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Analysis of Atlantic extratropical storm tracks characteristics in 41 years of ERA5 and CFSR/CFSv2

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1 **ABSTRACT:** This work aims to analyze and compare ERA5 and CFSR/CFSv2 from 1979 to 2019 with
2 1-hourly outputs, regarding their ability to reproduce storm tracks and the main characteristics of **cyclones**
3 **at middle and high latitudes** in the North Atlantic (NA) and South Atlantic (SA) Oceans. The cyclone
4 tracking was based on relative vorticity at 850 hPa and the intensity is measured using the maximum 10-
5 meter wind speed. The climatology produced for both datasets shows the main characteristics of the NA
6 and SA storm tracks, such as seasonal variability and genesis regions. The use of 1-hourly fields improves
7 tracking in areas with complex terrains, such as the lee of Andes (SA) and Greenland (NA). The
8 differences in cyclone numbers and characteristics between datasets are small. 92.7% and 93.1% of ERA5
9 cyclones have an identical correspondent storm in CFSR/CFSv2, in the NA and SA respectively. Genesis
10 and lifetime statistics show that CFSR/CFSv2 may present inconsistency between forecast and analysis
11 sequential time-steps. Large differences remain in the intensity distributions, in which the CFSR/CFSv2
12 presents stronger cyclones than ERA5. Divergences between the datasets decrease when the comparison
13 is made using only CFSv2, particularly in the South Atlantic.

14 **Keywords:** Extratropical cyclones; storm tracks; cyclogenesis; South Atlantic Ocean; North Atlantic
15 Ocean; reanalysis.

16

17 **1. Introduction**

18

19 **Cyclones** are key features of the day-to-day weather variability at middle and high latitudes.

20 Storminess is an important risk for offshore structures and ship routing, particularly due to their

21 associated extreme winds and waves (Ponce de León and Guedes Soares, 2012; Vettor and

22 Guedes Soares, 2016; 2017). Safe and profitable engineering operations depend on weather
23 forecasts and metocean statistics, the last being usually produced from reanalysis data produced
24 by operational centers around the world (Campos et al., 2018; 2019). Transient system variability
25 in the extratropics are the contributor to not only errors in wind-wave forecasts but also for
26 problems associated with the representation of topographic and sea surface temperature gradient
27 effects in ocean models (Chelton et al., 2004). Cyclone tracks are usually obtained using 6-
28 hourly data sources, which are necessary to produce reliable cyclone tracks but are insufficient
29 for some ocean engineering problems, such as wave hindcast and forecast models. In this paper
30 **cyclone tracks** in the Atlantic Ocean from two modern reanalysis datasets are compared, the fifth
31 generation of reanalysis from the European Centre for Medium-Range Weather Forecast
32 (ECMWF; Hersbach and Dee, 2016) (ERA5), and the Climate Forecast System Reanalysis
33 (CFSR; Saha et al., 2011), and Climate Forecast System version 2 (CFSv2; Saha et al., 2014)
34 from the National Center for Environmental Prediction (NCEP). Besides the analysis of these
35 two datasets and the discussion, an important contribution of this work is to produce **a cyclone**
36 database that can be used to support ocean engineering and coastal hazard estimations, together
37 with an evaluation of the main differences between the two datasets.

38 Automated methods for cyclone identification and tracking have been developed in the past
39 decades, due to the increase of available data produced by Global Circulation Models (GCMs)
40 and reanalyses, led by the improvement of computational resources. These objective methods are
41 based on a Lagrangian approach that generally uses low-level vorticity or surface pressure
42 criteria to identify and track cyclones (e.g., Murray and Simmonds, 1991; Sinclair, 1994;
43 Hodges, 1994; 1995). Since then, a wide set of cyclone climatologies have been produced for the
44 Northern Hemisphere (e.g., Hoskins and Hodges, 2002), Southern Hemisphere (e.g., Jones and

45 Simmonds 1993; Sinclair 1994; Simmonds and Keay, 2000; Hoskins and Hodges, 2005), North
46 Atlantic (e.g., Pinto et al., 2005; Trigo, 2006; Dacre and Gray, 2009, Grise et al., 2013), and
47 South Atlantic Oceans (e.g., Mendes et al., 2010, Reboita et al., 2010, Gramscianinov et al.,
48 2019). The basic product of the tracking method is the collection of cyclone trajectories within a
49 defined region and period. The spatial statistic distribution of this collection of trajectories
50 defines the storm track position – the preferred location of **cyclone** propagation.

51 Following the development of GCMs, the use of analyses and reanalyses was a valuable
52 improvement to the atmosphere and ocean dynamics studies (Parker, 2016). Reanalysis products
53 are based on a model allied to data assimilation, and thus, can provide a complete spatial
54 coverage at a regular resolution. Despite the verification and validation performed by
55 development centers (e.g., Kalnay et al., 1996; Saha et al., 2011; 2014), it is important to
56 evaluate the performance of these datasets for particular applications, such as extratropical and
57 tropical cyclones, and precipitation. Several studies have carried out intercomparisons of storm
58 tracks obtained from different datasets for the whole globe (e.g., Hodges et al., 2003; 2011),
59 Northern Hemisphere (e.g., Raible et al., 2008), North Atlantic sector (e.g., Trigo, 2006) and
60 South Atlantic sector (Reboita et al., 2018; Crespo et al., 2020a). Hodges et al. (2011) compared
61 the storm track distribution and intensity in four reanalysis: the Modern Era Retrospective-
62 Reanalysis for Research and Applications (MERRA; Rienecker et al., 2011), the 25-yr Japan
63 Reanalysis (JRA25; Onogi et al., 2007), the ECMWF Interim Reanalysis (ERA-Interim;
64 Simmons et al. 2007), and the CFSR. They found larger discrepancies between the older and
65 newer products and attributed their findings to the improvement of data assimilation techniques
66 and increase of resolution. According to them, modern reanalysis inter compares better than the
67 older ones for cyclone densities. However, differences remain large between CFSR and ERA-

68 Interim for cyclones intensities, and also for densities in some regions of the Southern
69 Hemisphere. Stopa and Cheung (2014) evaluated 30 years of wind and wave data from the CFSR
70 and ERA-Interim using altimeter and buoy observations. While ERA-Interim presented lower
71 error metrics, CFSR showed a better performance in the upper percentiles associated with
72 extreme events. The large differences between datasets are generally associated with the failure
73 in the representation of extreme events (e.g., Stopa and Cheung, 2014; Campos et al., 2018).
74 Winds are often underestimated at some locations, mainly in the Southern Hemisphere, due to
75 the lack of observational data (e.g., Stopa and Cheung, 2014). This problem contributes to the
76 misrepresentation of cyclones, particularly the most intense ones, which leads to issues in wind-
77 wave climate hindcast and forecast (e.g., Kumar et al., 2003; Campos and Guedes Soares, 2016;
78 2017; Bakhtyar et al., 2018; Mattioli et al., 2019; Campos et al., 2019), and storm surge
79 estimations (e.g., Colle et al., 2010; Booth et al., 2016; Sebastian et al., 2019).

80 Therefore, it is important to evaluate cyclone and storm track characteristics of datasets
81 available at high temporal resolution, since 1-hourly fields are frequently used to support the
82 production of wave hindcasts and forecasts, and energy sector assessments. The main goal of this
83 study is to present and evaluate the Atlantic cyclone climatology for middle and high latitudes
84 that can be used by research and industry applications, since there is a lack of this type of
85 product available (e.g., Dacre et al., 2012), particularly for the South Atlantic Ocean. Therefore,
86 two main questions for this study are: (1) How does the 1-hourly ERA5 and CFSR/CFSv2
87 cyclone tracks for the Atlantic storm track compare with previously published studies?; (2) What
88 are the main differences between the two datasets regarding the basic cyclone and storm track
89 characteristics? The analysis is focused on the mean characteristics, spatial distribution and
90 intensity of the cyclones, which are important features that control the wind and wave climates.

91

92 **2. Data and Methods**

93 **2.1. Datasets**

94 ERA5 is the latest reanalysis produced by ECMWF, available from the Copernicus Climate
95 Change Service (CS3). This reanalysis has been produced using 4D-Var data assimilation in
96 ECMWF's Integrated Forecast System (IFS), version CY41R2. The atmospheric variables used
97 in this work are on a 31 km (0.28125°) horizontal grid with 1-hourly outputs from 1979 to 2020.
98 ERA5 replaces the ERA-Interim, and benefits from its antecessor's development in model
99 physics, core dynamics and data assimilation. One of the most important innovations of ERA5 is
100 output of hourly analyses that can widely support risk and operational management in diverse
101 sectors, such as renewable energy (e.g., Olauson, 2018). Moreover, Belmonte Rivas and
102 Stoffelen (2019) found that ERA5 surface winds present a 20% improvement relative to ERA-
103 Interim, using ASCAT observations as verification. An overview of the main characteristics of
104 ERA5 and a comparison with ERA-Interim can be found in Hersbach et al. (2018).

105 The CFSR is the latest version of the NCEP climate reanalysis and covers the period from
106 1979-March/2011. The reanalysis was produced using a coupled atmosphere–ocean model: the
107 NCEP Global Forecast System (GFS) for the atmosphere and the Geophysical Fluid Dynamics
108 Laboratory Modular Ocean Model version 4 (MOM4) for the ocean (Saha et al., 2010). The
109 CFSv2, the operational descendant of the CFSR, was released in March 2011, and it has been
110 running operationally since then. The CFSR and CFSv2 have a horizontal native resolution of
111 T382 (~ 38 km) interpolated to a $0.5^\circ \times 0.5^\circ$ grid. Both the reanalysis and analysis are produced
112 originally in 6-hourly intervals, but a 1-hourly time series are also available from some variables
113 and consist of the analysis followed by the sequence of hourly forecasts until the next analysis

114 cycle. The hourly sequence provided might have abrupt changes in atmospheric fields every time
115 when a forecast time-step changes to analysis time-step, since the last is corrected by data
116 assimilation. Despite this eventual inconsistency along the period, it is important to evaluate the
117 hourly data since these products are used for ocean engineering applications. Moreover, it is the
118 only way to compare CFSR/CFSv2 with ERA5 1-hourly data. Differences between products are
119 expected and need to be discussed to support future choices and/or changes.

