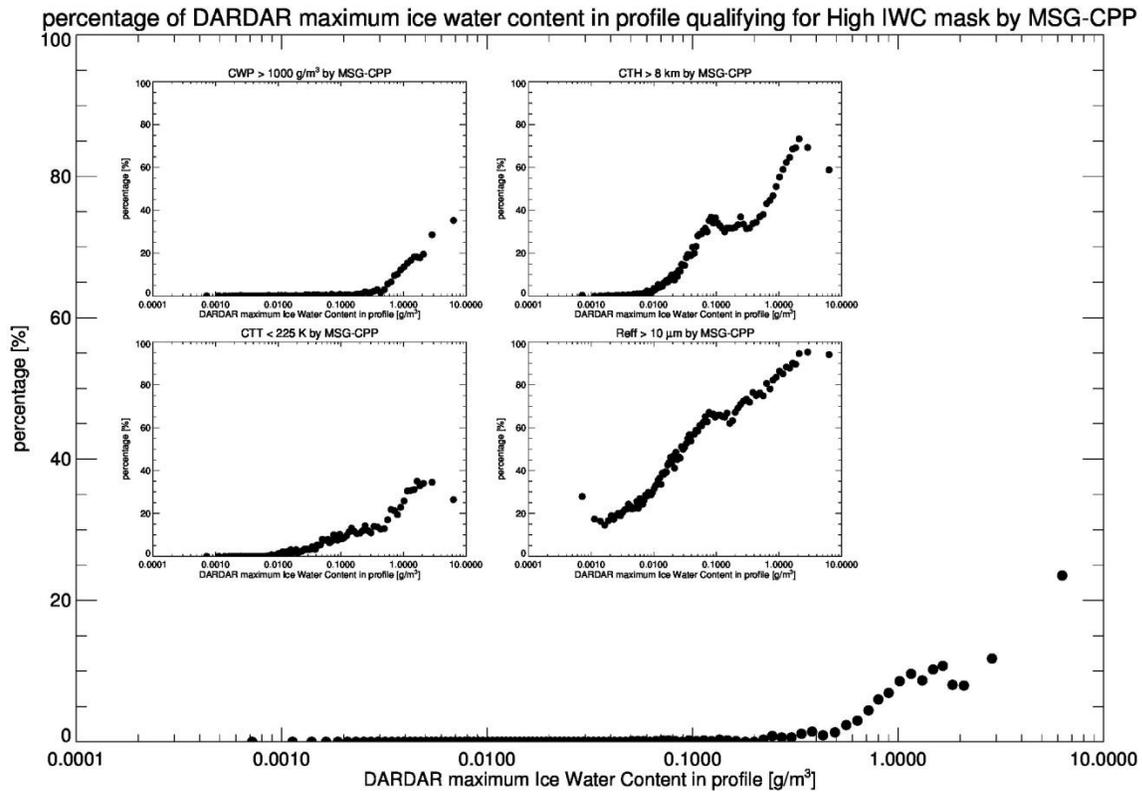


785

786 **Figure 5.** As Figure 4 but filtered according to the root-mean-square value of the effective radius
 787 of each DARDAR effective radius profile.

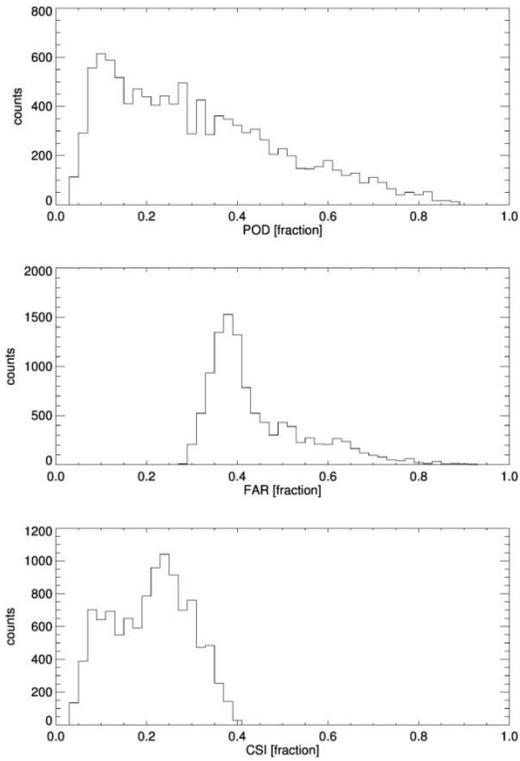
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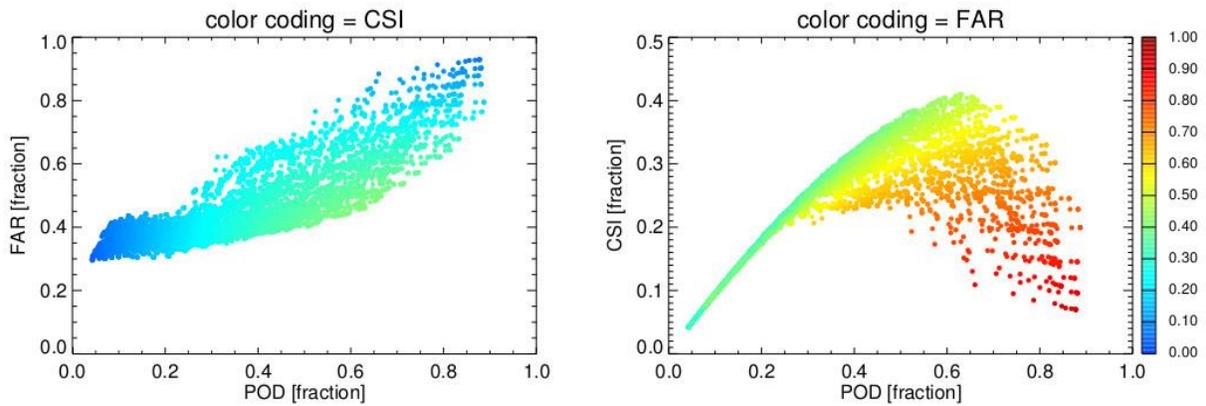
790

