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# Early 21st Century cyclone climatology: a 3D perspective. Basic Characterization

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#### 34 Abstract

35 Extra-tropical cyclones are a prelevant feature in the climate at middle and high latitudes. Despite their 36 importance, most studies typically focus only on cyclones identified at a single atmospheric level and on events close to the surface. This paper provides a new perspective on the Southern Hemisphere (SH) cyclone 37 38 events based on the multilevel cyclone tracking algorithm STACKER. The algorithm, using relative vorticity, detects the raw tracks at single levels and objectively combines them to provide the 3D events and 39 their evolutionary timeline. As a result, a 3D cyclone climatology, based on ECMWF Reanalysis ERA-I data 40 41 from 12 pressure levels in the troposphere and lowermost stratosphere is presented. To the best of our 42 knowledge, this is the first analysis carried out throughout the troposphere and the lowermost 43 extratropical/subpolar stratosphere in order to give a comprehensive picture of the cyclone events as physical 44 entities throughout their lifetime. Cyclone properties analysed are track densities, translational velocity, 45 vorticity and lifetimes. For the subtropical and extra-tropical SH, results support many previous ideas about 46 cyclone characteristics, but new insights are also obtained. A total of 58231 multilevel cyclone events lasting 47 at least 2 days were detected, with vertical structures spanning two or more levels. This means an average of 303 cyclone events of all types per month, between 2001 and 2017, disregarding seasonality. Results show 48 that cyclones are most frequently detected at the lowest levels of 925 and 700 hPa. By considering that 49 cyclonic systems can be grouped into families according to their vertical extent, results per month on average 50 51 show that shallow systems are the most frequent events with approximately 248 systems detected, followed by 43 intermediary and 11 deep events. Shallow and deep systems have a large percentage of events with 52 genesis at 925 and 700hPa. Density statistics show that shallow events are present at all latitude ranges 53 mostly poleward of 30°S with high and medium intensities, while intermediate ones are mostly restricted to 54 mid-latitudes and deep events are mostly confined to sub-polar and polar latitudes. Cyclones over Antarctica 55 seem to be mostly intermediary and deep cyclones, with longer lifetimes and lower velocities. 56

57 Keywords: STACKER, 3D cyclone climatology, feature tracking, relative vorticity, multilevel structures.
58 Dynamic programming, Optimal algorithm

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## 60 1. Introduction

Cyclone activity represents an important feature of the general circulation of the atmosphere because they 61 transport large amounts of energy, momentum and moisture polewards. The passage of cyclones is also 62 63 linked to severe weather in terms of rainfall, snowstorms and strong winds (Sinclair, 2020), In a climate that is expected to become warmer in the future, with more frequent severe events, understanding changing 64 cyclone behaviour is a particularly complex and important challenge, especially considering their potential 65 economic and human impact (IPCC, 2007, 2014). At mid-latitudes, the cumulative behaviour of cyclones is 66 what constitutes the storm tracks (Catto, 2018). As Valsangkar et al. (2018) point out with regard to future 67 climate change and the associated changes in the storm tracks, understanding the genesis and life-cycle of 68 extra-tropical cyclones is an issue of great relevance. The analysis of the cyclones must include not only 69 70 their characteristics, location, intensity and frequency but also identify and track their path, origin and 71 evolution.

Many studies have addressed the topic since van Bebber (1882) studied cyclones with a manual analysis of synoptic weather charts. Since then, a considerable number of analysis methods have been developed with a wide variety of results, depending on the availability of the parameters considered, the cyclone definition applied and the algorithm designed to track them (e.g., Neu et al, 2013, Grieger et al, 2018). Examples of such studies are, among others, Sinclair (1994, 1995, 1997; 2002); Inatsu, (2009); Reboita et al. (2009); Eichler and Gottschalck, (2013), Hoskins and Hodges (2005).

