

A characterization of thermal structure and conditions for overshooting of tropical and extratropical cyclones with GPS radio occultation

R. Biondi¹, A. K. Steiner¹, G. Kirchengast^{1,2} and T. Rieckh¹

¹Wegener Center for Climate and Global Change (WEGC), University of Graz, Graz, Austria

²Institute for Geophysics, Astrophysics, and Meteorology/Inst. of Physics, University of Graz, Graz, Austria

Correspondence to: R. Biondi (riccardo.biondi@uni-graz.at)

Abstract

The thermal structure of Tropical Cyclones (TCs) in different ocean basins is studied using Global Positioning System (GPS) Radio Occultation (RO) measurements co-located with TCs' best tracks. The objective of this work is to understand the mutual influence of TCs and atmospheric parameters in different regions. We selected more than 20000 GPS RO profiles co-located with TCs in a time window of 6 hours and space window of 600 km from the TC center in the period 2001–2012 and classified them by intensity of the cyclone and by ocean basin. The results show that tropical cyclones have different characteristics depending on the basin, which affects the cloud top altitude and the TC thermal structure which usually shows a negative temperature anomaly near the cloud top altitude. In the northern hemisphere ocean basins, the temperature anomaly becomes positive above the cloud top while in the southern hemisphere ocean basins it stays negative up to about 25 km of altitude.

Furthermore, in the southern hemisphere the storms reach higher cloud top altitudes than in the northern hemisphere ocean basins, indicating that possible overshootings overpass the climatological tropopause more deeply at extratropical latitudes. The comparison of the TC thermal structure with the respective monthly mean tropopause altitude allows a detailed analysis of the probability for possible overshooting. While the co-locations between GPS ROs and TC tracks are well distributed in all the ocean basins, conditions for possible overshootings are found to be more frequent in the southern hemisphere basins and in the North Indian ocean basin. However, the number of possible overshootings for high intensity storms (i.e. TC categories 1-5) is highest in the West Pacific ocean basin.

1 Introduction

Tropical cyclones are destructive events causing every year many deaths, injuries and damage to human property and landscape. They are the natural catastrophes accounting for the major economic losses in several countries including the US (Pielke et al., 2003; Emanuel,

39 2005). So far studies on tropical cyclones are not able to detect clearly trends in the frequency
40 and intensity of these phenomena nor to understand what impact climate change could have
41 on them (Landsea et al., 2006; Emanuel et al., 2008; Emanuel, 2013; Kunkel et al., 2013).
42 However it is predicted that major economic losses due to tropical cyclones may be doubled
43 in the future (Mendelsohn et al., 2013).

44 TCs hit whatever they find on their way without distinction of poor or rich countries.
45 Recently the landfall of hurricane Sandy was considered one of the most destructive events in
46 US east coast history (Halverson et al., 2013) while typhoon Haiyan created a devastating
47 tragedy in the Philippines (Chiu, 2013).

48 We are nowadays able to predict the track of TCs (100–200 km error) with good
49 accuracy within 12 to 24 hours (Goerss, 2000; Chandan et al., 2012), but we are still far from
50 forecasting the intensity of the storm (Emanuel, 1999; De Maria et al., 2005; Lin et al., 2013)
51 and understanding its development (Montgomery et al., 2012).

52 Satellite measurements have drastically improved the TC forecast (e.g., Dvorak, 1975)
53 and monitoring accuracy (Brueske and Velden, 2003; Demuth et al., 2004; Velden et al.,
54 2006) by using different remote sensing instruments on meteorological and research satellites.
55 Further progress was made in the last decade by the Global Positioning Systems (GPS) Radio
56 Occultation (RO) technique (e.g., Huang et al., 2005).

57 Wong and Emanuel (2007), Luo et al. (2008) and Vergados et al. (2013) demonstrated
58 that there is a connection between the cloud top height and cloud top temperature with the
59 intensity of the storm. Biondi et al. (2012; 2013) showed a correlation between the cloud top
60 altitude and the storm's thermal structure. The knowledge of the thermal structure gives
61 important information on the cloud top height and this entails a better understanding of
62 atmospheric circulation and troposphere-stratosphere transport, which are still poorly
63 understood (Danielsen, 1993; Folkins and Martin, 2005).

64 The measurement of atmospheric parameters (such as temperature) with high vertical
65 resolution and accuracy at the tropopause level is difficult especially during severe weather
66 events (e.g TCs). Polar-orbiting satellites in low-Earth orbit do not provide suitable temporal
67 and spatial (vertical and horizontal) resolution to study mesoscale weather phenomena.
68 Geostationary satellites have excellent horizontal and temporal resolution for this purpose, but
69 lack precise vertical discrimination, and offer little information about the tropical or
70 subtropical tropopause. Ground-based measurements are too sparse and often not reliable in
71 the Upper Troposphere and Lower Stratosphere (UTLS).

72 Many studies have been conducted to determine the altitude of the storm cloud top
73 height using satellite instruments and different techniques (Knibbe et al., 2000; Koelemeijer et
74 al, 2002; Poole et al., 2002; Platnik et al., 2003; Minnis et al., 2008; Chang et al., 2010;
75 Biondi et al., 2013), but the results depend strongly on the physical retrieval method and on
76 the satellite data used (Sherwood et al., 2004), with errors ranging from about 400 m (Biondi
77 et al., 2013) for a selected number of cases to 3 km (Chang et al., 2010). Some other studies
78 have analyzed the UTLS during TCs using limb sounding measurements such as AIRS and
79 MLS with a vertical resolution of 2 km to 3 km (Ray and Rosenlof, 2007).

80 The GPS RO technique (Kursinski et al., 1997; Anthes, 2011; Steiner et al., 2011)
81 allows for the estimation of atmospheric temperature in remote areas and during extreme
82 weather events with global coverage and high vertical resolution and accuracy (Steiner et al.,
83 2013), avoiding temperature smoothing issues in the UTLS (given by microwave and infrared
84 radiometers) and improving the poor temporal and spatial coverage given by satellite lidars,
85 radars, and balloon soundings.

86 The objective of this study is to analyze the thermal structure of TCs by using RO
87 measurements for different storm intensities and different ocean basins where TCs develops.
88 We aim to show that the RO measurements are well suited for studying severe storms and for
89 evaluating the storms' contribution to the atmospheric circulation (Pommereau and Held,
90 2007; Corti et al., 2008; Romps and Kuang, 2009).

91 In section 2 we describe the datasets used, in section 3 we give a description of the
92 methodology, and in section 4 we describe the results obtained analyzing all the RO profiles
93 co-located with TCs. In the final section, we report the conclusions highlighting the possible
94 future developments and applications.

95 96 **2 Data description**

97 98 **2.1 Tropical cyclones best tracks**

99
100 We have downloaded the TCs best tracks from the International Best Track Archive
101 for Climate Stewardship (IBTrACS, <http://www.ncdc.noaa.gov/ibtracs/>) (Knapp et al., 2010)
102 in netCDF format. IBTrACS is a complete archive containing information about TCs all
103 around the world combining the data acquired by several agencies responsible for different
104 ocean basins. For all the TCs the most important characteristics are reported, including: TC
105 name, date and time of acquisition (every 3 or 6 hours depending on the agency), latitude and

106 longitude of the TC center, source (agency data provider), wind speed (averaged over 1 min
107 or 10 min depending on the agency) and pressure.

108

109 **2.2 GPS radio occultation temperature**

110

111 We have used the GPS RO products level 2 (L2) (including refractivity, temperature
112 and pressure) processed by the Wegener Center for Climate and Global Change (WEGC)
113 through the new Occultation Processing System (OPS) version 5.6 based on University
114 Corporation for Atmospheric Research (UCAR) version 2010.2640 orbit and excess phase
115 data (Schwaerz et al., 2013). The WEGC OPSv5.6 is based on a geometrics optics retrieval
116 combined with a wave optics retrieval in the lower and middle troposphere. A bending angle
117 optimization is performed at high altitudes with co-located short-range forecast profiles of the
118 European Centre for Medium-Range Weather Forecasts (ECMWF).

119 The vertical resolution ranges from about 100 m in the lower troposphere to about 1
120 km in the stratosphere (Gorbunov et al., 2004; Kursinski et al., 1997). The horizontal
121 resolution is about 1.5 km across-ray and ranges from about 60 km to about 300 km along-ray
122 (Melbourne et al., 1994; Kursinski et al., 1997).