791 **Figure 6.** Fraction of DARDAR profiles (table 2) identified by MSG-CPP High IWC. DARDAR
 792 profiles are sampled according to the maximum IWC value within the profile. The insert shows
 793 the same statistic but for different MSG-CPP parameter thresholds used in the MSG-CPP High
 794 IWC mask v1 separately.



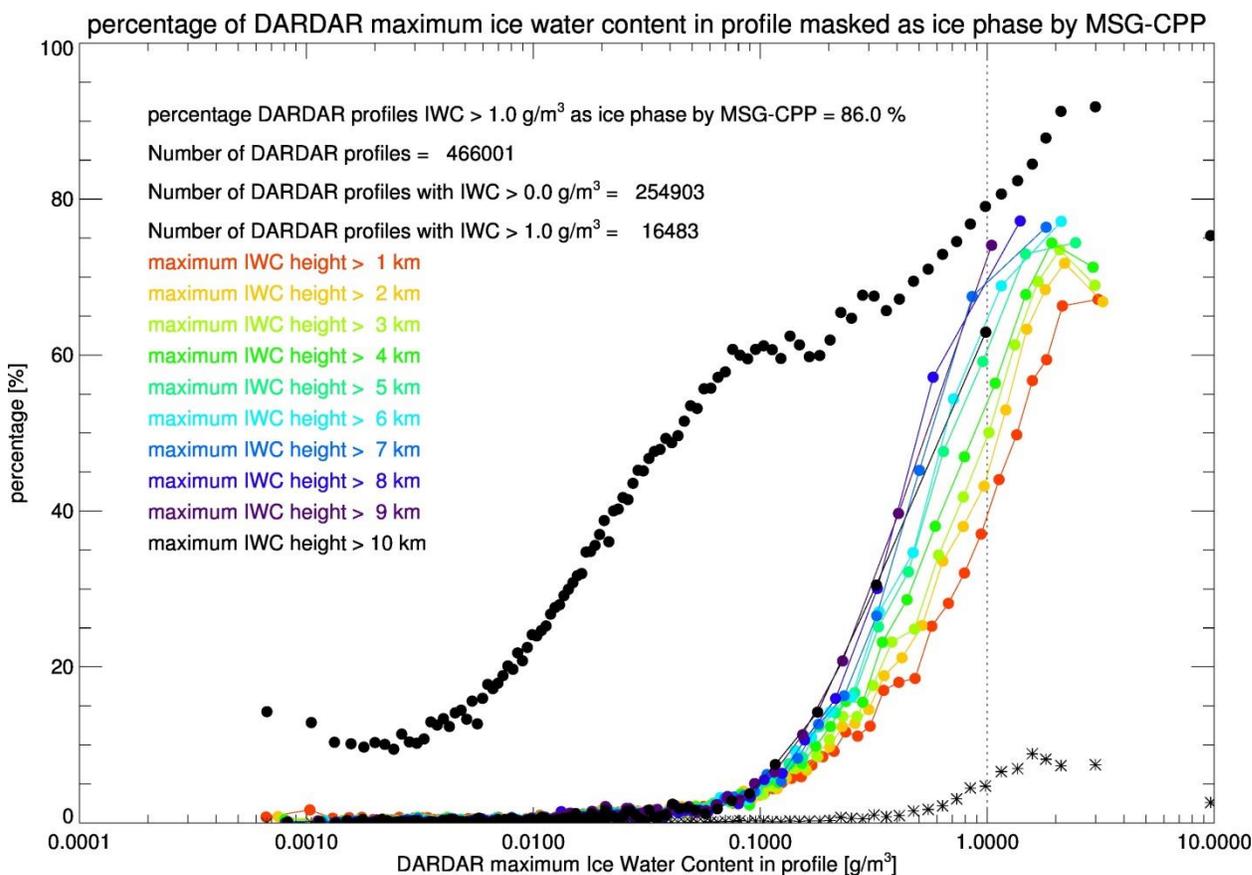
795

796 **Figure 7.** The MSG-CPP parameter threshold settings were varied as follows: $100 < CWP <$
 797 1000 with steps of 100 g/m^2 , $225 < CTT < 275$ with steps of 5 K , $0 < COT < 100$ with steps of
 798 $10 [-]$, and the height of the maximum IWC values in the DARDAR profile varying between 1-9
 799 with steps of 1 km .