Many methods used to detect and track cyclones are based on some variant of the neighbour point tracking 78 (NPT) method, which consists of two step: first, the cyclonic system centres, defined as a local maximum or 79 80 minimum value of a climatic variable, are detected at each time step; and secondly the track is obtained by linking these points together based on the nearest neighbour method (Kelemen et al., 2015) (Satake et al., 81 82 2013; Flaounas, 2014). Currently available algorithms mostly track atmospheric events broadly across the globe using mean sea level pressure (MSLP), geostrophic vorticity, geopotential heights, potential and 83 84 relative vorticity, singly or in combination (Hanson et al., 2004; Picornell et al., 2001; Jansa et al., 2001; Trigo et al., 1999, Hoskins and Hodges, 200; Flocas et al, 2010; Kouroutzoglou, et al., 2012). The most 85

86 frequent variables used are local minima in MSLP or maxima or minima in vorticity (depending on hemisphere) at a single geopotential height or pressure level (Pepler and Dowdy, 2020; Walker et al., 2020). 87 An efficient algorithm implies the use of a decision tree formulated around constraints on cyclone properties 88 89 in order to be able to identify feature values (typically values above or below a prescribed value). The detected centres are then organised into the cyclone trajectories. The algorithm also has to deal with the fact 90 that cyclones may split or merge with other cyclones. Because cyclones can have diverse characteristics and 91 evolution at various levels, a single-level analysis will affect the climate statistics and conclusions derived 92 from such algorithms. Despite the fact that the vertical structure of a system is known to play a major role 93 94 in its development and impacts (Pepler and Dowdy, 2020), most of the analyses typically focus on cyclones identified at a single atmospheric level and in events close to the surface. 95

96 There are very few analyses that consider multilevel events and those that do usually only span levels up to 97 500 hPa. Lim and Simmonds (2007) compared cyclone tracks at six levels, between MSLP and 500hPa, to 98 assess the vertical climatology of SH cyclones for the austral winter months (JJA), for the period 1979-2001. 99 The analysis was based on cyclone tracks defined in terms of multiple-level events by considering their variations in height, as well as sequences of multilevel overlaps defined for track points at different 100 contiguous levels at a given timestep (whose coordinates at an immediate upper level fall within a 4° latitude 101 radius ( $\approx$ 444 km) of the track point being considered at the lower level). This is carried out at each time step, 102 103 comparing track points at subsequent levels. Results of this bottom-to-top approach composition were further separated into shallow (up to 700hPa) and well-organized cyclones (at least up to 500hPa). Their results 104 showed that cyclones are frequently detected at the surface and at 500 hPa, with a minimum frequency value 105 106 at 700 hPa, while about 52% of SH winter events have a vertically well-organized structure, extending 107 through the 500-hPa level.

Pepler and Dowdy (2020) based on the results of Lim and Simmonds (2007) and using mean sea level pressure (MSLP) from ERA-Interim reanalysis data, carried out a study of the global distribution of cyclones at six vertical levels to analyse how the frequency of deep or well-organized events varies around the world, with a focus on south eastern Australia. They found that about 50% of global cyclones show a coherent vertical structure extending to at least 500 hPa, while shallow cyclones are most common in the global mid

113 latitudes. On the other hand, the results obtained when the cyclone analysis was restricted to Australia showed that deep surface cyclones tend to be stronger, larger, and longer-lived than shallow surface 114 cyclones, and they also have higher maximum rain rates and wind speeds than shallow surface cyclones, 115 resulting in significantly larger total rainfall accumulations. Therefore, their findings clearly highlight the 116 117 need and benefits of examining cyclones over multiple levels of the troposphere due to the importance of 118 deep events for causing extreme weather events. Given these results, and in order to give a more coherent three-dimensional picture of cyclone structure and evolution, a multi-level, self-consistent cyclone tracking 119 120 algorithm is needed. Including a greater number of atmospheric levels in the algorithm will allow us not only 121 to delve into more detailed information of each level, but also to analyse the systems from a new perspective to give a full 3D view of the cyclone lifecycles. 122