123 Physical temperature is retrieved based on an optimal estimation retrieval with co-
124 located ECMWF short-term forecast profiles as background data (the latter contribute relevant
125 information in the middle and lower troposphere). For the present study of TCs we use the
126 OPSv5.6 physical temperature profiles.

127 From this OPSv5.6 archive we use data from the following missions: the Satélite de
128 Aplicaciones Científicas C (SAC-C) from 2001 to 2011 (Hajj et al., 2004), the CHALLENGING
129 Minisatellite Payload (CHAMP) from 2001 to 2008 (Wickert et al., 2001), the Gravity
130 Recovery And Climate Experiment A (GRACE-A) from 2007 to 2012 (Beyerle et al., 2005),
131 the Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)
132 from 2006 to 2012 (Anthes et al., 2008). In order to have available a suitable mean reference
133 field against which anomalies can be defined, we have created a GPS RO temperature
134 reference climatology averaging all the GPS RO profiles collected in the period 2001 to 2012
135 from the different missions to monthly means for a $5^{\circ} \times 5^{\circ}$ horizontal resolution. The
136 climatology is finally provided at a vertical sampling grid of 100 m and at a horizontal grid
137 sampled at $1^{\circ} \times 1^{\circ}$ in longitude and latitude and it will be denoted in the following sections as
138 T_{clim} .

139

140 **3 Methods**

141

142 **3.1 Tropopause altitudes**

143 Tropopause altitudes were computed from individual RO temperature profiles
144 (Rieckh et al., 2014), using the lapse rate definition of the World Meteorological
145 Organization (WMO, 1957). This definition allows for finding multiple tropopauses, which
146 was a requirement for this study. The WMO states that:

- 147 1. “The first tropopause is defined as the lowest level at which the lapse rate decreases
148 to $2^{\circ} \text{C km}^{-1}$ or less, provided also the average lapse rate between this level and all
149 higher levels within 2 km does not exceed $2^{\circ} \text{C km}^{-1}$.”
- 150 2. “If above the first tropopause the average lapse rate between any level and all higher
151 levels within 1 km exceeds $3^{\circ} \text{C km}^{-1}$, then a second tropopause is defined by the
152 same criterion as under (1). This tropopause may be within or above the 1 km
153 layer.”

154 An example of tropopause altitudes as a function of latitude is shown in Fig. 1 with about
155 60000 cases in January 2007 (a) and in July 2007 (b): the tropopause has a seasonal
156 variability with higher altitudes during the northern hemisphere winter (Rieckh et al., 2014).

157 We finally computed monthly mean tropopause altitudes based on the individual
158 tropopause altitudes for each month and for zonal means of 10 degree width in latitude. Cloud
159 top altitudes were then compared to mean tropopause altitudes (plus/minus standard
160 deviation) for the detection of possible overshootings into the stratosphere.

161

162 **3.2 Tropical cyclone cloud top height**

163 The mean GPS RO latitude and longitude tangent points were co-located with the TCs
164 center coordinates in a time window of 6 hours and a space window of 600 km (Tab. 1),
165 leading to more than 20000 collocation cases. The RO profiles were also sub-selected, for
166 checking the sensitivity to selection criteria, in a shorter time window (of 3 hrs and 1 hr) and
167 in a smaller space window of 300 km. The results were found consistent with the larger
168 dataset (6 hours and 600 km), which we finally used in this study, allowing for a larger
169 number of samples for more robust statistics.

170 We investigated different ocean basins as shown in Fig. 2: North Atlantic (NA), East
171 Pacific (EP), West Pacific (WP), South Pacific (SP), North Indian ocean (NI) and South

172 Indian ocean (SI). For any ocean basin the profiles were classified (Tab. 2) using a common
173 storm intensity scale (Tropical Depression, Tropical Storm, TC categories 1-5) given by the
174 Saffir-Simpson Hurricane wind scale.

175 Due to the large dimensions of a TC and its relatively slow horizontal movement, it is
176 possible that the same RO profile is selected more than once with different temporal and
177 spatial distances from the TC center. In these cases we have included only the co-located RO
178 profile with the shortest delay.

179 For any ocean basin and for each storm category we have sampled the RO profiles
180 around the storm center as shown in Fig. 3, where we show the distribution of GPS RO
181 profiles within 6 h and 3 h around the center of tropical storms in the North Atlantic ocean
182 basin. In Fig. 4 we show the distribution of the same profiles along the real tracks in latitude
183 and longitude.

184 For each ocean basin and each storm category we computed the temperature anomaly
185 (T_{anomaly}) of any single RO profile comparing the temperature during the storm (T_{storm}) with
186 the local monthly mean climatology (T_{clim}) as defined in section 2.2 (i.e. in the respective 1°
187 $\times 1^\circ$ bin):

$$188 \quad T_{\text{anomaly}} = T_{\text{storm}} - T_{\text{clim}} \quad (1)$$

190
191 We finally averaged all the profiles in the same ocean basin for each storm category to
192 be able to compare the thermal structure characterizing the basin itself.

193 In all the ocean basins the TCs often move from the tropics to extra-tropical areas
194 (especially in the North Atlantic and the West Pacific). We categorized the profiles as
195 “tropical” between 20°S and 20°N and as “extra-tropical” beyond 20° latitude as shown in
196 Tab. 2, for highlighting the different thermal structures with the variation of latitude.

197 For monitoring possible overshooting conditions during a storm we computed the
198 height of the lowest anomaly minimum (H_{coldest}) between 10 and 22 km of altitude for each
199 T_{anomaly} profile (Biondi et al. 2013), the monthly mean tropopause altitude ($H_{\text{mm_trop}}$) of the
200 respective month and area (section 3.1), and the corresponding standard deviation of the
201 monthly mean tropopause altitude ($H_{\text{mstd_trop}}$). We used the multi-annual standard deviation
202 estimate for each month of the year here (e.g., October 2001 to 2012 data for October;
203 sensitivity testing showed that using standard deviation estimates for individual months leads
204 to essentially the same results).

205 For robustness, we used two different references for detecting the possible
206 overshooting conditions:

207

$$208 \quad H_{\text{coldest}} > H_{\text{mm_trop}} + H_{\text{mstd_trop}} \quad (2)$$

$$209 \quad H_{\text{coldest}} > H_{\text{mm_trop}} + H_{\text{mstd_trop}} + 1.0 \text{ km} \quad (3)$$

210

211 where 1.0 km is the uncertainty for TC cloud top altitude detection using GPS RO as
212 estimated by Biondi et al. (2013) from analysis with co-located lidar data. The uncertainty
213 occurs mainly due to the finite resolution of RO data (see section 2.2), and also due to co-
214 location uncertainty, whereas the RO geopotential height and hence altitude allocation error is
215 only about 10 m in the troposphere and around the tropopause within the 50°S and 50°N
216 latitude band of interest here (Scherllin-Pirscher et al., 2011). If H_{coldest} satisfies Eq. (2) it is
217 considered to be indicative of possible overshooting when the lowest anomaly minimum (the
218 cloud top) overpasses the tropopause monthly mean altitude plus its standard deviation. Eq.
219 (3) defines an even more robust condition where H_{coldest} is considered to be indicative of
220 possible overshooting when the lowest anomaly minimum (the cloud top) overpasses the
221 tropopause monthly mean altitude plus its standard deviation plus the 1 km uncertainty
222 margin.

223 We have used these two different thresholds, one less and one more conservative, for
224 detecting the possible overshooting because there is still a large uncertainty in the
225 atmospheric physics community in the overshooting detection. Equation (2) should be already
226 accurate enough due to the temperature accuracy of GPS RO, but with Eq. (3) we want to take
227 into account also the uncertainty of the technique used for detecting the TC cloud top altitude
228 (Biondi et al., 2013). Since there is not enough independent reference data available for
229 validating the results at this point, we report both results and do not advocate a more exact
230 definition based on our current knowledge.

231

232 **4 Results**

233

234 **4.1 Thermal structure**

235

236 The temperature anomaly during tropical cyclones usually shows a tropospheric
237 warming and a sharp inversion just below the cloud top with a cooling corresponding to the
238 cloud top altitude (Biondi et al., 2012; Biondi et al., 2013). With reference to these results, we
239 assume that the storm cloud top altitude corresponds to H_{coldest} . However, we note possible

240 uncertainties regarding the cooling signature which may also be due to the presence of large-
241 scale dynamical response to latent heating below the cold anomaly (Randel et al., 2003;
242 Holloway and Neelin, 2007) or to gravity waves originated by the TC (Tsuda et al., 2000;
243 Kiladis et al., 2001; Kim and Alexander, 2015).