800

801 **Figure 8.** False Acceptance Rate (FAR) and Critical Success Index (CSI) as function of the
 802 Probability Of Detection for different definitions of the MSG-CPP High IWC mask definitions
 803 and their success in detecting High IWC values in DARDAR IWC profile data. The definitions
 804 of POD, FAR and CSI and the range of CPP parameter thresholds which were varied for the
 805 High IWC mask versions can be found in the corresponding paragraph of the paper.



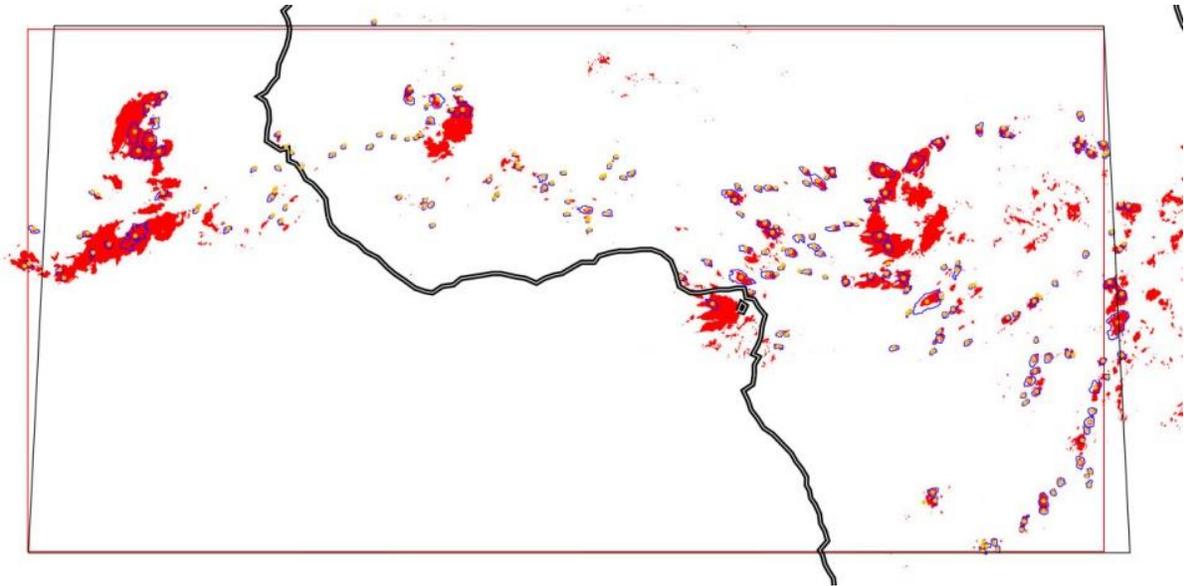
806

807 **Figure 9.** Similar to Figure 6 (asterisks, High IWC mask v1) but for High IWC mask v2.
 808 The black dots indicate the number of MSG-CPP cloud identified as ice given the
 809 maximum IWC within the DARDAR profile. The colored lines indicate the percentage of
 810 MSG-CPP pixels that qualify for the High IWC mask v2 pixels for DARDAR profiles with

811 the height of the maximum IWC above the given altitude. See the main document for a
812 description of the corresponding MSG-CPP parameter thresholds.