120

121 **2.2. Cyclone identification and tracking**

122 The cyclones are identified and tracked in both reanalyses using the TRACK program
123 (Hodges, 1994; 1995; 1999) following the pre-processing steps described in Hoskins and Hodges
124 (2002; 2005). The cyclonic features were identified using the relative vorticity, which is
125 computed using the zonal and meridional wind components at 850 hPa in spherical coordinates
126 to avoid latitudinal bias (Sinclair, 1997). Sinclair (1994) highlighted the benefit of using vorticity
127 instead of mean sea level pressure (MSLP) for the detection of cyclones in mid-latitudes, where
128 the surface pressure gradient can be strong so that cyclones appear without a closed isobar. For
129 this reason, the use of vorticity allows the early identification of cyclones that would only be
130 detected by MSLP when intensification occurs or they move to higher latitudes. The vorticity
131 field contains many small scale structures, particularly at the high resolution, which can cause
132 problems during the identification process and tracking on the synoptic scale. To prevent this
133 issue and focus on synoptic scales, the vorticity was spectrally filtered by converting to the
134 spectral representation and truncating to T42, tapering the spectral coefficients to smooth the
135 data. Large-scale atmospheric features were also removed by setting zonal wavenumbers ≤ 5 to
136 zero. Hoskins and Hodges (2002) present more details about the filtering.

137 The cyclonic features are identified by determining the local maxima. In the Southern
138 Hemisphere, where negative vorticity indicates cyclonic circulation, the vorticity fields are first
139 scaled by -1. **First, the central position of the cyclonic feature is determined** by the grid point
140 maxima that exceed a threshold of $1 \times 10^{-5} \text{ s}^{-1}$ (1 cyclonic vorticity unit (CVU)) on a polar
141 stereographic projection. **This identification threshold is suitable to capture even weak cyclonic**
142 **centers in the filtered vorticity field (T42), since it is smoother than the original vorticity one**
143 **(e.g., Hoskins and Hodges, 2002; 2005).** The feature **central** locations are refined by computing
144 the off-grid maxima using B-spline interpolation and steepest descent maximization and then
145 converted back to spherical coordinates. The tracking is initialized using a nearest neighbors
146 search method. The initial set of tracks is refined by minimizing a cost function for track
147 smoothness, subject to adaptive constraints (Hodges, 1999), that operates both forwards and
148 backward in time. The high time resolution reduces ambiguity during tracking. The displacement
149 constraint applied was 2.0° , except in the tropics (20°N - 20°S) where it was set as 0.5° . Due to
150 the large amount of data, the tracking was performed using monthly files. Thus, post-processing
151 was applied to connect tracks between the months, using the same displacements rules described
152 above.

153 Finally, identified systems that are not cyclones were excluded. In this step, cyclonic features,
154 such as thermal lows, mesoscale storms, and some convergence areas were removed by
155 considering only systems that last at least 24 hours and that travel further than 1000 km, such as
156 used by Gramscianinov et al. (2019) for the South Atlantic Ocean. The thresholds are more
157 relaxed than the ones commonly used in North Atlantic storm track studies (e.g., Hoskins and
158 Hodges, 2002; 2005; Hodges et al., 2011; Dacre and Gray, 2009), but it maintains consistency
159 throughout the entire Atlantic. The use of a higher minimum lifetime threshold (e.g., 36h or 48h)

160 would exclude some systems with regional importance (e.g., Gramscianinov et al., 2019; 2020).
161 Gramscianinov et al. (2020) considered cyclones with a minimum of 12h lifetime and 500km
162 displacement, to include short-lived systems that might be important for extreme waves along the
163 Southern Brazilian coast. However, the use of such a low displacement threshold results in
164 including continental lows and non-developed cyclonic systems in the climatology. **Figure 1**
165 **shows the genesis and track densities of cyclonic systems that live at least 24 hours with the total**
166 **displacement between 500 and 1000 km. In the North Atlantic, 23% (ERA5) and 26%**
167 **(CFSR/CFSv2) of the cyclonic systems were excluded with the 1000 km (~10°) displacement**
168 **threshold, while in the South Atlantic they represented a smaller portion of 15% (ERA5) and**
169 **21% (CFSR/CFSv2). Although these values can be considered important, the track density**
170 **reveals that systems with small mobility (semi-stationary) are mainly continental and thermal**
171 **lows generated in complex terrain, and troughs that are generated in frontal zones, without**
172 **enough forcing for full-development. The genesis densities are smaller when compared to active**
173 **cyclone genesis regions reported in the literature (e.g., Hoskins and Hodges, 2002; 2005), and**
174 **the track density is restricted to the generation point revealing the small influence of the systems,**
175 **which mostly do not reach the ocean.**

176 Since the main interest of this work is **on cyclones at middle and high latitude**, we considered
177 for further analysis storms which pass within the extratropical latitudes of the South Atlantic
178 (85°S-25°S, 75°W-20°E) and North Atlantic (85°N-25°N, 65°W-0°E). The selected domains
179 include areas where occurs subtropical cyclones generated both by genuine subtropical genesis
180 and by transition process between tropical and extratropical cyclones (e.g., Guishard et al., 2009;
181 Evans and Braun, 2012; Gozzo et al., 2014). In this way, subtropical cyclones may be included in

182 the set of tracks, since no distinction between subtropical and extratropical cyclones was made in
183 the present work.

184

185 **2.3. Cyclone diagnostics**

186 The statistical analysis consists of information for the tracks, including mean lifetime of
187 cyclones, cyclone speed, and displacement. Standard seasons are used for the entire period
188 (1979-2019): December-February (DJF), March-May (MAM), June-August (JJA), and
189 September-November (SON). Spatial statistics are computed for each reanalysis using the
190 spherical kernel estimator approach, described by Hodges (1996). The differences between track
191 and genesis densities of the two datasets were tested using Monte Carlo significance test
192 (Hodges, 2008) with 1000 samples of the set of tracks for each dataset.

193 Maximum 10-m wind speed is used for the comparison of cyclone intensities. The 10-m wind
194 speed is added to each track by a general search for the maximum value within a 6° radius of
195 cyclone center (Bengtsson et al., 2009). This additional information was used to construct
196 maximum intensity distributions for both ERA5 and CFSR/CFSv2. Moreover, identification of
197 matched tracks between the datasets was made to perform a more direct comparison of the
198 cyclone intensities. A storm was considered to be the same in ERA5 and CFSR/CFSv2 when the
199 mean separation distance between cores was less than 2° (geodesic) and they overlap in time by
200 at 50% of their points. The criteria used here is stricter than the one applied in Hodges et al.
201 (2011), where the minimum mean separation distance was 4° . The choice of a smaller distance
202 agrees with the focus of this work, linked to ocean engineering applications, in which smaller
203 differences in the system position may lead to large biases in the wind and wave fields.

204

205 **3. Results**

206 **3.1. Genesis and track densities**

207 Before the direct comparison between storms tracks in each dataset, the climatology of the
208 cyclones is presented, using ERA5 as a reference, to provide an overview of the storm track
209 pattern and genesis variability in the North and South Atlantic Oceans.

210

211 *3.1.1. North Atlantic*

212 The track and genesis densities in the North Atlantic domain for the entire period, boreal
213 winter (DJF) and summer (JJA) are shown for the ERA5 and CFSR/CFSv2 in Figure 2 and
214 Figure 3. The North Atlantic storm track is represented by the region of maximum track density
215 [> 10 cyclones $(10^{-6}, \text{km}^2)^{-1} (\text{month})^{-1}$] extending northeastward, from the East of North
216 American coast to Greenland and North Europe. A northern path of the storm track strengthens in
217 DJF, along the eastern side of Greenland, due to the increase in genesis activity at this location.
218 The genesis density shows four regions favorable to cyclogenesis [> 2 cyclones $(10^{-6}, \text{km}^2)^{-1}$
219 $(\text{month})^{-1}$]: lee of the southern Rockies (35°N, 102.5°W), West Atlantic (40°N, 75°W), East
220 Atlantic (centered at 50°N, 25°W), and in the eastern coast of Greenland.

221 All genesis regions within the North Atlantic domain are more active during the boreal winter
222 (DJF). However, the genesis region along the eastern North American coast is active all year,
223 being a location with high baroclinicity due to the sea surface temperature gradients provided by
224 the warm Gulf Stream. The surface temperature contrast does not give only conditions to genesis
225 but also to the intensification of pre-existing cyclones and perturbations that come from
226 continent - which may be generated on the lee side of Rockies. Grise et al. (2013) constructed a
227 genesis density distribution using not the first track point of each cyclone but the location where

228 storms exceeded the growth rate of 2 CVU per day, and they found a major genesis density along
229 the east coast of North America and less at the Rockies. The genesis region at the lee of the
230 northern Rockies and its consequent storm track density along the continent (e.g., Hoskins and
231 Hodges, 2002) does not appear in Figure 3 because these cyclones dissipate in the northeast
232 portion of the North American continent, outside the North Atlantic domain (Dacre and Gray,
233 2009). The genesis densities along the east Greenland coast are higher in Figure 3 than in some
234 previous studies selecting cyclones that last more than 48 h (e.g., Hoskins and Hodges, 2002;
235 Dacre and Gray, 2009; Grise et al., 2013). Trigo (2006) used the 24h threshold and also obtained
236 a more pronounced genesis density in Greenland.