244 As shown in Fig. 5, this behaviour is in general similar for TCs in the tropical and
245 extra-tropical areas, but in the extra-tropical area the amplitudes of tropospheric warming and
246 cloud top cooling are amplified. In Fig. 5 we show as example the 84 RO profiles (69 extra-
247 tropical and 15 tropical) of a TC category 2 in the North Atlantic basin. The temperature
248 anomaly profiles at the storm's location are computed relative to the monthly mean
249 temperature climatology (2001 to 2012) for the respective location ($1^\circ \times 1^\circ$ bin). The same
250 feature is evident in all the other ocean basins for all the categories (not shown). The mean
251 temperature anomaly for tropical profiles (yellow line) reaches a maximum of about 2.5 K at
252 about 10 km of altitude and a minimum of about -2.5 K near 16 km of altitude. The mean
253 temperature anomaly for extra-tropical profiles (light blue line) shows the same features but
254 more pronounced with a maximum of about 6 K and a minimum of about -4 K.

255 Figure 6 shows mean temperature anomaly profiles for the West Pacific Ocean basin
256 and the South Pacific Ocean basin, respectively, for all storm categories as representative of
257 the two hemispheres. Overall during a TC, the troposphere is warmer than the climatological
258 mean and the cloud top is colder. In the northern hemisphere above the altitude H_{coldest} there is
259 a warming in the stratosphere, which is not well present in the southern hemisphere.

260 Figure 7 gives an overview of the minimum temperature anomaly versus altitude of
261 the coldest point for all ocean basins and storm categories. Tropical Depressions (TDs) and
262 Tropical Storms (TSs) usually reach the coldest point at lower altitudes (4 basins out of 6) and
263 the TCs in categories 4 and 5 reach the coldest point at higher altitudes. No relevant
264 differences can be highlighted for the storm categories 1, 2 and 3. The coldest anomalies are
265 found in the South Pacific for all storm categories: between -8 K and -6 K for TCs, between
266 -6 K and -5 K for TSs and about -4 K for TDs. For this area, the H_{coldest} also is at higher
267 altitudes (between 17.4 km and 17.9 km) than in any other basin (Tab. 2). Temperature
268 anomalies over the South Indian ocean are also usually colder than in the other ocean basins
269 (except South Pacific), with higher H_{coldest} . In the southern hemisphere the storms reach
270 higher altitudes than in the northern (Tab. 2) and they also have colder cloud tops.
271 Another feature characteristic of storms is the double tropopause (Danielsen, 1993; Corti et
272 al., 2008; Biondi et al., 2012; Biondi et al. 2013; Davis et al., 2014), which is visible in Fig.
273 6b for TC category 5 (dotted lines). This is also apparent for all the TC categories in the

274 Northern Indian ocean basin (not shown), since the small number of cases does not smooth
275 the double variation such as it happens for the other ocean basins and categories.

276

277 **4.2 Tropopause uplift and possible overshooting**

278

279 The overshooting due to convective systems and TCs is an important topic for
280 understanding the atmospheric circulation and the climate changes (Pommereau and Held,
281 2007; Romps and Kuang, 2009), but it is still debated due to the difficulties of measuring
282 atmospheric parameters during severe events. Using the definition of possible overshooting
283 conditions given by Eq. (2) and Eq. (3) we compared any single anomaly temperature profile
284 with the corresponding zonal monthly mean tropopause altitude, computed for latitude bands
285 with 10 degree width, obtaining the results reported in Tab. 3 and 4. Tab. 3 reports the details
286 for each ocean basin and each storm category distinguishing between events in the tropical or
287 extra-tropical area. Tab. 4 gives a summary.

288 As already described in section 3.2 and following the findings of Biondi et al. (2012
289 and 2013), we assume that the lowest temperature anomaly minimum corresponds to the TC
290 cloud top altitude and the cyclone's strong convection causes the local tropopause uplift.
291 According to this theory the TC creates a double tropopause where the primary tropopause is
292 due to the presence of the TC's cloud top and the secondary tropopause is the former
293 tropopause which is pushed up by the convection (Biondi et al., 2012; Biondi et al., 2013).

294 In Tab. 3 it is evident that the number of possible overshootings obtained by using Eq.
295 (3) is much lower (about one third) than the number obtained by using Eq. (2), as should be
296 expected from the former threshold criterion being more conservative. However, the
297 distribution of the possible overshootings over the ocean basins is the same (not shown), but
298 with a reduced number of cases from Eq. (3), so the same considerations done hereafter for
299 Tab. 3 and Fig. 8 are also valid for possible overshootings computed with Eq. (3).

300 Figure 8 shows the distribution map of co-locations between GPS RO and TC tracks
301 for different intensities. Figure 9 shows the distribution map of possible overshootings
302 detected using Eq. (2). The area with the highest overshooting probability from strong
303 cyclones is found to be the Western Pacific ocean. Our results are consistent with the
304 overshooting patterns reported by Romps and Kuang (2009) with only a small difference in
305 the East Pacific ocean basin where we do not see too many overshooting conditions. The
306 comparison between Fig. 8 and Fig. 9 highlights the presence of strong cyclones in all ocean
307 basins including the North Atlantic and East Pacific ocean basins, but the occurrence of

308 possible overshootings is much lower in these basins than in the West Pacific and South
309 Indian ocean basins.

310 The results show that in general conditions for possible overshootings into the
311 stratosphere are found more often in the tropics (26.8%) than in the extra-tropics (13.5%). In
312 the southern hemisphere, possible overshootings are more frequent (38.9% of tropical cases
313 and 25% of extra-tropical cases) than in the northern hemisphere (20.2% of tropical cases and
314 9.9% of extra-tropical cases). The possible overshootings mostly come from tropical cases
315 with high intensity storms. The lowest percentage of possible overshooting conditions is
316 detected in the Eastern Pacific ocean area (6.3% for tropical cases and just 6.6% of extra-
317 tropical cases). The highest percentage is detected in the Southern Pacific area with 40.9% of
318 tropical cases and 48.4% of extra-tropical cases. It is also high in the Indian ocean with 34.5%
319 and 38.3% in the northern and southern tropics, respectively, and 46.6% and 40.1% in the
320 northern and southern extratropics, respectively (in this case the number of co-locations is
321 very small). We do not give any detail on the statistics by intensity, since the number of cases
322 for higher intensities (i.e. categories 3 to 5) is too small.

323 The monthly mean tropopause altitudes in the tropics between 20° S and 20° N ranges
324 between 16 km and 17.5 km altitude depending on the season. In the extra-tropics between
325 20° and 30° latitude it is about 1 km lower, and exhibits higher variability. Between 30° and
326 40° latitude, the tropopause altitude ranges from 11 km to 15 km (Fig. 1).

327 Figure 10 shows the difference between the cloud top altitude and the corresponding
328 monthly mean tropopause (also reported in Tab. 3). The highest percentage of cases with
329 differences larger than 3 km is detected for extra-tropical cases in the South Indian ocean
330 basin. In general, in the North Atlantic and East Pacific ocean basins the cloud top altitudes
331 do not overpass the tropopause by more than a few hundred meters (green dots in Fig. 10).

332 Figure 11 shows, in a statistical summary view, an example of possible overshooting
333 detection results in the Western Pacific ocean basin for TSs at different latitudes (0°-20°; 20°-
334 30°; 30°-40°), as reported in Tab. 3. The magenta stars into the shaded area, according to Eq.
335 (2) and Eq. (3), denote the storm cloud top altitudes not overshooting into the stratosphere, the
336 magenta stars into the white area are accounted as possible overshooting according to Eq. (2),
337 and the green stars are accounted as possible overshooting according to Eq. (3). The
338 distribution over the year shows that storms occur from April to December over the Western
339 Pacific at 0°N to 20°N and mainly from July to October at 20°N to 40°N. Overshootings are
340 found in each investigated latitude zone when storms occur. Hardly any overshootings are
341 found from July to September in the Tropics (0° to 20°N).