123 Hodges (1994, 1995, 1999) has developed a detection and tracking algorithm TRACK. The algorithm can use relative vorticity pressure/geopotential anomalies computed from MSLP and geopotential as in Lim and 124 Simmonds (2007). By using Hodges's algorithm and the starting point provided by Lim and Simmonds 125 (2007) for the implementation, we have extended the algorithm to create a comprehensive fully automated 126 127 algorithm for the processing and combination of cyclone tracks at multiple levels. A detailed description of this algorithm, named STACKER, can be found in Lakkis et al. (2019). Briefly, the algorithm determines 128 129 which cyclone events independently tracked at different levels are to be combined into single (multi-level) 130 events, preserving all the track features detected at each level. The STACKER was built using a Smoothness 131 Cost Function approach (Lakkis et al. 2019). European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis ERA-Interim (ERA-I) products for the SH were used. In Lakkis et al (2019). 132 STACKER was applied to track events for the 2015 winter (JJA) in the SH, using tracks determined at 7 133 levels between the surface and the vicinity of the tropopause. For validation, three multilevel events, which 134 135 developed with different characteristics near Southern South America, were selected and compared with GOES cloud imagery, ERA-I cloud cover and winds. A very high correspondence was observed between 136 137 the multilevel tracked events, GOES cloud imagery and ERA-I selected variables.

The purpose of the present study is to develop a 3D cyclone climatology for the SH during the first decades
 of the 21<sup>st</sup> century using the STACKER algorithm, including both single-level and multilevel analysis. This

140 climatology is based on 17 years (2001-2017) of ECMWF Reanalysis ERA-I data using 12 pressure levels in the troposphere and lowermost stratosphere. The vertically tracked cyclones are categorized into families 141 defined by their vertical extent given by the maximum number of levels present in each cyclone event 142 (shallow, intermediate and deep) and height of occurrence. In section 2, we present the ERA dataset and the 143 144 analysis techniques used. Results are presented in section 3, focusing on the analysis of the density, intensity, 145 lysis and genesis region as well as translational velocity. Finally, a discussion and concluding remarks are presented in section 4. To the best of our knowledge, this is the first analysis to attempt the combination of 146 147 such a large number of atmospheric levels in the lifetime of the cyclone systems, viewing them as vertically 148 coherent physical entities, rather than sample slices at specific pressure levels.

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# 2. Data and Methodology

This study follows closely the methodology in the previous SH cyclone tracking study of Lakkis et al (2019, 151 152 L4DC from now on), and draws from concepts introduced in Lim and Simmonds (2007) and Hoskins and Hodges (2005). In order to cover the tropospheric depth more completely and to provide insights of the 153 cyclonic events throughout their entire life cycle, the analysis explores a wider range of pressure fields for 154 cyclone track activity between 925hPa and 100hPa than in our previous work (12 levels vs. 7 levels in 155 L4DC). The study area spans the latitude band 14°S to 78°S. The tracking is performed using the STACKER 156 157 algorithm (L4DC) involving single level cyclone tracks obtained with the TRACK algorithm (Hodges, 1995, 1999) for the following twelve pressure levels: 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 850 and 158 925 hPa. Potential cyclone centres at a given level are initially identified in the T42 filtered data as minima 159 160 (for SH) by comparing the relative vorticity values of each grid point to its neighbouring grid points and then refined to find their off-grid locations using B-splines and steepest descent minimization (Hodges, 1995). 161 As was mentioned in the Introduction, cyclones can have any lifespan at a given level, but multi-level events 162 are only retained when they persist for at least 2 days. Following the criteria adopted in L4DC, the relative 163 vorticity threshold used is  $-1.0 \times 10^{-5 \text{ s}-1}$  at all levels. This is set at a comparatively low value to capture as 164 much of the cyclone life cycle as possible during any season (A more restrictive threshold will reduce the 165 number of systems identified but will also shorten the life cycles of those that are identified, even more so 166

167 for the weaker summer systems). These points are then initialised into a set of tacks using a nearest neighbour method and are then refined by iteratively swapping points between tracks forward and backwards in time 168 to minimize a cost function for track smoothness. The cost function is subject to adaptive constraints for 169 displacement distance and track smoothness suitable for the extra-topics (Hodges, 1999). This produces the 170 171 minimal set of smoothest tracks. The L4DC analysis has been expanded to include more pressure levels and 172 to improve the space resolution and time evolution of cyclones. Using the objective function criterion, as in 173 L4DC.the STACKER algorithm is designed to associate all tracks obtained from a given (single-level) 174 feature-tracking algorithm that represent the same synoptic event at different vertical levels The process is 175 performed iteratively over adjacent pressure levels until the stacking of tracks is complete. For robustness of results, the algorithm works both bottom-to-top and top-to-bottom (stacking lower level tracks under 176 higher level tracks in the latter case), capturing such features as upper level troughs or cut off lows. Further 177 details of the STACKER algorithm, including the relative vorticity choice, parameterization criteria, event 178 179 validation and preliminary statistics, can be found in L4DC.