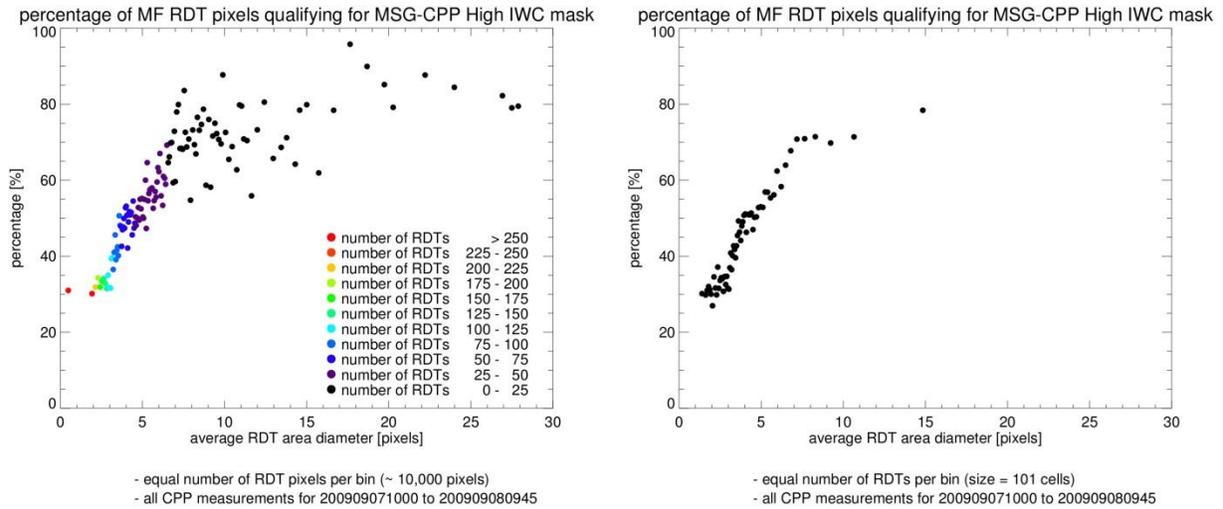
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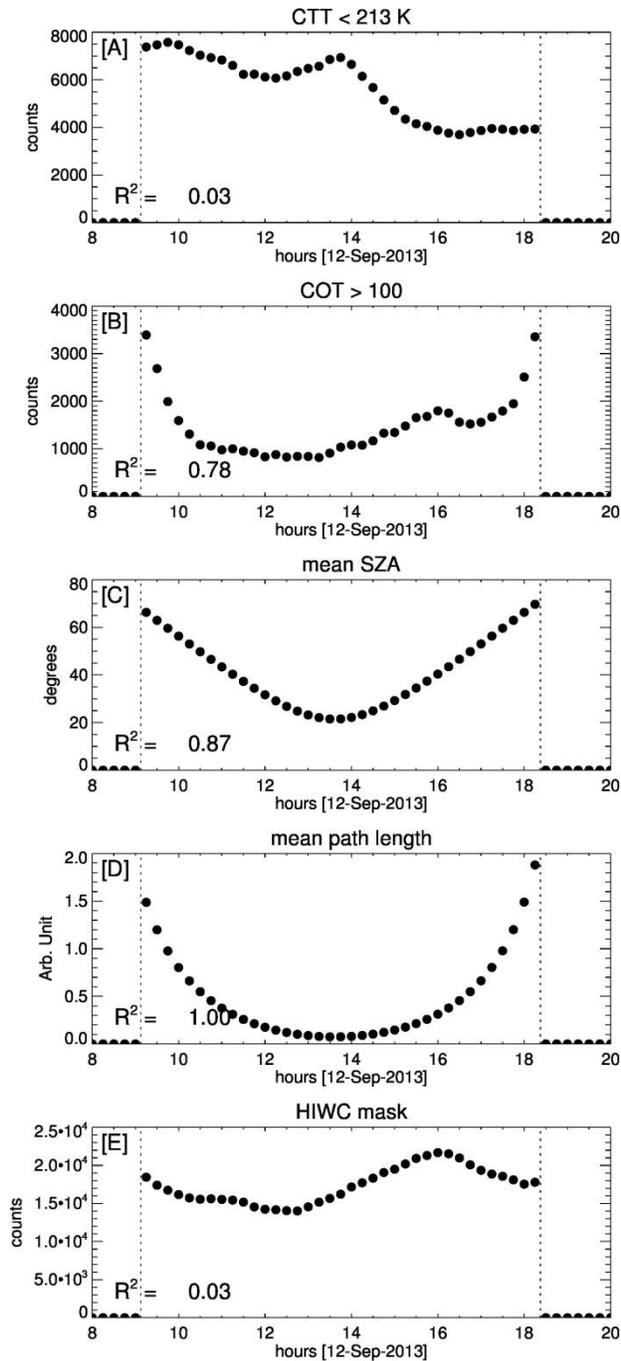
815

816 **Figure 10.** An example of the comparison between RDT areas (blue outlines) and the High IWC
817 mask (red). RDT and the High IWC mask are taken at (7 September 2009 13:15:00 UTC. The
818 orange dots indicate the center of the RDT areas. The black and red boxes are for visualization
819 purposes only.



820

821 **Figure 11.** Correlation between average RDT area (square root of number of pixels with RDT
 822 cell) and fraction of pixels per cell identified by the High IWC mask for AIRBUS event 24. For
 823 the left plot each dot represents approximately of 10,000 RDT pixels, for the right plot each dot
 824 represents an equal number of RDT cells. The color coding in the left plot indicates the number
 825 of RDT cells for each dot. The Figures represent one 24-hour period of RDT and MSG-CPP
 826 measurements on 7 and 8 September 2009.



827

828 **Figure 12.** SEVIRI and MSG-CPP statistics of tropical hurricane Humberto on 12 September
 829 2013. Panel [A] shows the number of SEVIRI pixels with cloud top temperatures < 213K (-
 830 60°C), panel [B] shows the number of SEVIRI pixels with CTO > 100, panel [C] shows the
 831 average SZA for the area, panel [D] shows the mean path length (1/cos(SZA)) of the area and

832 panel [E] shows the number of SEVIRI pixels qualifying for the MSG-CPP High IWC mask.
833 Between the dotted lines are the times when for all SEVIRI pixels within the area MSG-CPP
834 data was available. The correlation coefficients denote the time correlation of the parameter
835 shown within the panel and the mean path length in panel [D], and only for the period between
836 the dotted lines.

837

838 **Supplementary Information.**

839 **S1.1 Analysis of AIRBUS in-service events**

840 As a first step, the cases from the AIRBUS event database were evaluated, which in total covers
841 59 events. Of those events, about half fell outside the SEVIRI disc (29 of 59). Of the remaining
842 30 events, two were suspect, and for 19 events no daytime measurements were available, leaving
843 nine (9) events for which MSG-CPP data was available.

844 A detailed meteorological and data analysis of all 30 events within the SEVIRI disc was then
845 performed. The database contains a brief meteorological analysis of the event, images of all
846 available MSG measurements surrounding the event (± 3 hours) for a $\pm 2^\circ$ area around the event
847 location of brightness temperatures and MSG-CPP parameters (if available). These images serve
848 to identify and characterize the type of convection and convective activity of the event.
849 Furthermore, time series of spatial average brightness temperatures and average MSG-CPP
850 parameters (if available) were provided for ± 3 hours around the event, and averages were
851 calculated for measurements within a radius of 10 km, 25 km, 50 km and 100 km. The purpose
852 for the time series is to identify the stage of the convective activity (developing, mature, aging).