342

343 **5 Conclusions**

344

345 The thermal structure of TCs in different ocean basins and the conditions for possible
346 overshooting of cloud tops into the stratosphere, were investigated based on GPS RO
347 measurements. The results indicate that the effects of TCs on the UTLS should be studied in
348 connection to the ocean basin where they develop, since their thermal structure is clearly
349 connected to the basin. In particular, basins in the northern and southern hemisphere show a
350 different thermal structure:

351 In the southern hemisphere, storms reach higher altitudes and the cloud top is colder
352 than in the northern hemisphere. The temperature anomaly above the cloud top becomes
353 positive in northern hemisphere ocean basins while it stays negative up to about 25 km of
354 altitude in the southern hemisphere ocean basins. The reason of this warming above the storm
355 cloud top in the northern hemisphere is not clear yet and is a topic of further investigations.

356 A double tropopause characterizes a storm (Biondi et al., 2012; Biondi et al., 2013),
357 which is evident in all the ocean basins for all storm intensities (not shown) and can be
358 definitely defined as a feature reflecting the high-altitude convection dynamics. Comparisons
359 between the monthly mean tropopause altitude and the storm cloud top altitude indicate a
360 significant fraction of possible overshootings. Results show that the possible overshootings
361 will overpass the climatological tropopause more deeply at extra-tropical latitudes (Tab. 3),
362 where the tropopause is lower, but there is no clear tendency connected to specific basins.

363 While the co-locations between GPS ROs and TC tracks for all the intensities are well
364 distributed in all the ocean basins, conditions for overshooting occur more frequently in the
365 southern hemisphere and in the North Indian ocean basin. However, the number of possible
366 overshootings for high intensities (i.e., TC categories 1 to 5) is higher in the West Pacific
367 ocean basin. In this area, conditions for overshooting are found for a percentage of 30% to
368 50% of the cyclones, especially within tropical latitudes.

369 We have demonstrated that the GPS RO technique is very well suited for monitoring
370 and understanding the TCs thermal structure and its contribution to the atmospheric
371 circulation through possible overshootings into the stratosphere. With the actual RO missions
372 we are not able to fully monitor all TCs with high temporal resolution. Currently the number
373 of RO profiles is decreasing due to the degradation of Formosat-3/COSMIC. In the near
374 future several new missions are planned (e.g., COSMIC-2, MetOp-C, PAZ and GEROS), and
375 with the support of new Global Navigation Satellite System (GNSS) constellations (e.g., the

376 European Galileo) and the availability of the Russian Global'naya Navigatsionnaya
377 Sputnikovaya Sistema (GLONASS) we may be able to adequately monitor all TCs.

378 To date the number of GPS ROs is about 2500 per day, but with the new mission
379 COSMIC-2, for example, the coverage will increase to more than 10000 per day and the
380 density of profiles in the tropics will be higher due to a lower inclination of six of the twelve
381 planned COSMIC-2 satellites. This will definitely be an advantage for the study of TCs.

382
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387 RO orbit and excess phase data, ECMWF for access to its analysis and short-term forecast
388 data, and WEGC for OPS development and provision of the most recent OPSv5.6 RO data.

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Distance from the TC center [km]	Number of RO
0-30	47
30-100	503
100-200	1579
200-300	2603
300-400	3674
400-500	4949
500-600	7223

567 Table 1. Number of RO profiles co-located with TCs within increasing distance from the
 568 center of the TC.

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	TD	TS	Cat1	Cat2	Cat3	Cat4	Cat5
NA	15.4	15.5	15.9	16	16	16.2	14.4
WP	15.6	16.3	16.3	16.4	16.4	16.5	17.2
EP	15.6	15.7	15.7	15.8	16	15.9	15.1
<i>SP</i>	<i>17.8</i>	<i>17.7</i>	<i>17.8</i>	<i>17.4</i>	<i>17.6</i>	<i>17.4</i>	<i>17.9</i>
NI	16.6	16.6	17.7	16.3	17.5	17.4	17
<i>SI</i>	<i>17.5</i>	<i>17.9</i>	<i>17.4</i>	<i>17.7</i>	<i>17.3</i>	<i>16.7</i>	<i>17.8</i>

571 Table 2. Mean altitude (in km) of the lowest coldest point of temperature anomaly profiles for
 572 different ocean basins and different storm intensities. The southern hemisphere ocean basins
 573 are marked in *italic*.

574 NA=North Atlantic; WP=West Pacific; EP=East Pacific; SP=South Pacific; NI=North Indian;
 575 SI=South Indian.

576 TD=Tropical Depression; TS=Tropical Storm; Cat1=Tropical Cyclone Category-1;
 577 Cat2=Tropical Cyclone Category-2; Cat3=Tropical Cyclone Category-3; Cat4=Tropical
 578 Cyclone Category-4; Cat5=Tropical Cyclone Category-5.