237

238 3.1.2. *South Atlantic*

239 Figure 4 and Figure 5 show the cyclone track and genesis densities in the South Atlantic for
240 the ERA5 and CFSR/CFSv2, computed for the whole period, as well as divided into austral
241 summer (DJF), and winter (JJA). The main South Atlantic storm track is defined by the high
242 concentration of systems [> 10 cyclones $(10^{-6}, \text{km}^2)^{-1} (\text{month})^{-1}$] extending from west to east of
243 the domain, between 40°S and 55°S . Furthermore, there is a secondary storm track [> 6 cyclones
244 $(10^{-6}, \text{km}^2)^{-1} (\text{month})^{-1}$] that merges with the primary storm track, being considered a
245 subtropical branch. During the austral summer (DJF), the subtropical storm track spreads
246 northward, originating between 30°S and 35°S , while during the winter this branch is
247 concentrated in 35°S . The winter season variability in the South Atlantic storm track is linked to
248 changes in active genesis regions in South America, as is possible to see in the genesis density
249 spatial distribution (Figure 5).

250 The genesis density for all period shows three main regions of active genesis [> 2 cyclones
251 $(10^{-6}, \text{km}^2)^{-1} (\text{month})^{-1}$]: in Uruguay (35°S, 60°W), Argentinean coast (45°S, 65°W), and
252 Antarctic Peninsula (65°S, 60°W). Secondary genesis regions exist in the Southeast Brazilian
253 coast (27°S, 45°W), and southeast portion of South Atlantic (centered at 45°S, 10°W). The former
254 is only pronounced during the austral summer, while the last **has more genesis during** the winter
255 (e.g., Gramscianinov et al., 2019). In South America, the genesis regions at Uruguay are more
256 active during JJA, while the Argentina's genesis region is more active in DJF. However, the
257 genesis region in Argentina presents a high density of genesis during all year [> 5 cyclones $(10^{-6},$
258 $\text{km}^2)^{-1} (\text{month})^{-1}$]. The genesis region in Southeast Brazilian coast and Southeast South Atlantic
259 are more active in CFSR/CFSv2 climatology [> 2 cyclones $(10^{-6}, \text{km}^2)^{-1} (\text{month})^{-1}$] than in
260 ERA5.

261 The spatial distribution and seasonal variation presented in Figure 4 and Figure 5 are in
262 agreement with previous studies (e.g., Hoskins and Hodges, 2005; Reboita et al., 2010;
263 Gramscianinov et al., 2019). A more direct comparison can be made with results from
264 Gramscianinov et al. (2019) since the system duration and displacement threshold applied are the
265 same (24 h and 1000 km). They found a slightly more active genesis region in the Southeast
266 Brazilian coast in DJF. Also, the Uruguay genesis region is much more active in the present
267 work, with a genesis density almost 20% larger.

268

269 **3.2.Differences between ERA5 and CFSR/CFSv2 cyclones**

270 Table 1 shows the cyclone annual and seasonal mean frequencies computed for the entire
271 period (1979 to 2011). Such values were also computed for the split period linked to CFSR
272 (1979-March/2011) and CFSv2 (April/2011-2019) separately, to analyze the differences between

273 datasets. In general, ERA5 produces more cyclones than CFSR/CFSv2, which is expected due to
274 the higher resolution of the former. The differences between the two datasets are smaller in the
275 North Atlantic than in the South Atlantic in all cases. In the North Atlantic, the differences in
276 cyclone numbers are between 0.4% and 4.4%, being the lowest and largest differences detected
277 in MAM and JJA respectively. The period of JJA is the only season that CFSR/CFSv2 presents
278 more cyclones than ERA5. The differences between datasets for the South Atlantic vary from
279 6.3% to 2.3%. The largest difference occurs in JJA, the most active cyclonic season. By choosing
280 ERA5 as the reference, the CFSv2 improves the cyclone representation in the South Atlantic
281 when compared to its antecessor, since there is a reduction of differences between CFSv2 and
282 ERA5 when compared to CFSR and ERA5. It is not possible to conclude the same for the North
283 Atlantic, which presents a small increase or decrease of differences depending on the season.

284 The spatial distribution and intensity differences between ERA5 and CFSR/CFSv2 are
285 presented in the following subsections. The results focus on the storm track active season in each
286 ocean basin: boreal winter (DJF) for the North Atlantic, and austral winter (JJA) for the South
287 Atlantic.

288

289 *3.2.1. Spatial distribution*

290 The winter genesis and track density differences between the two datasets are presented in
291 Figure 6 for the North Atlantic (DJF) and South Atlantic (JJA). The difference is computed as
292 CFSR/CFSv2 minus ERA5, so positive (negative) values indicate that the CFSR/CFSv2 has
293 more (less) genesis or tracks in a location. Areas with significant differences (p -value < 0.01) are
294 marked with a black dot. First, for the North Atlantic, the track density difference shows that
295 ERA5 have more storm tracks than CFSR/CFSv2. The track differences do not show any dipole

296 patterns that would indicate shifts between storm tracks but, instead, the negative values are
297 distributed all over the main North Atlantic storm track paths from the eastern portion of the
298 eastern USA to Iceland and the UK. However, there are some local differences in genesis density
299 comparisons. The CFSR/CFSv2 presents a more concentrated genesis along the eastern coast of
300 North American, between 40°N and 55°N, and offshore areas. This genesis difference along the
301 coast generates an eastward shift of the east of North Atlantic genesis region between the two
302 datasets. The CFSR/CFSv2 also presents an active genesis region closer to the UK (15°W) than
303 ERA5 (25°W). Differences are larger in the South Atlantic, both in genesis and track densities.
304 The track density differences show that ERA5 presents a higher track density in most of the
305 domain, particularly where the South Atlantic storm track is typically found, between 40°S and
306 55°S, following the spiral pattern typical of the winter. Moreover, in the southwest of the domain,
307 in the Drake Passage (55°S and 66°S), there is a pronounced difference associated with cyclones
308 that come from the South Pacific Ocean. The genesis density difference shows that the
309 cyclogenesis regions over Uruguay and Argentina are more active in ERA5, while CFSR/CFSv2
310 favors genesis in the oceanic portion off of South America Eastern coast and Southeast of South
311 Atlantic. The genesis region in the Antarctic Peninsula is more active in ERA5, which are
312 connected to more cyclonic perturbations coming from the South Pacific.

313

314 *3.2.2. Cyclone intensity and additional characteristics*

315 Some important cyclones characteristics are shown in Table 2 for ERA5, CFSR/CFSv2,
316 CFSv2 and CFSR, for both oceanic basins. First, the mean initial vorticity is calculated by the
317 filtered vorticity (T42) at the time of the genesis in each track. The CFSR/CFSv2 presents larger
318 initial vorticity than ERA5, in all periods considered. The difference is larger for the South

319 Atlantic, where CFSR/CFSv2 cyclones are 10.4% more intense at the time of the genesis than
320 cyclones in ERA5. For the North Atlantic cyclones, CFSR/CFSv2 present storms 6.4% more
321 intense than ERA5. The cyclone propagation speed is similar between datasets, which is
322 expected once it is mainly dictated by the large scale flow. As is possible to see, regarding
323 cyclones' mean characteristics, the differences between ERA5 and CFSR/CFSv2 are small, and
324 not significant due to the large variance. Analyzing CFSR and CFSv2 separately, the differences
325 compared to ERA5 decrease in version 2. Despite the large standard deviation, the mean values
326 indicate that ERA5 cyclones seem to live longer and move further than CFSR/CFSv2 ones. To
327 investigate further the duration and displacement differences between the two datasets the
328 histograms of those cyclones characteristics are presented in Figure 7. In fact, the lifetime and
329 displacement distributions show that CFSR/CFSv2 presents a larger portion of small-distance
330 and short-life cyclones when compared to ERA5.

331 The intensity distributions are shown in Figure 8 for both the North Atlantic (DJF) and South
332 Atlantic (JJA) in two periods: from 1979 to 2019, and April/2011 to 2019, the last referring to
333 CFSv2 solely. Figure 8 also shows the intensity distribution of the matched tracks between
334 datasets. The percentage of matched tracks between ERA5 and CFSR/CFSv2 can be found in
335 Table 3. The maximum 10-m wind speed distribution for all cyclones shows that the
336 CFSR/CFSv2 presents more intense cyclones than ERA5, as its distribution is shifted to the
337 right. The mean maximum surface winds and percentiles of the distributions are displayed in
338 Table 4. CFSR/CFSv2 presents a higher mean and percentiles, and the differences between the
339 datasets are larger for the South Atlantic than North Atlantic. Additionally, the CFSv2 has a
340 broader distribution when compared to ERA5, although this is more evident in the North
341 Atlantic. The same behavior was observed by Hodges et al. (2011) when they compared CFSR

342 and ERA-Interim. The tendency of CFSR/CFSv2 to simulate more intense storms is reported by
343 previous studies (Hodges et al., 2011; Stopa and Cheung, 2014; Gramscianinov et al., 2020b). The
344 matching storms distribution reveals more about the dissimilarities between the datasets since it
345 compares the same storm simulated in each one. The intensity distribution of the matched tracks
346 is very similar to the distribution obtained with all tracks, due to the high correspondence
347 percentage between datasets (Table 3). Even for the matching cyclones distributions,
348 CFSR/CFSv2 cyclones are more intense than ERA5 ones, reinforcing its tendency to simulate
349 stronger storms. Analysing CFSR alone (not shown) does not change this behavior, but the
350 intensity distributions computed for CFSv2 and ERA5 between April/2011 and 2019, present a
351 slight increase in cyclones intensity in relation to the mean and past distribution. The distribution
352 computed for the end of the period is shifted to the right, and has a more pronounced tail to the
353 right side of maximum wind speed axis.