The data used in this study are from the ERA-I reanalysis, generated with a numerical model constrained by observational data (Dee et al., 2011). The data products include a large variety of variables, but in this study the core data were fields of relative vorticity (RV) at 6 hourly intervals, spanning the period 2001-2017, with the horizontal reanalysis resolution of  $1.5^{\circ} \times 1.5^{\circ}$ . For the interpretation of results in the discussion, horizontal wind components U, V in the upper troposphere and SST in the ERA-I database are also used.

Concerning the choice of data, an extensive discussion about the impact on the results of using different 186 187 climate variables for the event identification, different databases and methods, can be found in the recent literature (Hodges et al., 2011; Vessey et al., 2020). As mentioned in L4DC, Hodges et al. (2011), using 188 four different analyses (Japanese JR25, ERA-Interim, NASA MERRA and NCEP CFSR) showed that the 189 detected cyclones, in terms of numbers, location and spatial distribution, compared well between each 190 reanalysis. Slight discrepancies may arise primarily in the cyclone intensities and they are greater in the SH, 191 in regions of growth or decay. Ulbrich et al. (2009) also found some disagreements between results using 192 different reanalysis for both hemispheres, with some noteworthy differences in summer months. According 193

to them, the differences when comparing reanalysis datasets are mostly linked to different spatial resolutions.
 In a later analysis where eleven different methods for cyclone detection and tracking have been applied to a
 particular ECHAM5/OM1 model run under transient greenhouse gas forcing, Ulbrich et al (2013) concluded
 that in spite of differences in absolute cyclone track numbers between the different methods, there is an
 agreement between the results using these algorithms, both with respect to the distribution of cyclones and
 with respect to change signals.

- Three cyclone families are defined in terms of the maximum number of levels present in the events: shallow, intermediate and deep. Figure 1 shows this classification of events, as well as subdivisions into subfamilies, or subtypes, depending on the height ranges of the pressure levels where the events are detected. Note that the cyclones are classified into families on the basis of the maximum number of levels an event has at any stage during its lifetime. Events belonging to shallow and intermediate cyclone families are assigned to a sub-family depending on the level of occurrence of the lowermost level of each cyclone event. Deep events are not separated into subfamilies.
- The overall cyclone events and their family and type are considered in the subsequent analysis in order to 207 208 develop the 3D SH cyclone climatology. This analysis is further broken up into seasons: austral summer (DJF), austral autumn (MAM), austral winter (JJA) and austral spring (SON). The cyclone properties 209 210 analysed are: track densities, translational velocity, vorticity and lifetimes, between 14°S to 78°S. Genesis and lysis density distributions are also considered. All variables are plotted at 2x2° resolution for the full 211 212 study area. In the case of track densities, at a given timestep the total number of events where there is a track 213 position present at each 2°x2°area or grid point are computed and given as monthly mean seasonal values 214 for each season. These are corrected for grid point central latitude so that the density refers to equal area pixels. Lifetimes are obtained by considering the times and dates of the first and last positions of each cyclone 215 event. These values are then assigned to the grid points over which the cyclone event moved. All the lifetimes 216 in each grid point were then vertically averaged. The translational velocity and the vorticity are calculated 217 218 at each timestep and pressure level in a given event and averaged in height and assigned to the corresponding 219 grid point at each timestep. All values for events in each grid point were then averaged. The first (last) event

- position were considered for genesis (lysis) plots. Trajectories from (to) major genesis (lysis) areas are also
   considered.
- **3.** Results: **3D** Cyclone climatology, a family perspective
- 223 **3.1** An overview of family distribution