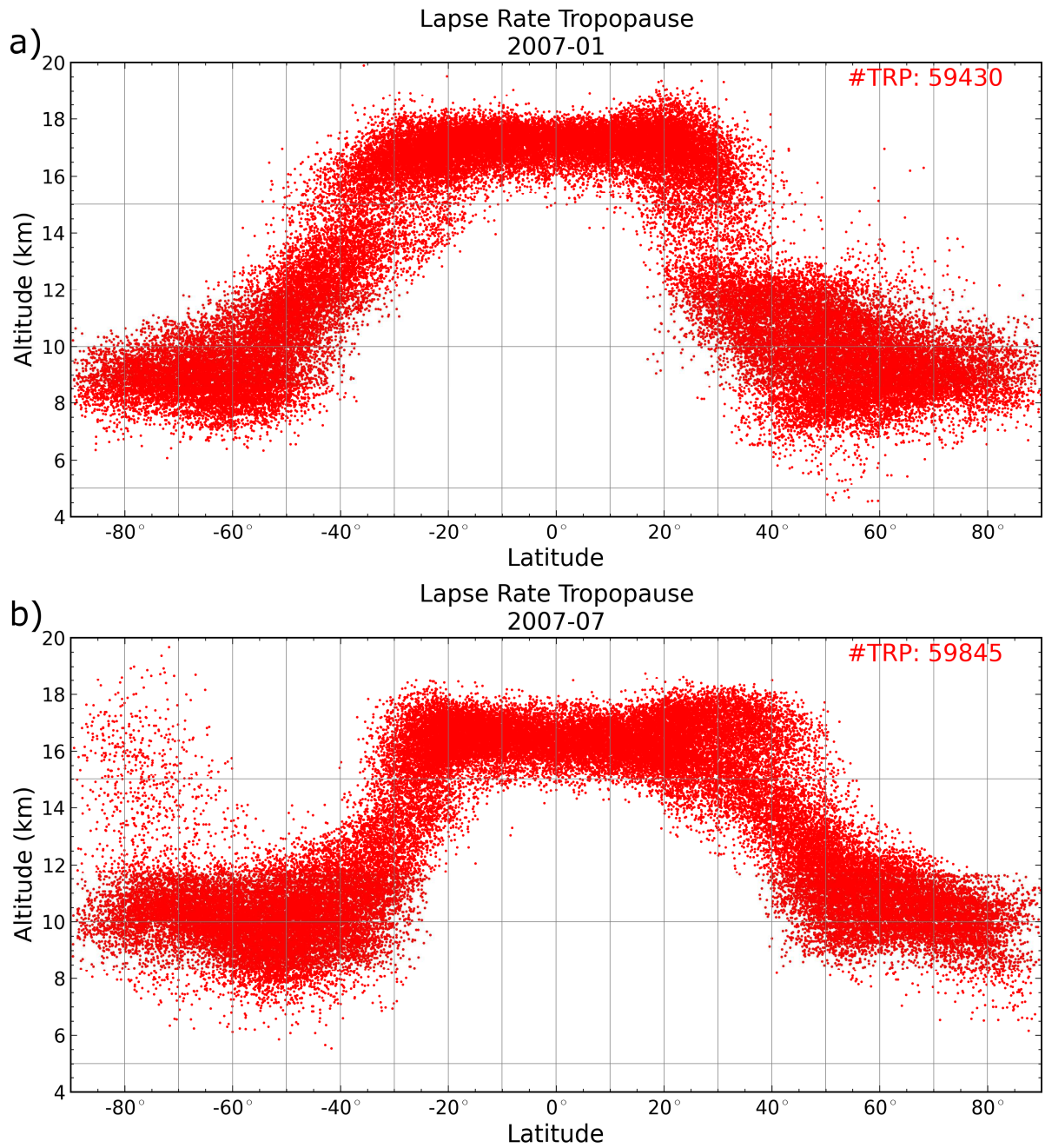
		TD			TS			Cat1			Cat2			Cat3			Cat4			Cat5		
		No occ	overshoot		No occ	overshoot		No occ	overshoot		No occ	overshoot		No occ	overshoot		No occ	overshoot		No occ	overshoot	
			[%]	[km]		[%]	[km]		[%]	[km]		[%]	[km]		[%]	[km]		[%]	[km]		[%]	[km]
NA	tropical	267	8/4	2.1/3.1	285	7/2	1.8/3.6	57	2/0	1.3/0.0	15	7/0	0.8/0.0	8	0/0	0.0/0.0	27	15/4	2.2/6.0	3	0/0	0.0/0.0
	extra ₂₀₋₃₀	255	12/5	2.5/3.6	395	7/3	2.4/3.6	121	4/0	1.3/0.0	53	9/0	1.4/0.0	37	5/3	2.8/4.7	26	12/0	1.1/0.0	2	0/0	0.0/0.0
	extra ₃₀₋₄₀	194	9/4	3.3/4.8	537	13/6	3.4/4.8	163	16/7	3.7/5.2	16	10/0	1.9/0.0	4	0/0	0.0/0.0	3	0/0	0.0/0.0	0	0/0	0.0/0.0
WP	tropical	625	22/9	1.9/3.0	411	32/9	1.6/2.9	140	36/9	1.3/2.5	66	50/14	1.7/3.0	46	35/6	1.4/2.0	70	30/6	1.3/2.9	28	50/4	1.1/3.1
	extra ₂₀₋₃₀	350	22/8	2.2/3.4	459	31/10	2.0/3.2	174	32/10	1.9/2.9	90	22/6	2.0/2.7	64	17/5	1.8/2.8	56	21/2	1.3/2.0	13	69/23	1.7/2.8
	extra ₃₀₋₄₀	102	34/16	3.1/4.2	261	33/11	2.7/3.9	48	37/10	2.5/3.6	19	37/21	2.7/3.3	5	20/0	1.8/0	2	50/0	1.6/0.0	0	0/0	0.0/0.0
EP	tropical	668	6/1	1.3/3.3	415	6/1	1.6/3.8	100	5/2	1.6/2.7	40	3/0	1.5/0.0	38	13/5	1.8/2.6	35	14/9	1.8/2.2	4	0/0	0.0/0.0
	extra ₂₀₋₃₀	278	4/1	2.0/3.8	205	8/1	1.5/2.8	54	7/0	1.2/0.0	28	14/4	1.8/3.5	11	0/0	0.0/0.0	6	0/0	0.0/0.0	0	0/0	0.0/0.0
	extra ₃₀₋₄₀	10	30/10	4.5/8.4	2	50/50	3.5/3.5	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0
SP	tropical	214	38/15	1.7/2.6	156	41/8	1.4/2.6	49	55/18	1.4/2.2	14	43/7	1.2/1.7	11	27/0	1.2/0.0	13	31/8	1.2/2.0	3	100/33	1.7/3.4
	extra ₂₀₋₃₀	78	37/13	1.9/2.7	153	48/14	1.8/2.6	30	73/23	1.8/2.6	21	62/5	1.7/3.3	9	56/11	1.5/2.1	6	50/0	1.5/0.0	0	0/0	0.0/0.0
	extra ₃₀₋₄₀	11	64/9	3.1/3.7	77	55/25	3.0/3.6	1	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0
NI	tropical	176	34/11	1.5/2.3	67	34/12	1.6/2.5	7	57/0	1.1/0.0	1	0/0	0.0/0.0	2	50/0	1.0/0.0	5	40/0	1.2/0.0	3	0/0	0.0/0.0
	extra ₂₀₋₃₀	97	46/20	2.4/3.4	29	48/24	2.4/3.4	3	67/0	2.2/0.0	0	0/0	0.0/0.0	1	0/0	0.0/0.0	1	0/0	0.0/0.0	1	0/0	0.0/0.0
	extra ₃₀₋₄₀	1	100/100	4.0/4.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0
SI	tropical	811	37/14	1.7/2.6	496	40/11	1.6/2.5	101	39/15	1.8/2.6	55	44/20	1.6/2.1	52	42/12	1.7/3.3	18	39/0	1.2/0.0	1	100/0	0.9/0.0
	extra ₂₀₋₃₀	352	35/17	2.3/3.1	335	41/18	2.3/3.1	52	42/21	2.1/2.6	31	48/10	1.7/2.2	33	36/18	2.0/2.5	2	50/0	2.2/0.0	0	0/0	0.0/0.0
	extra ₃₀₋₄₀	37	57/35	3.9/4.7	139	60/37	3.5/4.1	2	50/0	3.0/0.0	0	0/0	0.0/0.0	1	0/0	0.0/0.0	0	0/0	0.0/0.0	0	0/0	0.0/0.0

Table 3. Total number of RO profiles (No occ) co-located with storms of different intensities, selected by ocean basin. Columns denoted "overshoot" give the number of possible overshootings in percent and the mean altitude difference between the storm cloud top and the corresponding monthly mean tropopause computed with Eq. (2) / Eq.(3). Acronyms are the same as in Table 2; see that caption for explanation.

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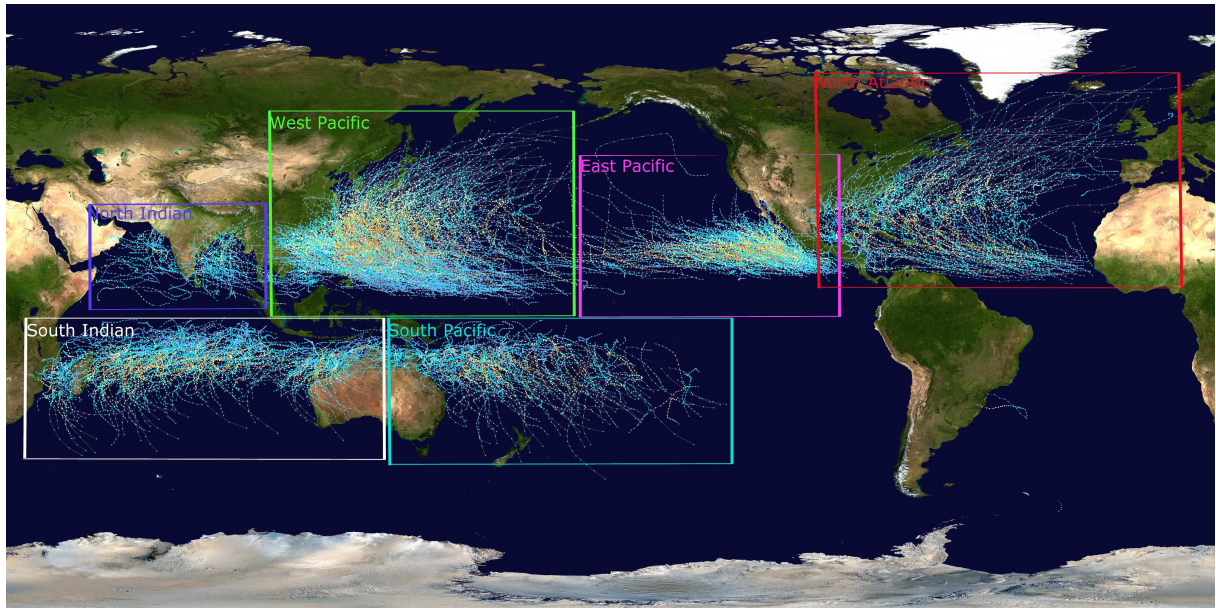
		Total	Percentage
North Atlantic	tropical	662	7.2 (2.7)
	extra	1806	10.7 (4.4)
West Pacific	tropical	1386	29.2 (8.9)
	extra	1643	28.8 (9.7)
East Pacific	tropical	1300	6.3 (1.3)
	extra	594	6.6 (1.5)
South Pacific	tropical	460	40.9 (12.4)
	extra	399	48.4 (15.8)
North Indian	tropical	261	34.5 (10.7)
	extra	133	46.6 (20.3)
South Indian	tropical	1534	38.3 (12.8)
	extra	1039	40.1 (19.6)
Northern Hemisphere	tropical	3609	20.2 (6.2)
	extra	7785	9.9 (3.5)
Southern Hemisphere	tropical	1994	38.9 (12.6)
	extra	2438	25.0 (10.9)
Tropical		5603	26.8 (8.5)
Extra-tropical		10223	13.5 (5.3)

591 Table 4. Summary of Tab. 3, reporting the percentage of tropical and extra-tropical cases
592 binned into ocean basins, hemispheres, and tropics/extratropics. The column “Percentage”
593 reports the percentage of possible overshootings computed with Eq. (2) and within brackets
594 the percentage of possible overshootings computed with Eq. (3).