853 Figure S1a shows an example of the MSG-CPP measurements of event 31. This event clearly
854 occurred right over a deep and strong convective event, with widespread iced cloud tops, high
855 CWP values, high COT, high clouds, cold cloud tops and strong precipitation.

856 Figure S1b shows the time series of area average MSG-CPP parameters. Most parameters are
857 fairly constant over the time period and independent of the area of averaging, indicative of
858 mature large scale convection. When looking near the location of this event (radius < 10 km), we

859 do see that both the COT and CWP were increasing near the event, indicating that the convection
860 was still active.

861 The nine events for which MSG-CPP data was available were further evaluated in detail to
862 determine similarities between these nine events. Figure S2 shows a scatter plot of various MSG-
863 CPP parameters falling within a 100 km radius of the event location. Panel (A) shows that the
864 closer the measurements to the event, the higher the CWP. Typically MSG-CPP CWP is larger
865 than 1000 g/m^2 near the events. Panel (B) shows that in general these clouds are cold clouds,
866 with cloud top temperatures below -40°C (233 K), and cloud heights of 8 km or higher. Panel
867 (C) shows that precipitation is directly related to the CWP, as expected [Roebeling et al., 2006;
868 Meirink, 2013]. Precipitation thus is not an independent parameter in the MSG-CPP
869 measurements. Finally, for all cases there the effective radius is $> 10 \text{ }\mu\text{m}$.

870 **S1.2 Construction of a provisional High IWC mask**

871 Based on the analysis presented in the previous section, a first MSG-CPP High IWC mask was
872 constructed. An MSG-CPP pixel is identified as potentially containing high IWC under the five
873 conditions listed in table S2.

874 Figure S3 shows an example of how these criteria subsequently decrease the number of MSG-
875 CPP measurements identified as high IWC events for AIRBUS event 31. Figure S4 shows the
876 last panel of Figure 3 but then for the entire SEVIRI disc. Clearly the High IWC mask strongly
877 reduces the number high IWC events. The strongest reductions in pixels are related to the
878 requirement of cloud phase being ice, the cloud water path $> 1000 \text{ g/m}^2$ and the cloud top height
879 $> 8 \text{ km}$ and cloud top temperature < 225 . Note that the cloud top height and cloud top
880 temperature are locally interchangeable.

881 Finally, Figure S5 shows the High IWC mask as in Figures S3 and S4 for all nine AIRBUS
882 events for which MSG-CPP is available. Unsurprisingly, all nine cases occur in areas identified
883 by the High IWC mask.

884 Although the High IWC mask as defined here identifies potential high IWC events in a way that
885 appears consistent with expectations, the limited number of AIRBUS events on which the High
886 IWC mask is based means that there is room for further refinement, for which an alternative
887 approach is needed as there are currently no other events available for analysis. Within the HAIC
888 consortium it was decided that the ‘next best thing’ was to compare and evaluate the High IWC
889 mask with radar and lidar observations from polar orbiting satellites.

890

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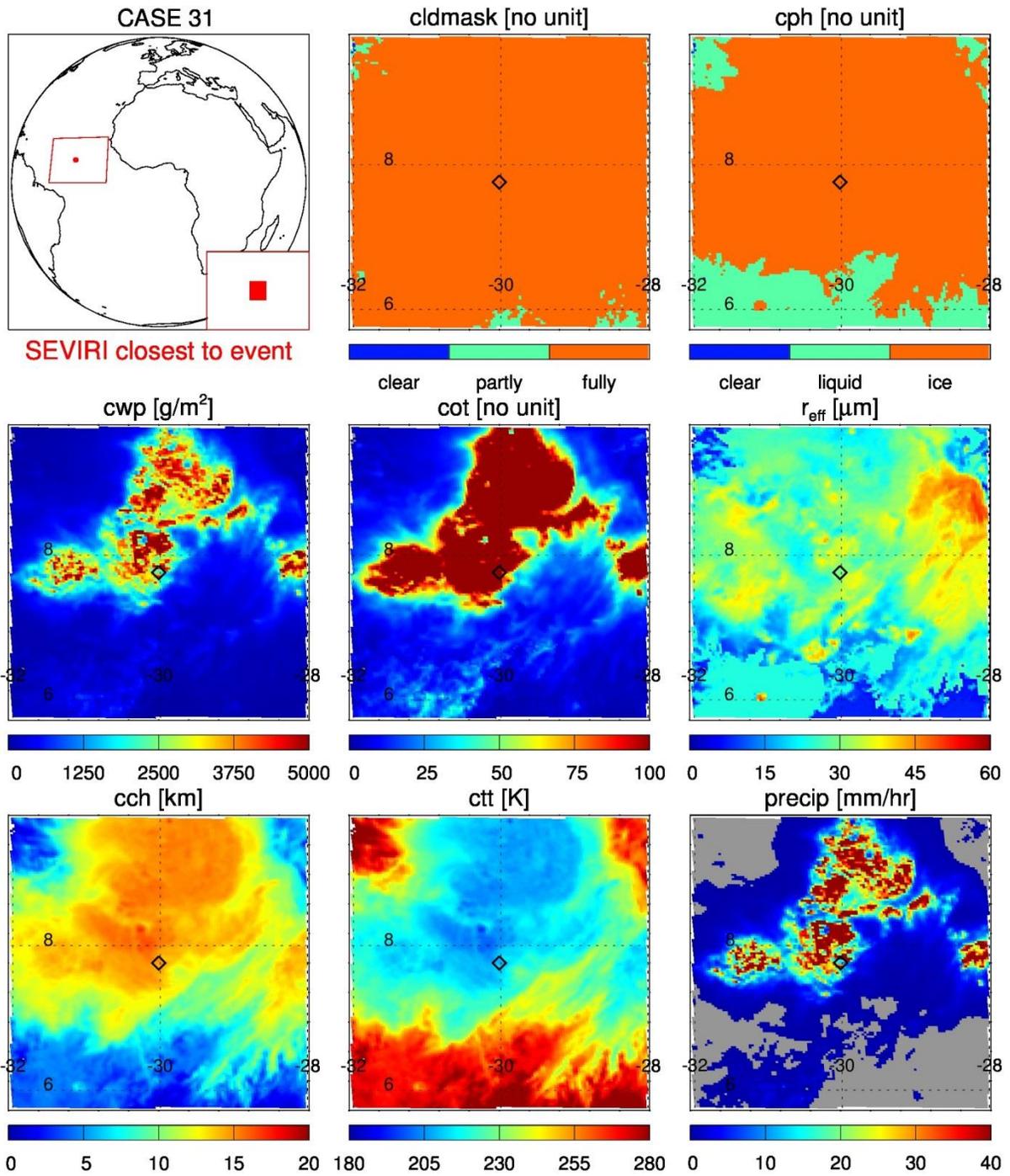
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893