The annual and seasonal frequencies of cyclones over the SH were obtained between 14° and 78°S during 224 the period 2001 to 2017. A total of 58231 multilevel events were detected corresponding to an average of 225 303 per month. This is composed of approximately 248-249 shallow systems, 43 intermediate systems and 226 11-12 deep events each month on average. The percentage of shallow events is greater than that reported by 227 228 Pepler and Dowdy (2020) and Lim and Simmonds (2007) and even in L4DC, but the latter only considered a single winter season. Tests carried out with the STACKER show that the greater the number of pressure 229 levels included in the analysis, the greater percentage of shallow systems that are detected, whereas the 230 231 intermediate and deep number of events remains fairly constant or even decreases. It is important to bear in 232 mind that using different approaches to the tracking and different datasets as input can lead to variations in the results. According to Raible et al. (2008), differences in the location and number of tracks could be due 233 234 to the choice of variable used. Additionally, the difference in frequency and number of events may also be linked to the criteria of minimum lifespan of the events included in the analysis. For example, Pepler and 235 Dowdy (2020) included events without a minimum lifespan threshold. 236

237 A preliminary inspection of the frequency distribution of events per level, i.e., TRACK outputs, indicates 238 that more cyclones are detected in the mid-troposphere, 600 and 500 hPa being the pressure levels with most events. The average frequency in cyclonic systems decreases, albeit slightly, in the 700-925 hPa range, with 239 minimum values at 700 hPa. A similar minimum was observed in both Lim and Simmonds (2007) and 240 Pepler and Dowdy (2020). In the upper troposphere/lowermost stratosphere, the 250 hPa level has the most 241 242 events detected. The annual histograms for cyclone families at different levels for all the events (not shown), 243 show the shallow family is the most populous with 47751 events, followed by 8235 intermediate and 2245 244 deep family events. When the frequency distribution is given in terms of the lowermost pressure level per event (constructed by assigning an event, determined by STACKER to the lowermost level present during 245 its lifecycle as previously explained), it shows two maxima at 925 and 700 hPa, with close to 13000 and 246

247 9000 cyclonic systems respectively. In other words, events are counted as units or entities defined by STACKER, not overall number of cyclone tracks obtained with TRACK. Above 700 hPa and up to 300 hPa 248 the vertical distribution of events is approximately constant with height, with an average of 6000 events per 249 level. When the lowermost level of a system is near the tropopause, and hence the system may extend into 250 251 the lower stratosphere, the number of events decreases to 4000 or less per level. In general terms, minimum 252 values are detected at 125, 200 and 850 hPa. Minimum values in the number of events are observed near the 253 surface, at 850hPa. Overall, close to 40% of detected events thus occur near the surface, while about 50% of 254 cyclones have their lowermost level in the mid troposphere up to 300hPa.

Figure 2a shows the lowermost level distribution by family. For the shallow events the distribution shows 255 that these systems are the most frequently detected throughout the entire period of analysis, with a large 256 257 percentage of events that have their lowermost level at 925 and 700hPa. Another secondary peak is found at 300hPa. Beyond that level the event count decreases rapidly. The intermediate cyclone family (Fig. 2b) has 258 259 rather similar number of events at 925, 700, 500, and 400hPa with maxima near the surface and at 500hPa. Finally, the family of deep events (Fig. 2c) has similar counts of events at 925 and 700hPa with an 260 261 exponential decay in the count above. All families have low event counts at 850hPa, i.e., fewer events appear to have their lowermost level at 850hPa. Results per family also show that on average, per year, the shallow 262 263 system translational velocity values were found to be close to 10 m/s, with lifetime values around 6.5 days, while the intermediate and deep systems display translational velocities of the order of 8 and 4 m/s 264 respectively, with similar mean lifetime values of 8.9 and 8.3 days. Translational velocities for shallows 265 systems reported here, are in good agreement with Lim and Simmonds who reported a translational velocity 266 ranging between 8.7-9.8 m/s. However, lifetimes here appear to be somewhat longer, probably due to the 267 268 use of relative vorticity tracking.

In order to provide a more detailed overview of these mean values of each family, Table 1 shows the zonal mean average translational velocity, vorticity, lifetime and density values, where each latitude band spans 8° of latitude and the values are given in terms of the average value of each properties within each band. On average, higher density values for all the events can be found between 50°S-60°S, while overall values decrease towards the Equator. Similar results were found in Keable et al. (2000). However, shallow
systems, by far the most numerous, have their highest frequency around 50°S-58°S.