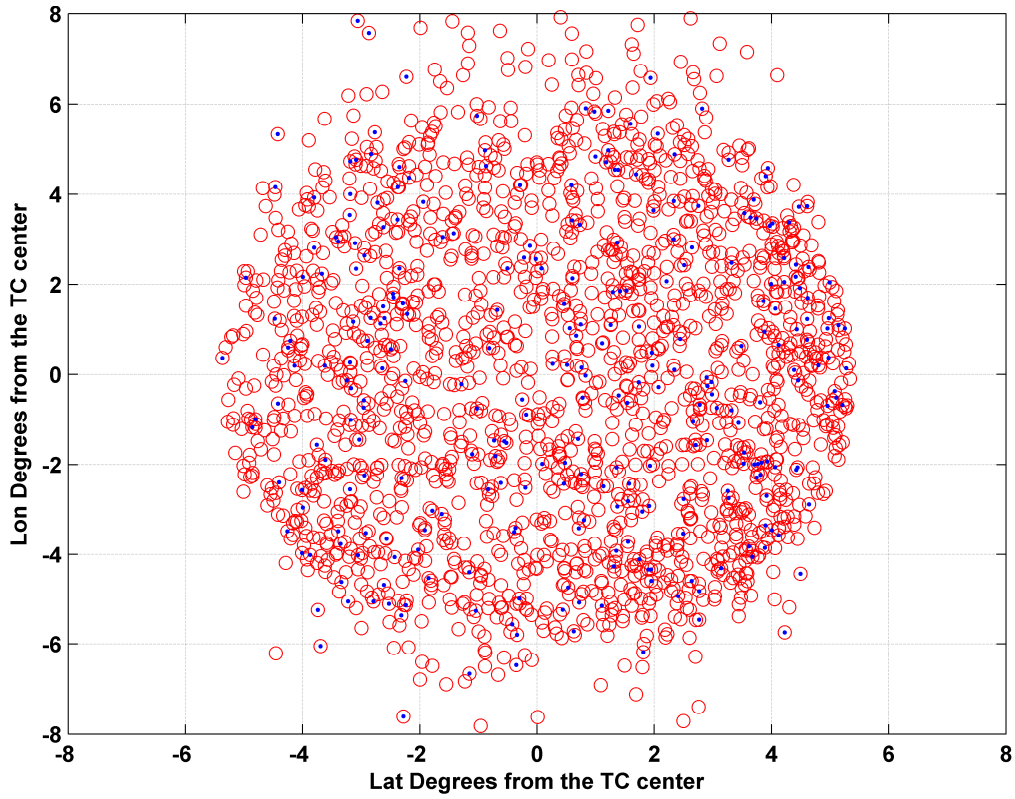
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Figure 1. Exemplary tropopause altitude distribution vs latitude during the northern hemisphere winter (a) and summer (b).

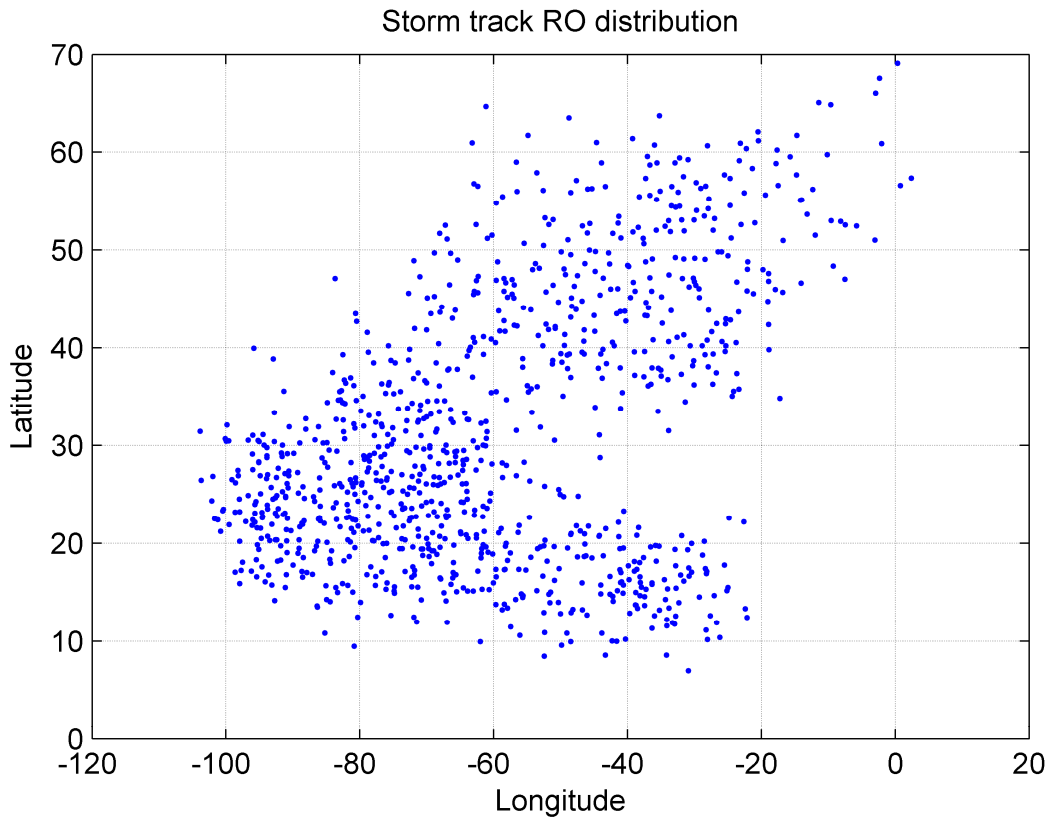


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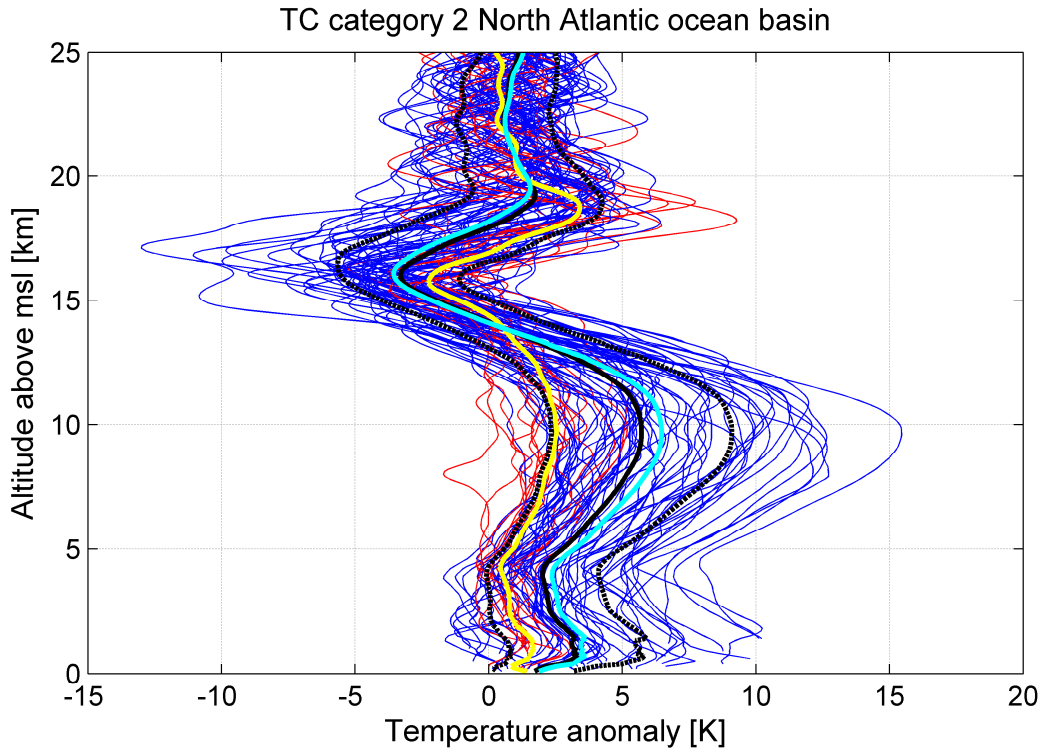
Figure 2. Illustration of TC tracks (background from Wikipedia) for ocean basins: North Atlantic (red), East Pacific (magenta), West Pacific (green), South Pacific (cyan), North Indian ocean basin (blue), and South Indian ocean basin (white).