YEAR	MONTH	DAY	HH:MM:SS
2008	01	02	09:18:01
2008	01	02	12:35:48
2008	01	03	13:19:04
2008	01	03	14:57:57
2008	01	03	16:36:50
2008	01	04	12:23:27
2008	01	05	16:24:30
2008	02	02	13:31:39
2008	02	02	16:49:25
2008	02	04	11:40:25
2008	02	05	10:44:47
2008	02	05	15:41:26
2008	03	02	13:00:45
2008	03	02	16:18:31
2008	04	01	09:55:30
2008	04	03	14:39:50
2008	04	03	16:18:43
2008	05	01	11:47:09
2008	05	02	14:09:18
2008	05	03	16:31:27
2008	05	04	13:56:57
2008	06	11	16:37:42
2008	09	02	15:31:07
2008	09	02	17:10:00
2008	10	04	10:34:40
2008	10	04	15:31:19
2008	10	04	17:10:12
2008	11	02	11:43:07
2008	12	01	11:12:50
2008	12	01	14:30:37
2008	12	03	12:39:24

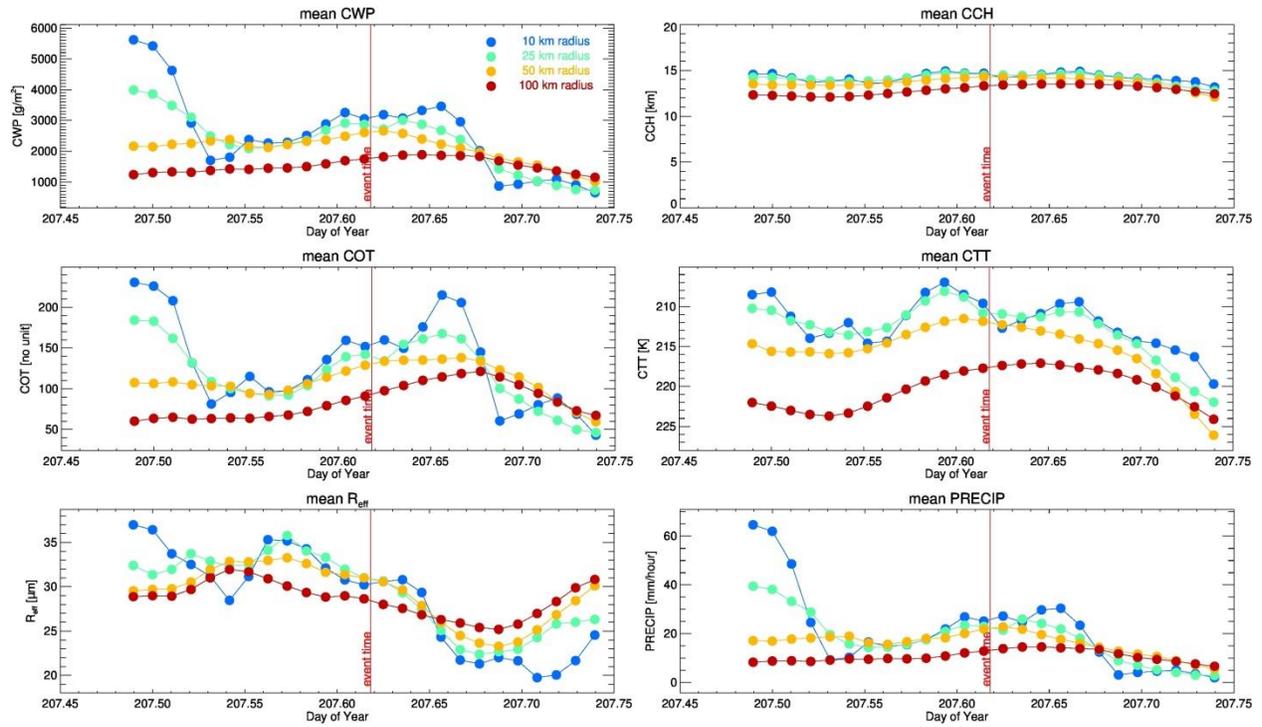
894

895 **Table S1.** Dates of equator crossing time of DARDAR orbits used for detection of High IWC
896 events in MSG-CPP.