For intermediate and deep events, results also show increasing differences poleward, in particular for deep ones. Higher densities can be found around 60°S-65°S, with translational velocities close to 10-12 m/s Vorticity in all cases show relative stable values across latitude bands. The results also show that overall, shallow and intermediate events are the fastest systems, with shorter lifetime while deep systems tend to move slower for the longest time. These characteristics are also analysed subsequently considering seasonal behaviour.

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# 3.2 2001-2017 Basic annual and seasonal cyclone spatial characteristics

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### 284 **3.2.1** Cyclone densities

Figure 3 shows the annual spatial distribution of cyclone density during 2001-2017 for all multilevel 285 cyclones detected (Fig. 3a). Cyclones are broadly distributed from the subtropics (approx. 30°S) into polar 286 regions. During this period, the highest cyclone density occurs in the extra-tropics, from mid-latitudes 287 towards Antarctica. High cyclone densities occur over the South Pacific. Somewhat lower cyclone densities 288 are observed at mid latitudes over the southern central Indian Ocean. Density variations, with maxima and 289 290 minima, can be observed near and over East Antarctica. Peak densities occur over the Antarctic Peninsula and into the Weddell sea as well as to the east of the Southern Andes, over the Santa Cruz province, 291 Argentina, and over the adjacent Atlantic Ocean. A secondary density maximum is also present over the 292 eastern Ross Sea. In the subtropics note the relatively high event density extending from the eastern edge of 293 the Central Andes (Mendoza and Neuquén provinces, Argentina) eastward over the Pampas region of 294 295 Argentina and Uruguay into the South Atlantic. Note also the density minimum surrounding the coast of South Africa, particularly on the Atlantic side. An interesting feature is the N-S density ridge to the west of 296 the Andes a few degrees off the coast of Chile, and the very low density region in between (cf. case studies 297 in L4DC). 298

The density distribution changes significantly when the density by cyclone families is considered (note the change in the scales). For shallow events (Fig. 3b), the distribution appears very similar to that shown for all events, but in this case the higher density values that extend from Antarctica to mid-latitudes can reach the
 subtropics with high densities, reaching the Rio de la Plata lower basin and coastal areas over Argentina,
 Uruguay and southernmost Brazil. Another subtropical high-density region is observed over eastern South
 Africa, extending towards the Indian Ocean. The similarity between the two distributions confirms that the
 shallow events are predominant in the total distribution throughout the entire period. The largest cyclone
 activity for these events can be found at 90°E, over Kaiser Wilhelm II Land, near the Dome Argus on the
 Antarctic Plateau, and over Tierra del Fuego, Argentina.

The intermediate cyclone family density plot (Fig. 3c) shows a cyclone belt surrounding Antarctica, centred near 50°S. It also shows significant regional density, albeit weaker, affecting part the Pampas region, Argentina, as well as the Rio de La Plata, between Argentina and Uruguay, at subtropical latitudes. At polar latitudes a very high density region can be seen to the east of the Antarctic Peninsula, extending over the Weddell Sea into the Southern Ocean/South Atlantic. Another small region of very high densities can be found over Kaiser Wilhelm II Land over Eastern Antarctica. Scattered higher density values can also be observed in the Southern Ocean, near 60°S, extending south of New Zealand almost to Tierra del Fuego.

315 The deep cyclone family density distribution shows a core region of cyclone activity in a ring around Antarctica near 60°S (Fig. 3d). The Weddell Sea once more is an area with higher cyclone activity. These 316 317 density plots show that, as the number of levels determining a cyclone event increase, their spatial distribution moves poleward, i.e., the possibilities for a cyclone to develop vertically increases poleward. 318 (cf. Table 1 where the number of events increases while the latitude increases). From the results it is evident 319 that most of the cyclones in the SH tend to develop over the oceans and their distribution show zonal features 320 linked to each family. While shallow events can be detected almost at all the latitude ranges, intermediate 321 cyclones mainly develop at midlatitudes, and deep systems are mostly confined to the polar region in 322 agreement with Table 1. The Andes mountain range and the South African plateau appear as significant 323 324 orographic features impacting cyclone distribution, in agreement with Inatsu and Hoskins (2004).