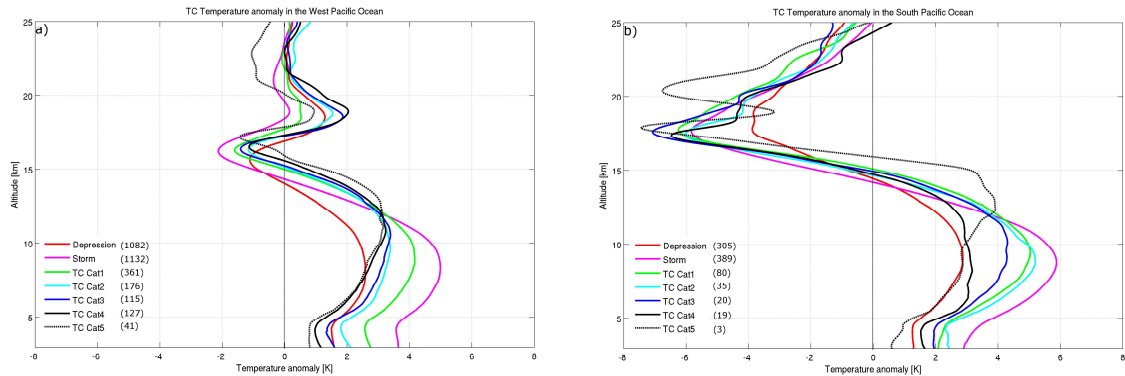
602
 603 Figure 3. Exemplary distribution of GPS RO profiles within 6 h (red circles) and 3 h (blue
 604 dots) around the center of a tropical storm in the North Atlantic ocean, within a spatial
 605 window of 600 km from the center.



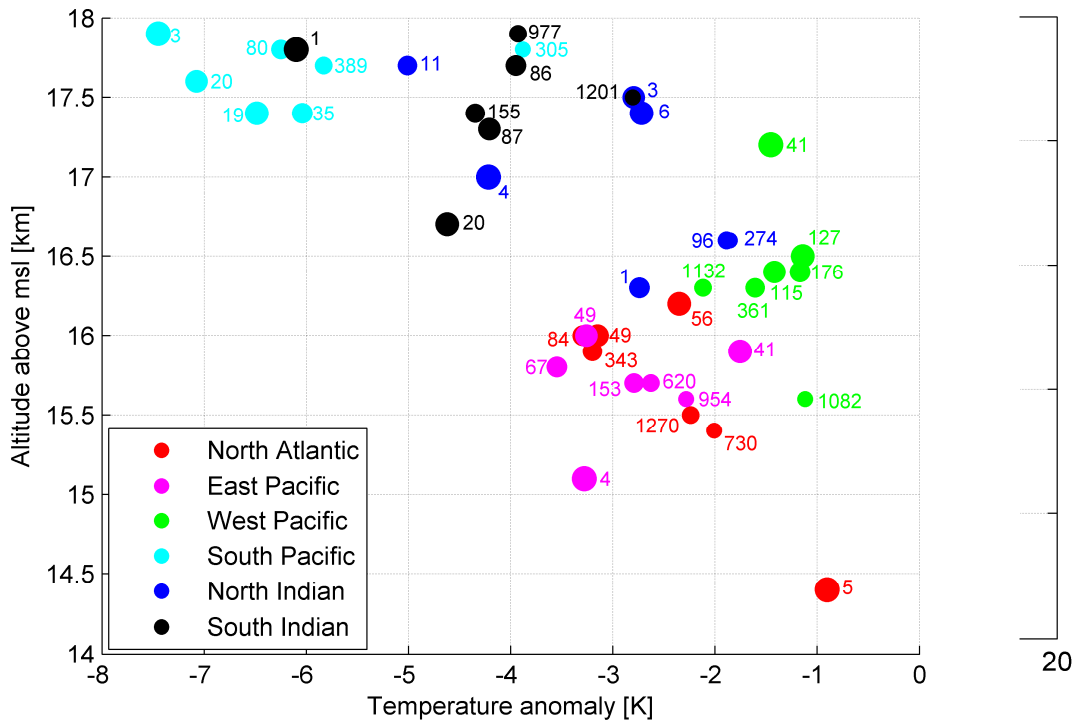
607 Figure 4. Exemplary distribution of GPS RO profiles in a time window of 6 h and spatial
 608 window of 600 km along 135 tropical storm tracks in the North Atlantic ocean basin.



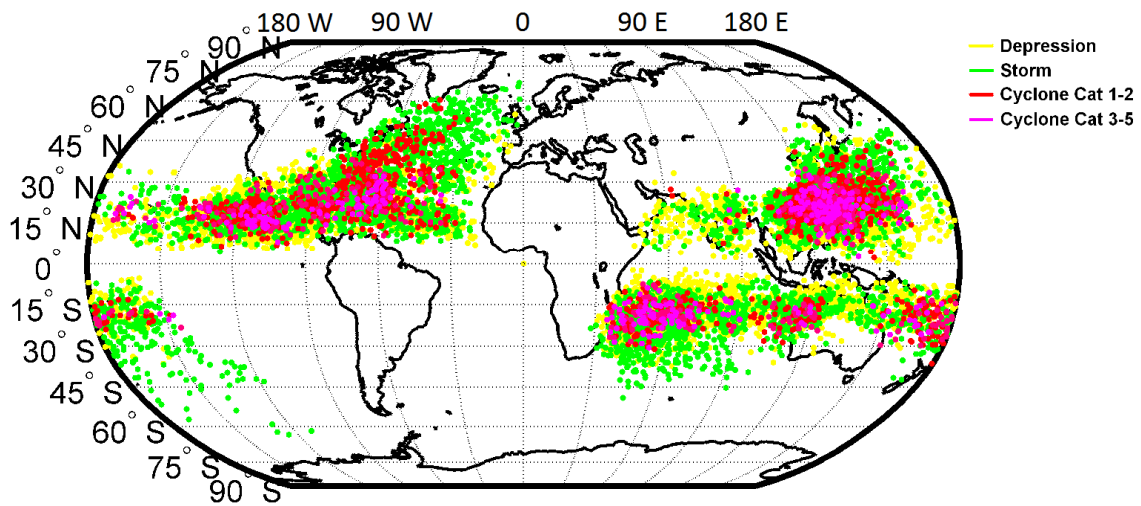
609 Figure 5. RO temperature anomaly profiles during TC category 2 in the North Atlantic basin.
 610 In red the tropical profiles, in blue the extra-tropical profiles, in yellow the mean anomaly of
 611 tropical profiles, in light blue the mean anomaly of extra-tropical profiles, in black the mean
 612 of all the profiles, and dashed black the mean plus/minus the standard deviation.



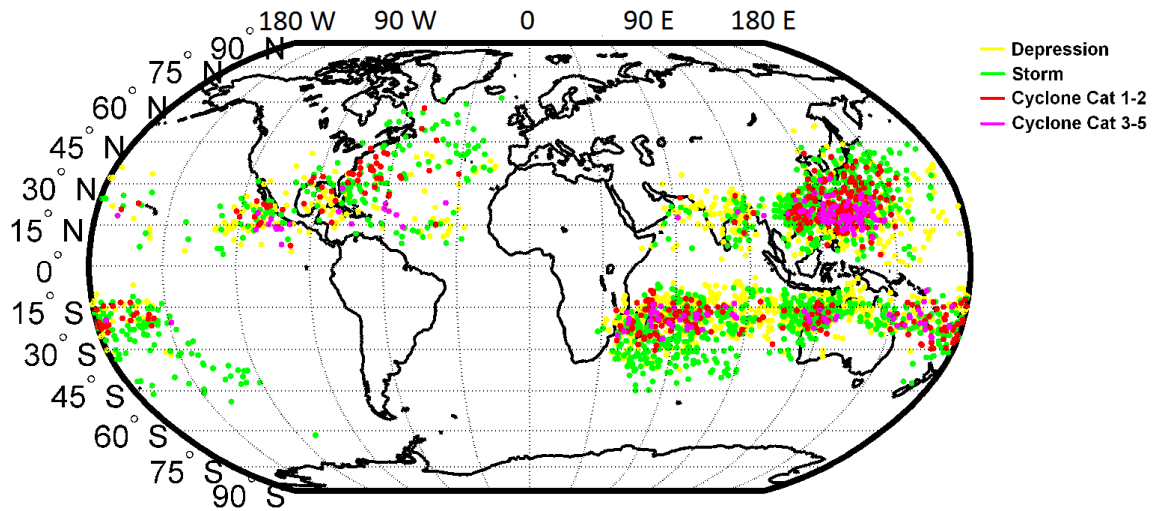
614 Figure 6. Mean temperature anomalies for different storm categories shown for: (a) West
 615 Pacific Ocean and (b) South Pacific Ocean. Numbers in brackets denote the numbers of
 616 observations.
 617