354

355 **4. Discussion**

356 The cyclone climatologies covering 41-years produced from ERA5 and CFSR/CFSv2 are in
357 good agreement with past studies for the North Atlantic (e.g., Hoskins and Hodges, 2002; Trigo,
358 2006; Dacre and Gray, 2009) and South Atlantic Oceans (e.g., Hoskins and Hodges, 2005;
359 Gramscianinov et al., 2019). Differences in genesis and track densities between the present and
360 past studies are expected, particularly due to the use of distinct cyclone tracking methods,
361 domains, and thresholds that define whether a cyclonic feature is a cyclone or not (Pinto et al.,
362 2005). The climatologies presented in this work show a higher cyclone density than Hoskins and
363 Hodges (2002, 2005), Dacre and Gray (2009), and Grise et al. (2013), since these authors remove
364 from their climatology cyclones that live less than 48h, which represent a large portion of the

365 systems in this study (Figure 7). However, when compared to Trigo (2006) and Gramcianinov et
366 al (2019), which also used the 24 hours as cyclone lifetime threshold, the densities presented in
367 this work are comparable (Figures 2-5). Genesis density in regions such as Greenland, in the
368 North Atlantic, and the southeastern Brazilian coast, in the South Atlantic, seem to be enhanced
369 by the addition of short-lived cyclones included in the statistics. These regions are also
370 highlighted when a smaller displacement threshold is applied (Figure 1). Crespo et al. (2020b)
371 showed five genesis region in South America without the application of any displacement
372 threshold, contrasting the three well-known cyclogenetic regions (Hoskins and Hodges, 2005;
373 Reboita et al., 2010; Gramcianinov et al., 2019). The use of displacement threshold is necessary
374 to avoid the inclusion of thermal and continental lows in the climatology, which may not develop
375 into a cyclone.

376 Another source of discrepancies between the present and previous studies is the use of 1-
377 hourly tracking, since most climatologies are constructed based on 6-hourly atmospheric fields.
378 The improved time-resolution tracking can result in slight differences in genesis position, such as
379 can be observed on the East South American coast. Despite the same tracking method and
380 thresholds, this work present a higher genesis density in Uruguay and a smaller density in the
381 Southeast Brazilian coast than Gramcianinov et al. (2019), which can be associated with the
382 identification of cyclones at earlier lifecycle stages with the use of 1-hourly tracking, instead of
383 6-hourly. Gramcianinov et al. (2019) used an artificial orographic barrier to impose an Andes
384 constraint to their tracking method, which could influence the genesis region position in their
385 work.

386 Regarding the main differences between the two data sets, ERA5 presents 3.7% more
387 cyclones than CFSR/CFSv2 (45.2 cyclones per year), which can be related to the higher

388 resolution of the former. The higher amount of cyclones in the ERA5 impacts the spatial
389 distribution differences both in the North Atlantic and South Atlantic. The track density
390 difference shows a homogeneous distribution in the major part of both domains and does not
391 reveal a shift between the tracks of the two datasets. The direct relation between model
392 resolution and the number of detected cyclones are indicated in many studies (e.g., Bengtsson et
393 al., 2006). The impact of resolution is affected by the orography representation and small-scale
394 processes important to genesis and growth. Therefore, the T42 filtering before the identification
395 process and tracking does not completely exclude the effects of the resolution on the
396 representation of cyclones in ERA5.

397 Cyclogenesis density differences show that CFSR/CFSv2 favors genesis off coast and above
398 the ocean sector, which induce a bias in genesis region along East of the North American coast
399 and Southwest of South American coast when compared to ERA5. This meridional shift in
400 genesis regions may also be related to resolution, once the best representation of orography, land
401 contrast and sea surface temperature can lead to early cyclone detection (e.g., Bengtsson et al.,
402 2006) in the ERA5. However, the differences in genesis densities are evidence of differences in
403 the track lengths between the two datasets. ERA5 presents cyclones that lived longer and travel
404 further than CFSR/CFSv2 (Figure 7), which can be addressed to the inconsistency between
405 forecast and analysis sequential time-steps. Abrupt changes in atmospheric patterns between the
406 forecast and analysis time-step can interrupt a track, breaking a unique cyclone track into two.
407 This continuity issue in CFSR/CFSv2 influences its genesis density, and also its stronger initial
408 vorticity, since a broken track leads to a new track that starts in a more mature stage of the
409 cyclone.

410 Cyclone annual mean and mean characteristics, such as displacement speed and initial
411 vorticity are similar between the two datasets, and their differences are less than 1 standard
412 deviation. Moreover, the track correspondence between the two datasets is high, being higher
413 than 90% to the whole period. In Hodges et al. (2011), the differences between more recent
414 datasets, ERA-Interim and CFSR, were smaller when compared to other older and coarser
415 resolution reanalysis. Both ERA5 and CFSR/CFSv2 are considered to be high-resolution global
416 products, and state of the art for analysis and reanalysis methodology.

417 The most pronounced difference is in the intensity distribution, which shows more intense
418 cyclones in CFSR/CFSv2 than in ERA5. The CFS family present a tendency to represent more
419 intense cyclones, winds and, consequently waves, as reported by several works (e.g., Hodges et
420 al., 2011; Stopa and Cheung, 2014; Gramscianinov et al., 2020b). There are no significant
421 difference between ERA5 and CFSR/CFSv2 when mean maximum wind speed is considered,
422 but the differences increase in the higher percentiles of the distributions (Table 4). The 10-m
423 wind components are diagnostic variables, and their computation depends on the different
424 boundary layers models component of each dataset. Even so, these parameters are widely used in
425 oceanography and ocean engineering studies and the evaluation of cyclone intensity by these
426 fields is of great value.

427 This study shows that the differences between ERA5 and CFSR/CFSv2 are larger for the
428 South Atlantic than North Atlantic. Other comparison studies found the same behavior (e.g.,
429 Hodges et al., 2003; 2011; Stoppa and Cheung, 2004). However, there is a decrease of
430 discrepancies between ERA5 and the more recent CFSv2 when compared to CFSR, particularly
431 in the South Atlantic Ocean. The decrease in differences between datasets in recent years reflects

432 the improvement of the models and increase in data availability as discussed by Hodges et al.
433 (2010).

434 The storm tracks for ERA5 and CFSR/CFSv2 used to produce the climatologies presented in
435 this work are available in <ftp://masterftp.iag.usp.br/EXWAV>. The provided product consists of
436 the set of monthly tracks files that contain the positional information of cyclones.

437

438 **5. Conclusions**

439 This study has evaluated and compared the cyclone climatologies for ERA5 and
440 CFSR/CFSv2 at middle and high latitudes. First, the performance of 1-hourly ERA5 and
441 CFSR/CFSv2 tracking in reproducing the Atlantic storm tracks was analyzed regarding the past
442 literature. Then, the two climatologies were compared to access the main differences between
443 them regarding the basics of storm track characteristics.

444 The storm tracks are in good agreement with past studies, both to North Atlantic (e.g.,
445 Hoskins and Hodges, 2002; Trigo, 2006; Dacre and Gray, 2009; Grise et al., 2013), and South
446 Atlantic Oceans (e.g., Gan and Rao, 1991; Mendes et al., 2010; Reboita et al., 2010;
447 Gramscianinov et al., 2019; Crespo et al., 2020b). The main North Atlantic and South Atlantic
448 storm track characteristics, such as the spiral pattern poleward, seasonal variability, and
449 latitudinal range are represented, as well as the well-known genesis regions within these ocean
450 basins. The use of hourly fields brought benefits to the tracking, particularly in areas with
451 complex terrains, such as the lee of Andes Cordillera in the South America, and East of
452 Greenland in the North Atlantic.

453 Differences between datasets showed that ERA5 has 3.7% more cyclones than CFSR/CFSv2,
454 which can be related to the finer resolution (e.g., Bengtsson et al., 2006). However, cyclone

455 annual mean and mean characteristics (e.g., displacement speed) are similar between the two
456 datasets, and 90% of the tracks correspond between them. An important difference between
457 ERA5 and CFSR/CFSv2 are the shifts in genesis density along the eastern coast, both in North
458 and South America, which can be an indication of resolution impact in cyclone development in
459 regions with complex orography, and temperature gradient. Furthermore, continuity issues in
460 CFSR/CFSv2 due to jumps that might occur where forecast time-steps change to analysis time-
461 steps can lead to broken tracks, and thus, differences between the two datasets, particularly
462 related to genesis statistics and cyclone duration lifecycle.

463 Other relevant differences between ERA5 and CFSR/CFSv2 are the intensity distributions,
464 particularly in the higher percentile of maximum 10-m wind speed. The CFSR/CFSv2 dataset
465 presents more intense cyclones than ERA5 and this behavior persists even when CFSR and
466 CFSv2 were evaluated separately. Other studies have already reported the ability of CFSR
467 (Hodges et al., 2011; Stopa and Cheung, 2014) and CFSv2 (e.g., Gramcianinov et al., 2020b) to
468 represent more extreme wind speed values. It is remarkable that in most of the analyses
469 performed in this work, the differences between datasets decrease when CFSv2 period is
470 analyzed separately, revealing rather a bias correction in the operational version of CFS or an
471 increase of available data and improvement of data assimilation method. In fact, the
472 discrepancies reduction is more pronounced in the South Atlantic, which reinforces the role of
473 data assimilation process in the convergence of the two datasets (e.g., Hodges et al., 2011; Stopa
474 and Cheung, 2014).