Figures 4 shows, for the SH during 2001-2017, the histograms of seasonal distribution of all the events according to the lowermost cyclone pressure level. Seasonally, the highest event count occurs in autumn, with 14682 systems detected over the 17 years, while the lowest count takes place in winter with 13780 events. Event counts for summer and spring are 14504 and 14638 respectively. However, results per family

329 (not shown) show a different seasonal distribution. While the shallow systems are mostly detected in summer and the lowest counts occur in winter, intermediate and deeps events are more frequent in winter, with fewer 330 331 systems observed in summer. This means that detected intermediate cyclones are approximately 13% of all 332 events in summer and 16% in winter. Deep events have a seasonal distribution similar to intermediates, albeit 333 with an enhanced seasonal variability. They represent close to 3% of all events in summer and 5% in winter. 334 This last result shows a similar behaviour to that reported by Reboita et al (2014) Jones and Simmonds 335 (1993) and Simmonds and Keay (2000), who noted that at 980hPa pressure, the austral winter is the most 336 cyclogenetic season, closely followed by autumn, spring and summer. Results show that in all seasons the 337 most populated lowermost levels are 925 and 700 hPa. In summer and autumn events with lowermost level at 300hPa have counts similar to the 700hPa values. Such a secondary maximum agrees with the seasonal 338 339 behaviour of cut-off lows (Reboita et al, 2010; Pinheiro et al, 2017; Pinheiro et al. 2019). Above 300hPa the 340 number of events decreases rapidly.

341 Figure 5 show the seasonal cyclones density for all the events. During autumn (Fig. 5b), the cyclone activity shows high values over West Antarctica, with hotspots in the area of the eastern side of the Antarctica 342 Peninsula, Weddell Sea, and the Filchner-Ronne Ice Shelf. Two other small high-density areas can be 343 observed for Antarctica. The cyclone density shows a ring of high values around the hemisphere with 344 345 maximum values near 50°S decreasing equatorward. This band has peak values south of Australia and New Zealand and in the vicinity of Tierra del Fuego/southern Patagonia, extending into the neighbouring South 346 Atlantic. In the subtropics cyclonic activity is present over Central Argentina to the east of the Andes 347 extending over the South Atlantic almost to South Africa. To the west of the Andes there is a minimum in 348 activity along most of the coast of Chile and, a few degrees into the Pacific Ocean, a parallel ridge of higher 349 density values. On the equatorward edge of the subtropics a secondary ridge of slightly higher density spirals 350 across the Pacific into the ridge off the coast of Chile. 351

# This overall pattern prevails during all the other seasons, with some variations. For example, in summer (Fig. 5a), a weak spiral signature can be seen over the Atlantic lower subtropics, from the coast of Brazil towards South Africa. In winter (Fig. 5c) and spring (Fig. 5d), when there are higher values in the 50°S band, the peak over the Weddell Sea region does not appear so strongly even though the cyclone density also increases there. During these seasons the subtropical density ridges spiral towards higher latitudes, over the Pacific

357 and Atlantic Oceans, with values similar to autumn. This spiralling structure, constantly present throughout the year and with variable seasonal intensity, was also observed by Lim and Simmonds (2007) and Hoskins 358 and Hodges (2005) but only for JJA. According to their study and that of Inatsu and Hoskins (2004), the 359 spiralling structure in the lower level of activity can be related with the stronger SST gradient of the oceans, 360 361 particularly in winter as well as the topography of South America and Africa. As would be expected, for all 362 the cyclone systems identified the seasons that display the lowest and highest densities are respectively the 363 summer and the winter/spring. Throughout the entire period for all seasons, the highest cyclonic density 364 values, except for some specific hotspot that occur with variations, are detected in the belt between 45-70°S. 365 This area is associated with the polar jet. The subtropical jet, which maximises in winter/spring appears to be associated with higher densities regionally observed in the subtropics, e.g., over the Pampas. Such 366 367 behaviour was also reported by Lim and Simmonds (2007) and more extensively addressed by Nakamura 368 and Shimpo (2004) in their description of the seasonal variation of eddies. They pointed out that in the middle 369 and upper troposphere strong westerly winds can act to force eddies to migrate away from the baroclinic zones, interacting in their growth or even leading to the suppression of their activity. Rudeva et al. (2015) 370 371 focused on the global analysis of variability of frontal activity using the Interim ECMWF Re-Analysis (ERA-I) from 1979 to 2013. They pointed out that in DFJ a shift of atmospheric fronts to the high latitudes can be 372 373 observed in the SH and this shift is consistent with the seasonality of other synoptic trends that show maxima during the austral summer in the SH. 374