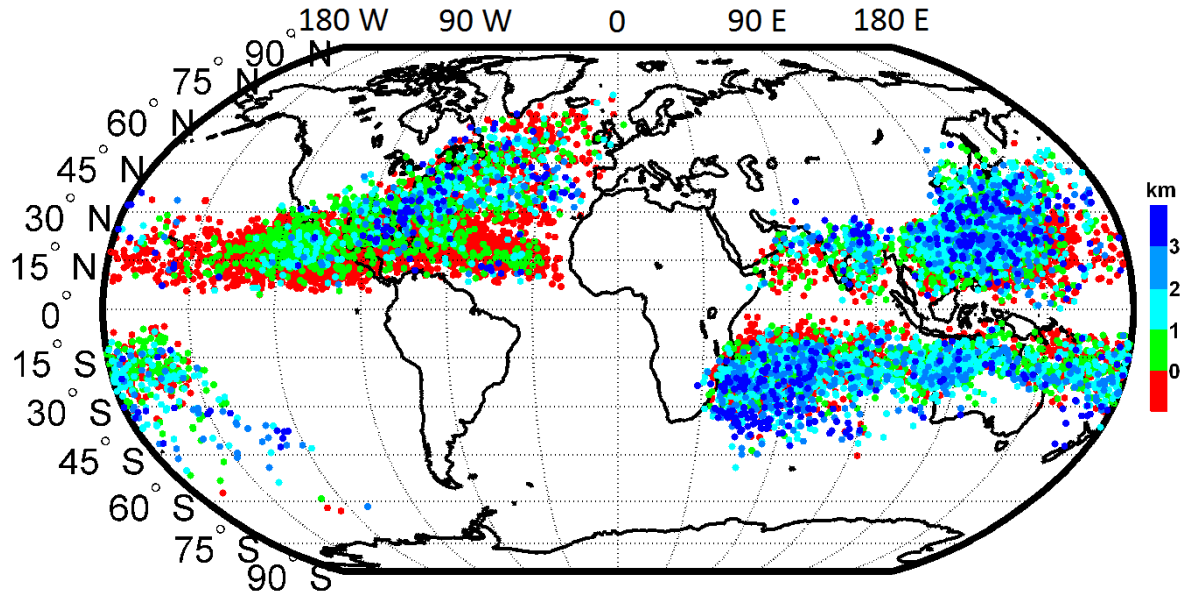
618
 619 Figure 7. Temperature anomaly versus altitude of coldest point for different ocean basins and
 620 different storm intensities. The colors denote different basins. The circle size denotes different
 621 intensities and increases with intensity, from the smallest to the biggest, in the following
 622 order: TD – TS – Cat1 – Cat2 – Cat3 – Cat4 – Cat5. The numbers represent the case number
 623 used for the analyses.



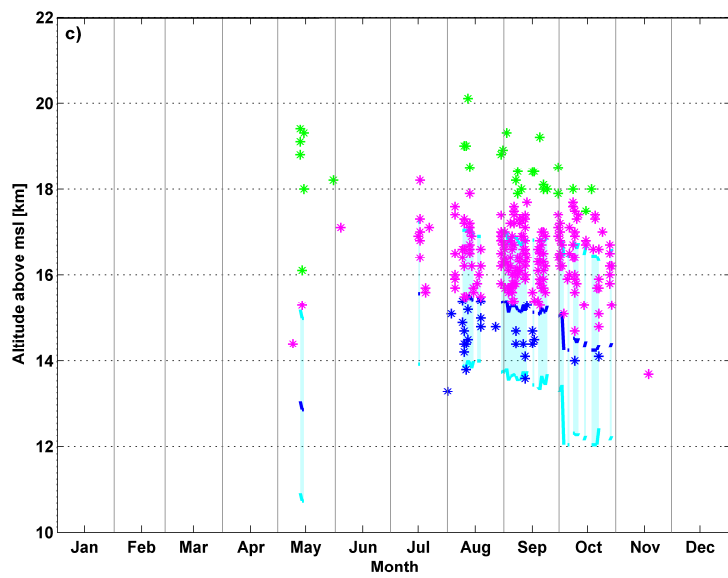
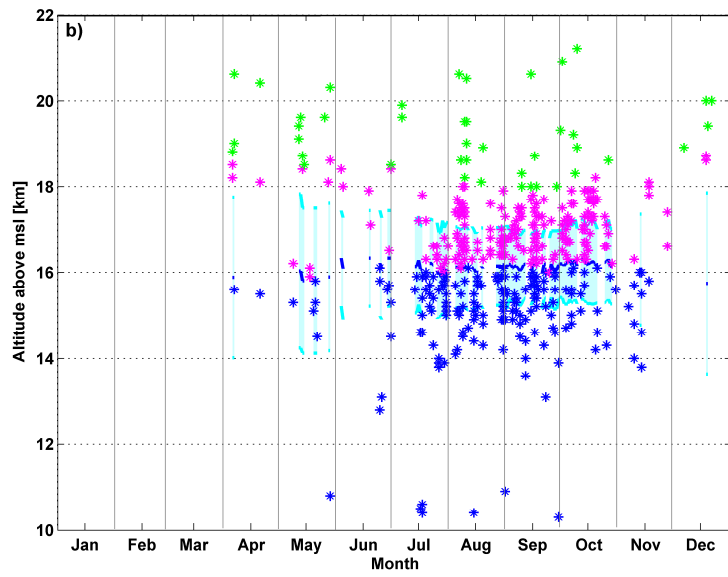
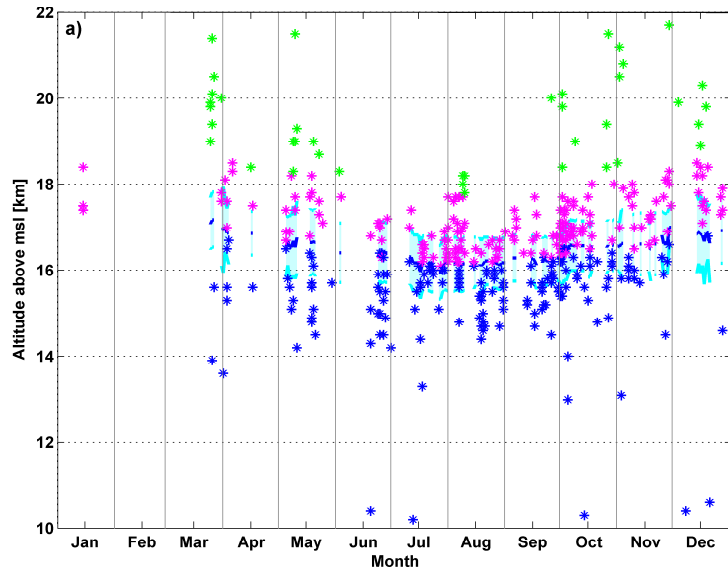
624
 625 Figure 8. Distribution map of GPS RO co-located with storms of different categories: tropical
 626 depression (yellow), tropical storm (green), tropical cyclone categories 1 and 2 (red) and
 627 tropical cyclone categories 3 to 5 (magenta).



628
 629 Figure 9. Distribution of possible overshootings for different storm categories: tropical
 630 depression (yellow), tropical storm (green), tropical cyclone categories 1 and 2 (red)
 631 and tropical cyclone categories 3 to 5 (magenta).



632
 633 Figure 10. Distribution of the difference between the cloud top altitude and the tropopause
 634 altitude for all the GPS RO profiles co-located with TC best tracks.



636 Figure 11. Monthly mean tropopause altitude (solid line) and standard deviation (light-blue
637 shaded area) for different latitude zones (a) 0° - 20° , (b) 20° - 30° , and (c) 30° - 40° in the
638 Western Pacific basin. The stars denote the storm cloud top altitudes below the mean
639 tropopause (blue), above the tropopause (magenta), and for overshooting according to Eq. (2)
640 (magenta with white background) and overshooting according to Eq. (3) (green), respectively.