475

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487

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675 **Tables**

676 **Table 1.** Mean number of cyclones tracked in ERA5 and CFSR/CFSv2 between 1979 and 2019, annual
 677 and seasonal mean. The mean are also computed for CFSR (1979-March/2011) and CFSv2 (April/2011-
 678 2019) alone. All cyclones that pass within the extratropical latitudes of the South Atlantic (SA; 85°S-25°S,
 679 75°W-20°E) and North Atlantic (NA; 85°N-25°N, 65°W-0°E) Oceans were considered.

		1979-2019				
		Annual	DJF	MAM	JJA	SON
NA	ERA5	551.0 ± 23.6	155.8 ± 9.7	140.9 ± 10.6	117.5 ± 8.3	136.7 ± 9.1
	CFSR/CFSv2	538.7 ± 21.2	152.9 ± 8.1	135.2 ± 11.3	118.0 ± 7.9	132.7 ± 8.8
SA	ERA5	730.9 ± 21.4	158.2 ± 10.0	184.8 ± 11.5	201.9 ± 11.7	186.0 ± 9.9
	CFSR/CFSv2	698.0 ± 19.7	154.2 ± 9.6	177.1 ± 10.6	189.3 ± 10.2	177.4 ± 10.0
		1979-2011				
		Annual	DJF	MAM	JJA	SON
NA	ERA5	537.8 ± 72.5	154.4 ± 14.8	137.7 ± 16.4	117.5 ± 8.7	135.8 ± 8.9
	CFSR	525.2 ± 69.9	151.7 ± 12.9	131.7 ± 16.9	117.5 ± 7.3	131.8 ± 8.4
SA	ERA5	709.2 ± 100.4	155.0 ± 14.1	180.9 ± 24.5	200.3 ± 11.8	184.6 ± 10.6
	CFSR	678.7 ± 97.5	151.5 ± 14.4	174.3 ± 24.3	187.8 ± 10.1	176.2 ± 10.4
		2011-2019				
		Annual	DJF	MAM	JJA	SON
NA	ERA5	538.1 ± 52.9	143.8 ± 36.6	137.2 ± 18.6	117.6 ± 7.0	139.6 ± 9.4
	CFSv2	528.6 ± 54.0	140.0 ± 35.6	133.1 ± 16.6	119.8 ± 10.0	135.7 ± 10.0
SA	ERA5	729.3 ± 57.9	152.4 ± 33.9	178.4 ± 22.3	207.7 ± 9.8	190.8 ± 5.1
	CFSv2	691.0 ± 61.2	147.1 ± 30.9	167.8 ± 21.6	194.6 ± 9.5	181.6 ± 7.6

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687 **Table 2.** Mean characteristics of cyclones for ERA5 and CFSR/CFSv2 (1979-2019), and computed for
688 for CFSR (1979-March/2011) and CFSv2 (April/2011-2019) separately. Initial vorticity is the filtered
689 relative vorticity at the time of genesis, and is scaled by -1 in South Atlantic. Displacement is computed
690 using the first and the last track point. All cyclones that pass within the extratropical latitudes of the South
691 Atlantic (SA; 85°S-25°S, 75°W-20°E) and North Atlantic (NA; 85°N-25°N, 65°W-0°E) Oceans were
692 considered.

1979 - 2019					
		Initial vorticity (CVU)	Lifetime (days)	Displacement (m)	Speed (km h ⁻¹)
NA	ERA5	2.7 ± 1.4	4.4 ± 3.0	2928.5 ± 1582.2	9.6 ± 4.7
	CFSR/CFSv2	2.8 ± 1.5	4.0 ± 2.6	2767.8 ± 1467.6	9.8 ± 4.6
SA	ERA5	2.9 ± 1.5	3.9 ± 2.6	3712.0 ± 2157.9	13.2 ± 5.3
	CFSR/CFSv2	3.2 ± 1.6	3.3 ± 2.1	3228.3 ± 1855.6	13.3 ± 5.3
1979 - 2011					
		Initial vorticity (CVU)	Lifetime (days)	Displacement (m)	Speed (km h ⁻¹)
NA	ERA5	2.7 ± 1.4	4.4 ± 2.9	2919.2 ± 1569.4	9.6 ± 4.6
	CFSR	2.9 ± 1.5	4.0 ± 2.6	2750.6 ± 1452.6	9.8 ± 4.6
SA	ERA5	2.9 ± 1.5	3.9 ± 2.6	3688.0 ± 2146.9	13.2 ± 5.3
	CFSR	3.3 ± 1.6	3.2 ± 2.1	3155.5 ± 1799.8	13.3 ± 5.3
2011 - 2019					
		Initial vorticity (CVU)	Lifetime (days)	Displacement (m)	Speed (km h ⁻¹)
NA	ERA5	2.7 ± 1.5	4.5 ± 3.1	2962.5 ± 1628.0	9.6 ± 4.8
	CFSv2	2.8 ± 1.6	4.1 ± 2.7	2830.7 ± 1519.6	9.8 ± 4.7
SA	ERA5	3.0 ± 1.5	4.0 ± 2.7	3797.7 ± 2194.7	13.3 ± 5.4
	CFSv2	3.2 ± 1.6	3.6 ± 2.3	3490.3 ± 2022.5	13.4 ± 5.3

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694 **Table 3.** Percentage of the number of matched tracks for ERA5 and CFSR/CFSv2 (1979-2019), CFSR
695 (1979-March/2011), and CFSv2 (April/2011-2019). Similar tracks are obtained in DJF for the North
696 Atlantic (NA), and JJA for the South Atlantic (SA) Oceans.

		1979 - 2019	1979 - 2011	2011 - 2019
NA	ERA5	92.7%	91.9%	87.1%
	CFSR/CFSv2	96.0%	94.9%	91.1%
SA	ERA5	93.1%	91.8%	89.2%
	CFSR/CFSv2	96.5%	95.4%	91.8%

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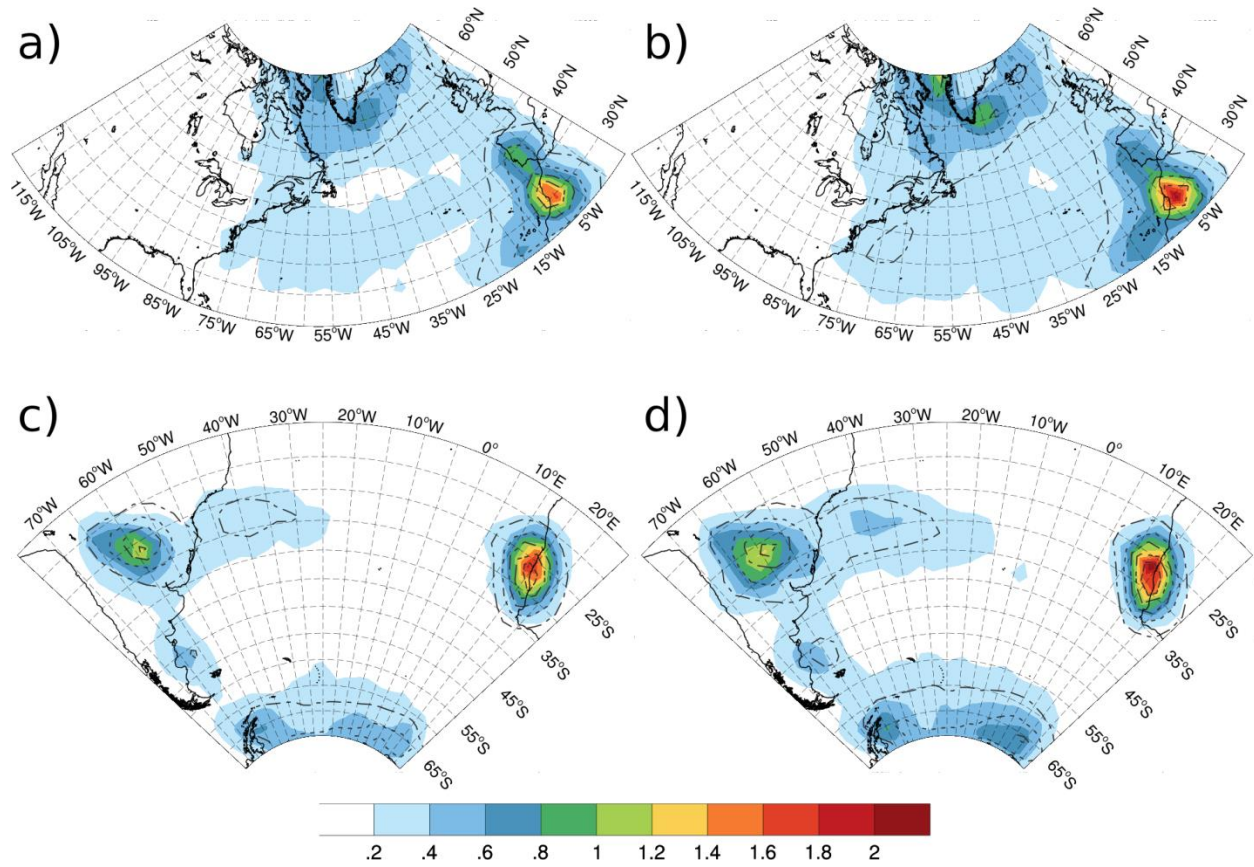
698 **Table 4.** Mean maximum 10-m wind speed (m s^{-1}) and percentiles of cyclones for ERA5 and
699 CFSR/CFSv2 (1979-2019) in DJF for the North Atlantic (NA), and JJA for the South Atlantic (SA)
700 Oceans. Matched cyclones are identical storms find in both datasets.