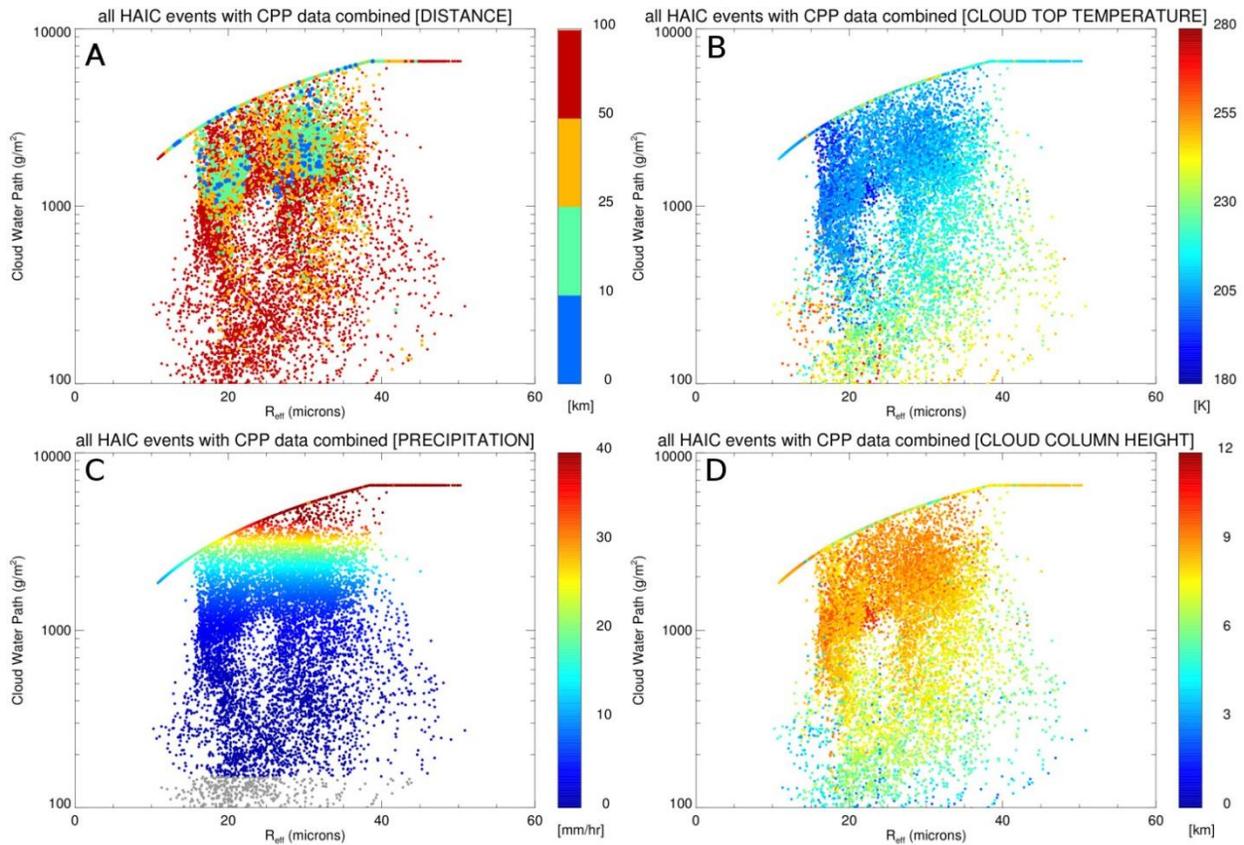
897

898 **Figure S1a.** Nearest MSG-CPP measurements for AIRBUS event 31. CWP = Cloud Water
 899 Path, COT = Cloud Optical Thickness, r_{eff} = effective radius, CCH = Cloud Column Height,
 900 CTT = Clout Top Temperature, precip = precipitation.



901

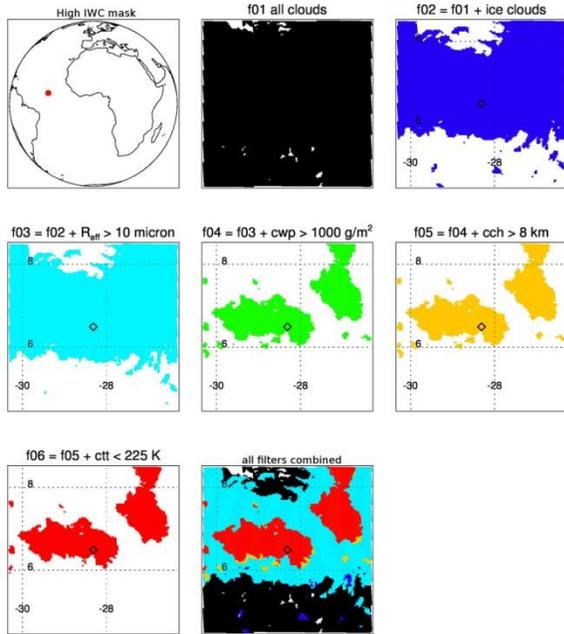
902 **Figure S1b.** Time series of area average MSG-CPP parameters for AIRBUS event 31 for the
 903 period ± 3 hours around the event and the areas with radii of < 10 km, < 25 km, < 50 km and $<$
 904 100 km.