		ERA5				CFSR/CFSv2			
		mean	50%	90%	95%	mean	50%	90%	95%
NA	all	21.4 ± 5.1	21.1	28.2	30.1	23.9 ± 6.4	23.7	32.5	35.0
	matched	21.5 ± 5.1	21.2	28.3	30.2	24.0 ± 6.4	23.8	32.6	35.0
SA	all	21.2 ± 4.8	21.0	27.3	29.3	23.4 ± 4.8	23.3	30.2	32.1
	matched	21.2 ± 4.8	21.0	27.4	29.3	23.4 ± 5.3	23.4	30.2	32.2

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702 **Figures**

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Figure 1. Genesis (shaded) and track (contour) densities computed for cyclones that last at least 24 hour and travel less than 1000 km for the (a) North Atlantic in ERA5 and (b) CFSR/CFSv2, and (c) South Atlantic in ERA5 and (d) CFSR/CFSv2. The density unit is cyclones/track per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km²). The track density contour are with contour interval 1 track per month per area, and the densities are calculated for 1979-2019.

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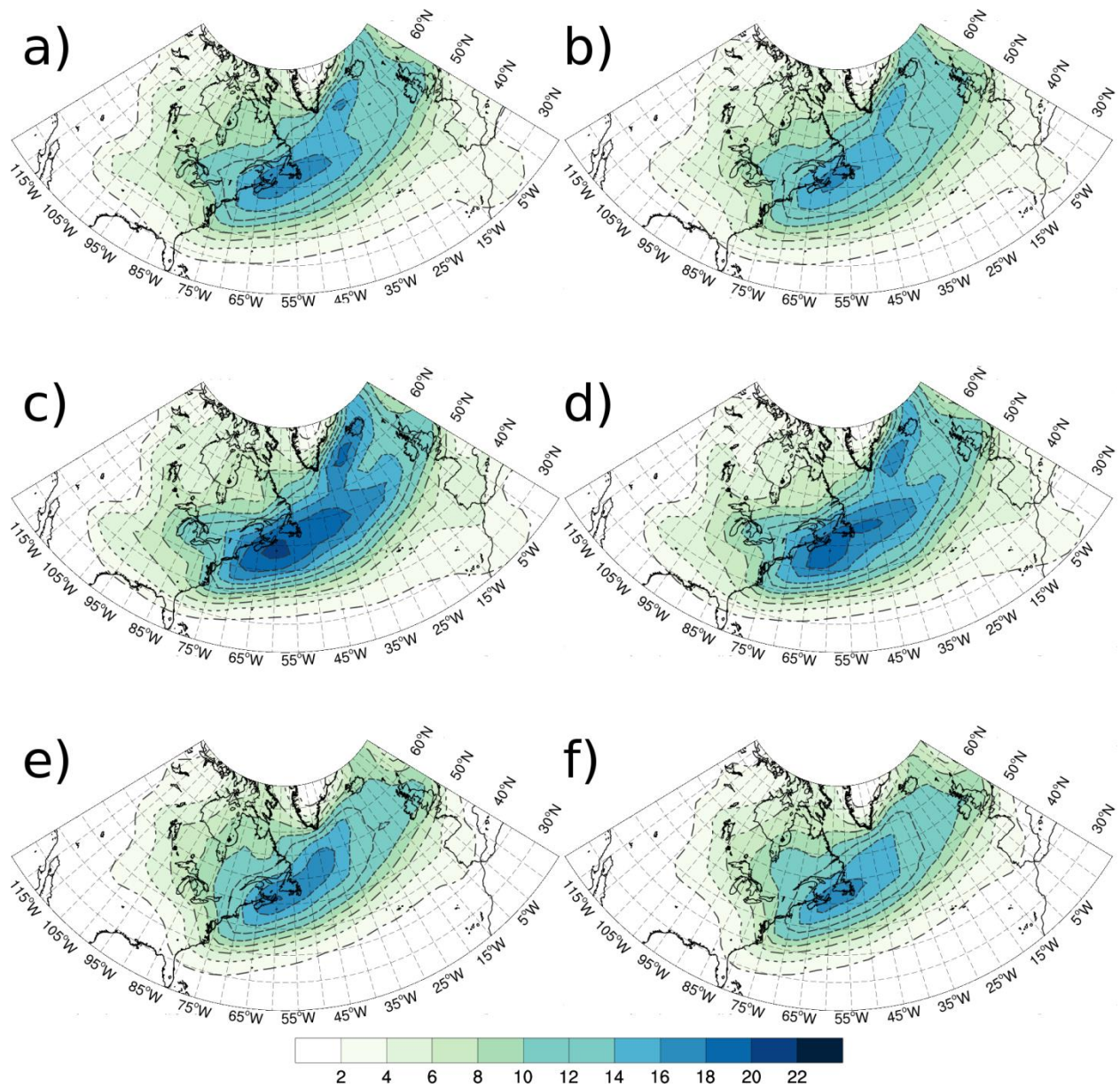


Figure 2. Track densities computed for the North Atlantic in (a,c,e) ERA5 and (b,d,f) CFSR/CFSv2, considering (a,b) all period (1979-2019), (c,d) DJF, and (e,f) JJA. The density unit is track per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km^2). The contour interval is 2 tracks per month per area.

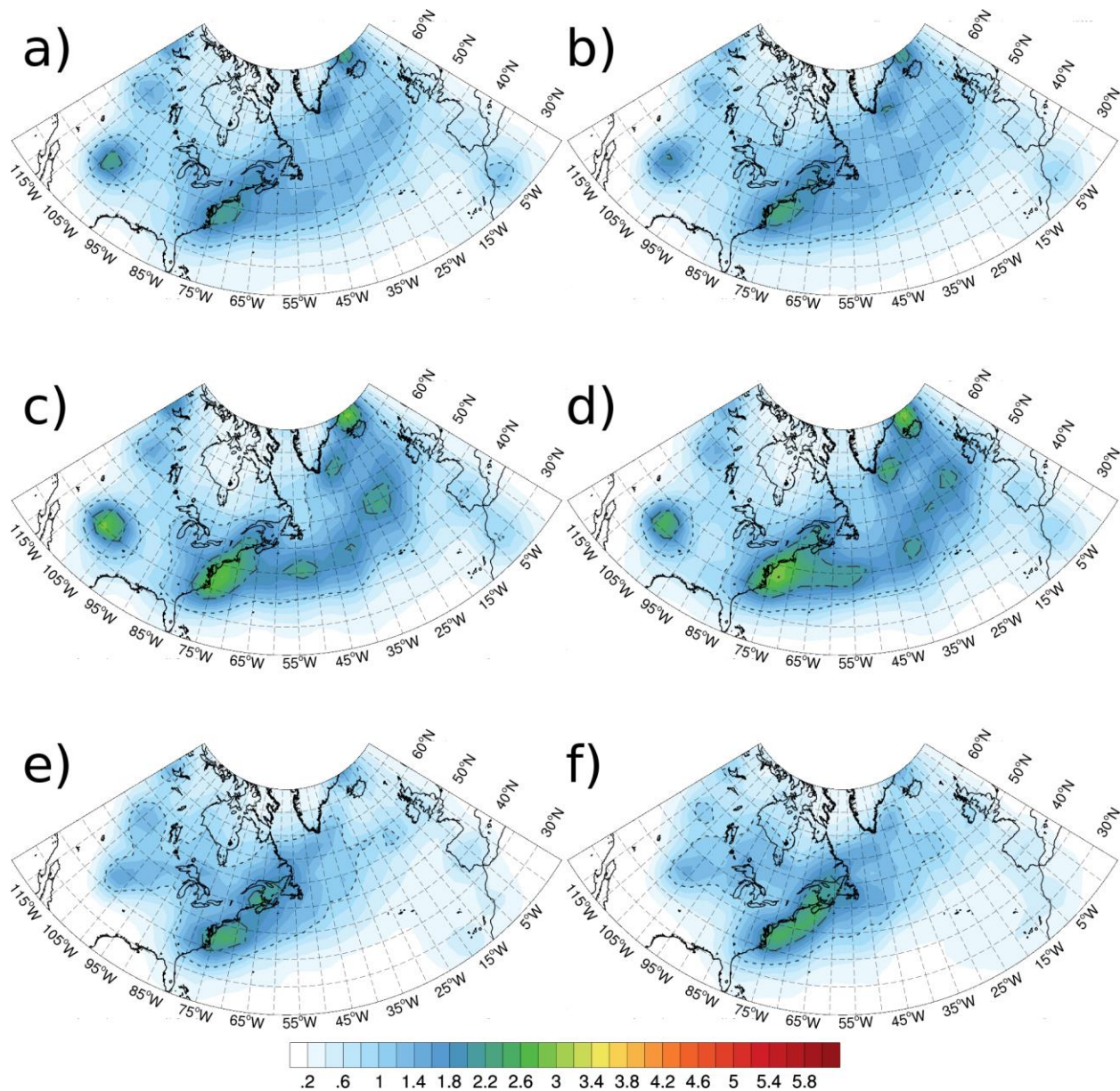


Figure 3. Genesis densities computed for the North Atlantic in (a,c,e) ERA5 and (b,d,f) CFSR/CFSv2, considering (a,b) all period (1979-2019), (c,d) DJF, and (e,f) JJA. The density unit is genesis per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km 2). The contour interval is 1 genesis per month per area.

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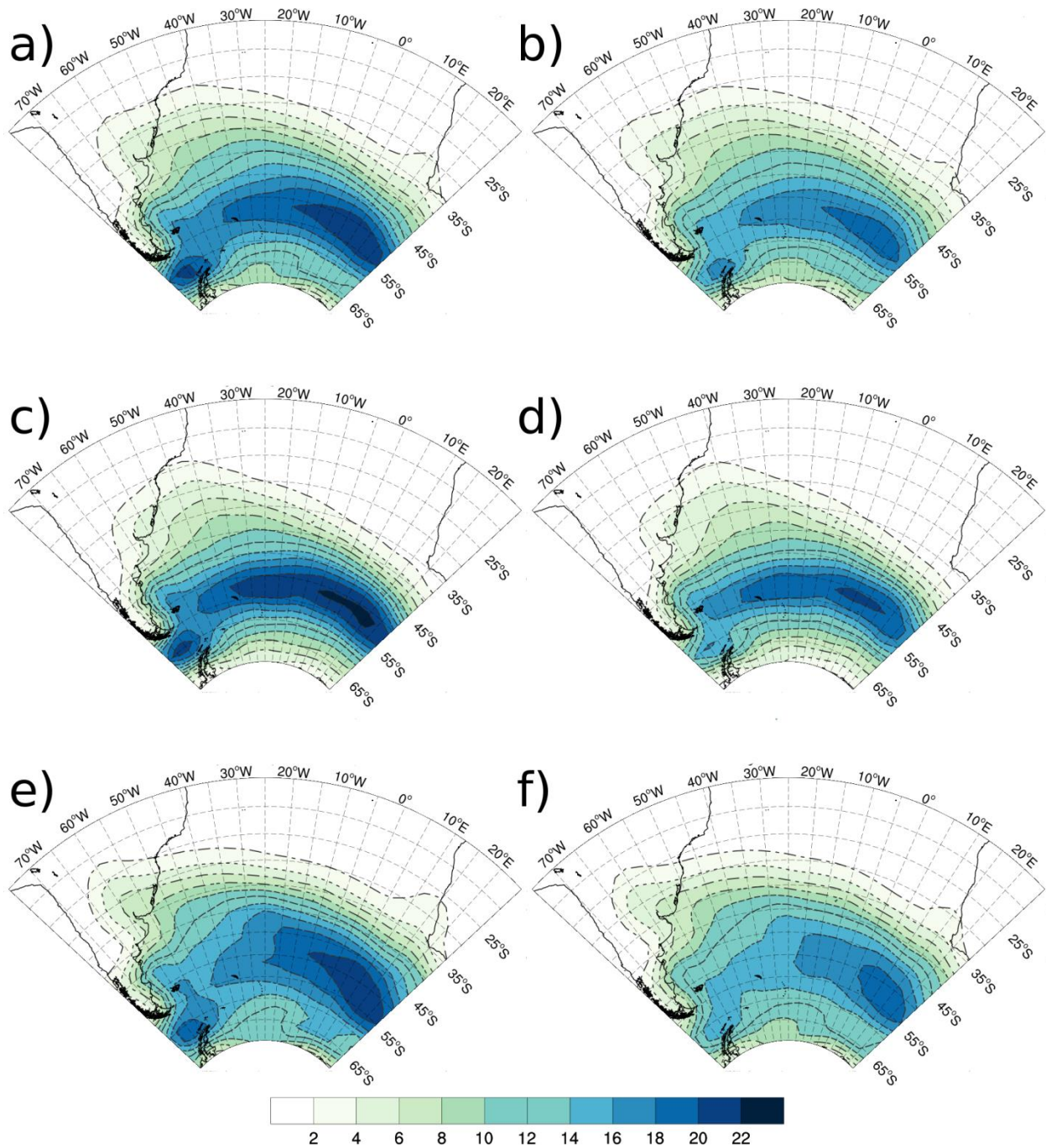


Figure 4. Track densities computed for the South Atlantic in (a,c,e) ERA5 and (b,d,f) CFSR/CFSv2, considering (a,b) all period (1979-2019), (c,d) DJF, and (e,f) JJA. The density unit is track per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km²). The contour interval is 2 tracks per month per area.

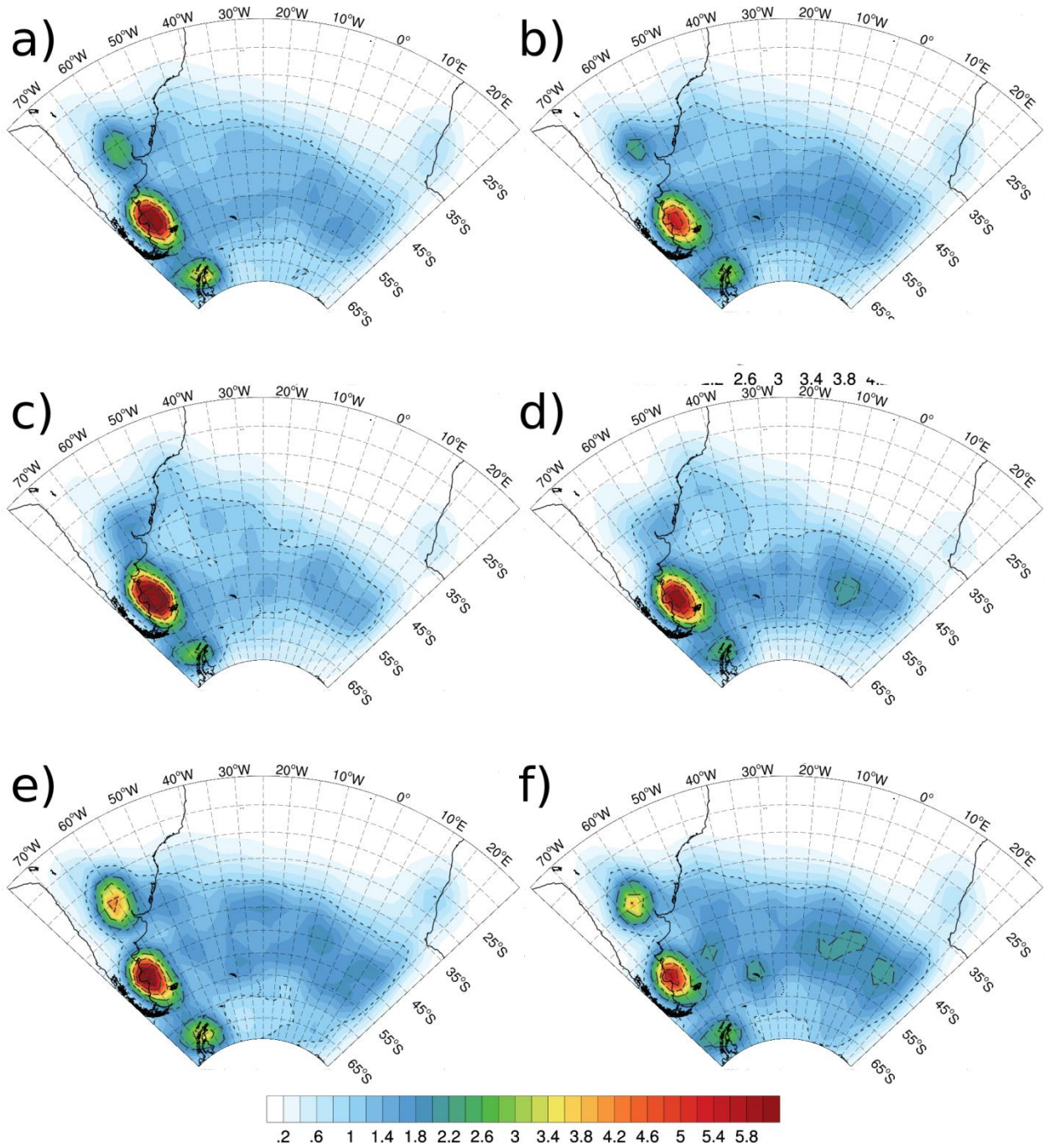


Figure 5. Genesis densities computed for the South Atlantic in (a,c,e) ERA5 and (b,d,f) CFSR/CFSv2, considering (a,b) all period (1979-2019), (c,d) DJF, and (e,f) JJA. The density unit is genesis per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km 2). The contour interval is 1 genesis per month per area.