905

906 **Figure S2.** Scatterplots of MSG-CPP parameters for the nine AIRBUS events for which MSG-
 907 CPP data is available. Only the MSG-CPP measurements closest to the event were taken. All
 908 panels show the CWP (g/m^2) as function of the effective radius (μm). The color coding indicates
 909 a third parameters: (A) radius within which MSG-CPP measurements were taken (km; distance
 910 to event location), (B) cloud top temperature (K), (C) precipitation (mm/hr) and (D) cloud
 911 column height (km). The upper line denotes a theoretical limit to the MSG-CPP relation between
 912 CWP and the effective radius.

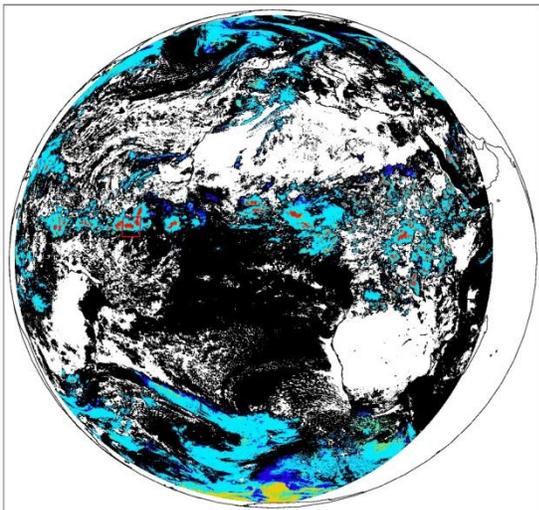
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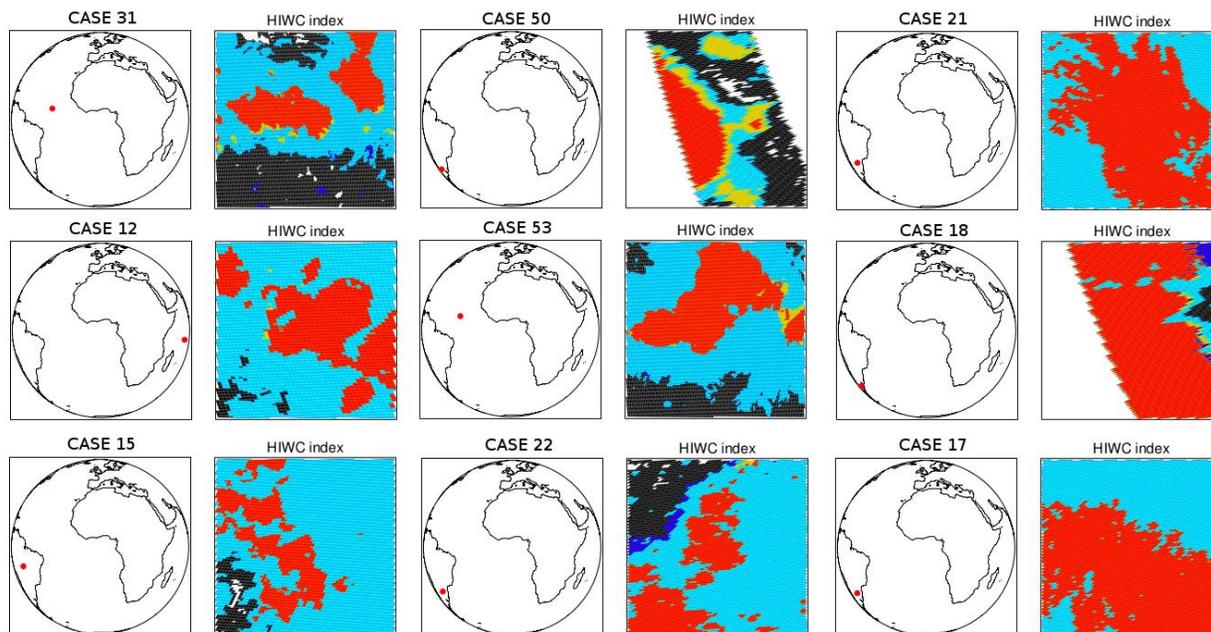
915 **Figure S3.** Filters applied for the of High IWC mask for AIRBUS event 31. Each panel indicates
 916 the filter applied as in the title compared to the previous panel. The first panel shows the region
 917 of interest, the last panel shows how each pixel is characterized.

- all cloud pixels
- + ice clouds
- + cloud particle effective radius > 10 micron
- + cloud water path > 1000 g/m²
- + cloud column > 8 km
- + cloud top temperature < 225 K



918

919 **Figure S4.** As the last panel of Figure S3 but for the entire SEVIRI disc.



920

921 **Figure S5.** As Figure S3, first and last panels, but for all nine AIRBUS events for which MSG-
922 CPP data is available (see table S1). Color coding as in Figures S3 and S4.

923

924