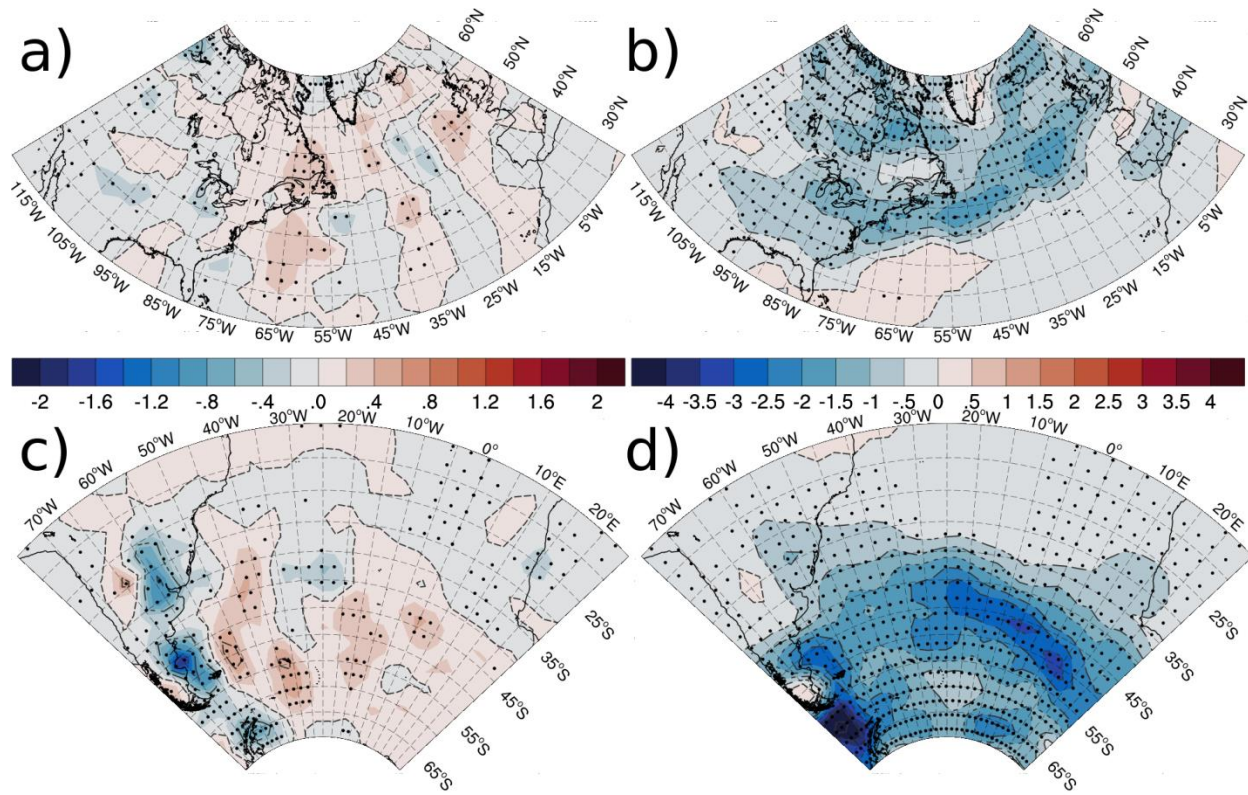


Figure 6. Densities differences in (a,b) DJF for the North Atlantic and (c,d) JJA for the South Atlantic, for the (a,c) cyclogenesis and (b,d) storm track. The density difference unit is cyclones/track per month per area, where the unit area is equivalent to a 5° spherical cap (10^6 km^2). The dots represent grid points where the trend is significant within 99% confidence level, and the differences are CFSR/CFSv2 minus ERA5 considering 1979-2019 period.

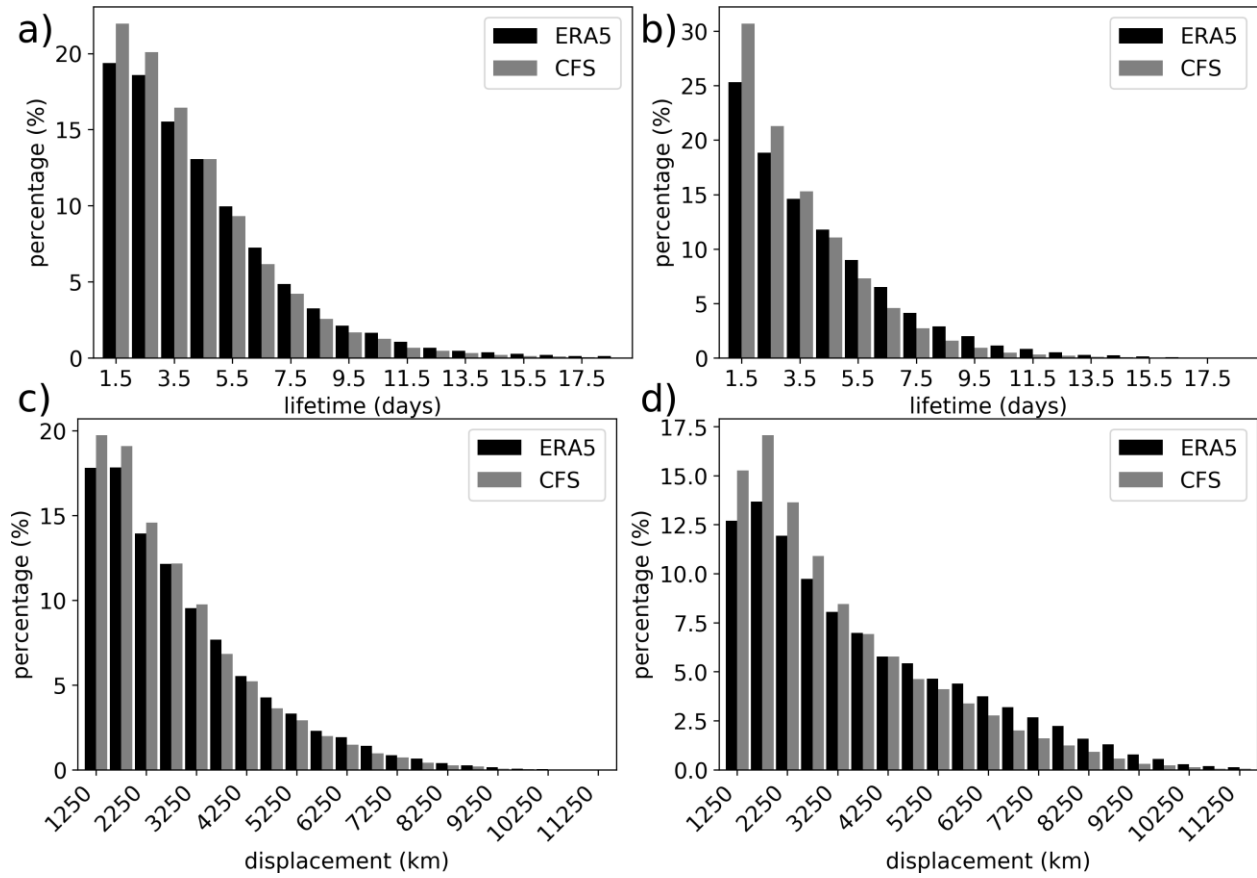


Figure 7 Histograms of cyclones (a,b) lifetime (days), and (c,d) displacement (km).for the (a,c) North Atlantic and (b,d) South Atlantic Oceans. The histograms were computed considering the whole 1979-2019 period for the ERA5 (black) and CFSR/CFSv2 (grey).

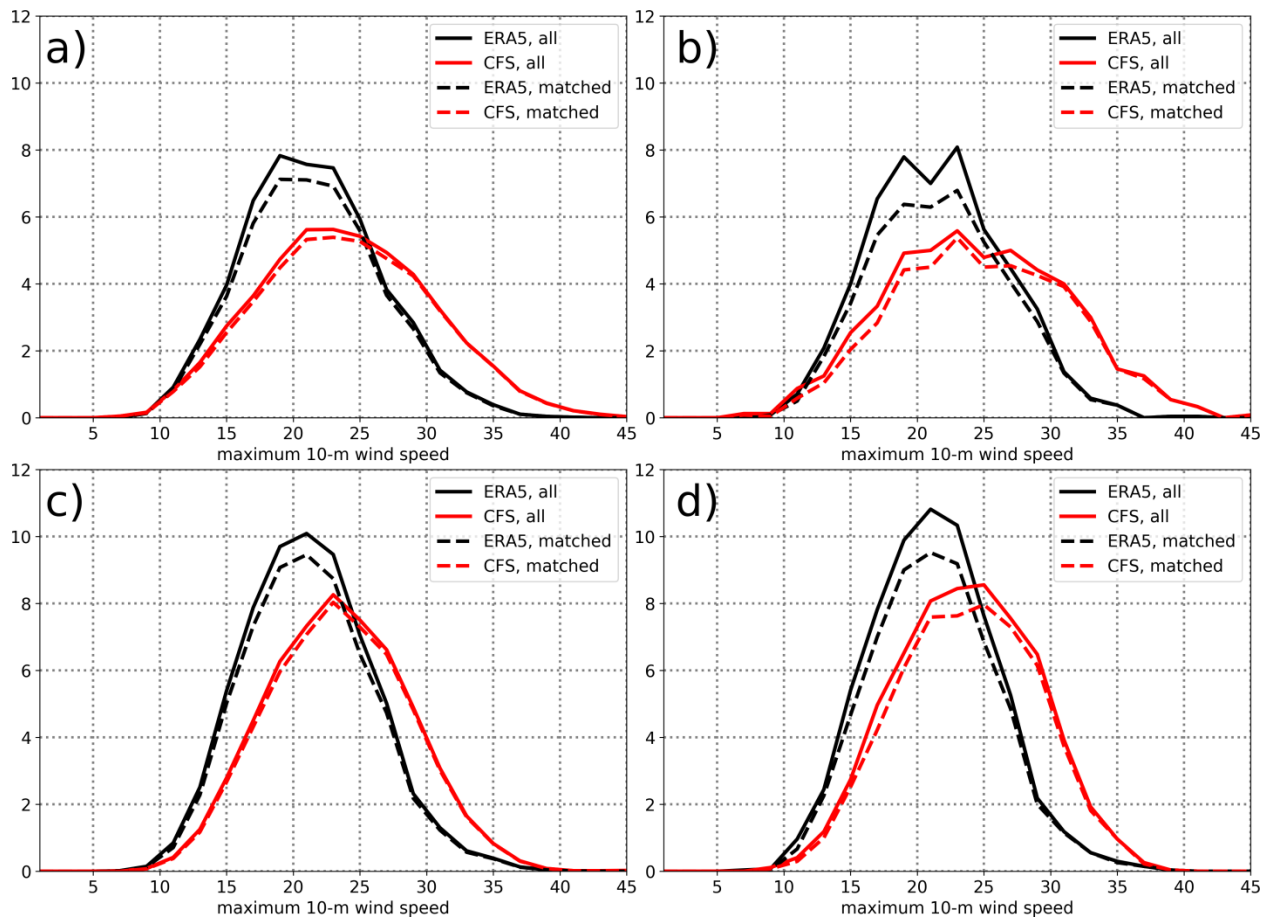


Figure 8. Cyclone’s maximum 10-meters wind speed (m s^{-1}) distribution for the (a,b) North Atlantic in DJF, and (c,d) South Atlantic in JJA, considering the period between (a,c) 1979 and 2019, and (b,d) April/2011 and 2019. ERA5 distributions are in black, and CFSR/CFSv2 are in red. The dashed lines are the distributions computed for the matched cyclones in each dataset. The y-axis is cyclone per month.