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# 3.2.2 Cyclone Genesis and Lysis

377 Figure 6 shows the genesis of cyclone activity throughout the year and seasonally disaggregated for all 378 events. Note that genesis is defined as the first appearance of the cyclone event, i.e., the first point identified 379 by the algorithm (hence sparse plots). Other researchers, by contrast, have defined genesis as a developing 380 stage (Grise et al; 2013). Most of the SH activity develops between 30°S and 70°S. There are three areas of 381 interest with high genesis that should be noted when considering all the events throughout the year for 2001-2017: along the lee side of the South American Andes between 30°S and 55°S; southern New Zealand; and 382 383 a broad band over the oceans, between Africa and New Zealand at 45-50°S (Fig.6a). According to Figure 3, 384 the largest number of events detected in these areas corresponds to shallows and intermediates systems. Over

South America the two most active genesis regions in the hemisphere can be found: Tierra del Fuego and Santa Cruz provinces in southern Argentina, and the eastern slope of the Andes in the Argentine provinces of Mendoza and Neuquén, both areas with predominantly shallow events. Secondary genesis regions in the hemisphere with high to intermediate density values of shallow and intermediate events, include the southern part of South Island, New Zealand, the western edge of the Ross Sea, near Oates Land, and the poleward end of the Antarctic Peninsula, both over Antarctica.

391 Hoskins and Hodges (2005) noted that the Patagonian genesis maximum is located along the downslope side 392 of the Andes. This region is located to the east of the Pacific stormtrack. The other maximum genesis region 393 on the lee side of the Central Argentina Andes, with an average height close to 6000 m a.s.l., which Hoskins 394 and Hodges (2005) suggest is most probably linked to "the shallow but strong systems on the subtropical jet 395 that cross the Andes" in agreement with Figure 3(b). The Ross Sea coastal area is an intermediate genesis 396 region throughout the year, maximising in winter. These regions, together with the genesis area in the 397 Antarctic Peninsula, were also highlighted by Bengtsson et al. (2006), who observed that the area of cyclogenesis across the Andes extended practically along the same longitude to the northern part of the 398 399 Antarctic Peninsula, i.e., along the main orographic barrier of the SH with its only break in the Drake Strait. 400 These cyclogenesis areas exhibit weaker activity in the SH summer than in the other seasons.

401 Figure 6b to 6e show the seasonal variability of SH cyclogenesis regions. These regions have intense activity throughout the year as well as seasonally, with relatively stable values, with some spatial variations. The 402 403 vicinity of Antarctica generally has lower event counts during the summer, and as the cold season approaches the activity increases to reach maximum activity near the Antarctic Peninsula/Weddell Sea in winter and 404 spring. The high activity area near Oates Land on the Ross Sea is observed throughout the year but especially 405 406 in summer. The region of the Argentine Central Andes also exhibits enhanced cyclogenesis during the austral winter and spring. On the other hand, the genesis regions over southern Santa Cruz and Tierra del Fuego 407 408 have enhanced cyclogenesis during spring and summer.

In the South American subtropics enhanced cyclogenesis can be observed over the southern humid Pampas region and over the Rio de La Plata Estuary from autumn through spring. Cyclogenesis over South Africa also increases during winter and spring. Over the oceans cyclogenesis varies more prominently both geographically and in intensity. During summer, cyclogenesis appears to be limited to the coast and Atlantic

413 Ocean near the south of the Pampas region and northern Patagonia. During autumn and winter enhanced cyclogenesis can be observed, albeit to a lesser extent in winter, as far equatorward as the coast of southern 414 Brazil and Uruguay. Over open ocean regions, cyclogenesis is weak during summer and mostly limited to 415 the Indian Ocean near 40-45°S. During autumn this region broadens poleward and extends into the Pacific. 416 417 Such broadening extends towards the subtropics during winter and spring. It finally becomes a ring spanning 418 southern mid latitudes. Also during this period over the Pacific Ocean, and to a lesser extent the Atlantic 419 Ocean, subtropics, weakly enhanced cyclogenesis areas can be observed spiralling from west to east towards 420 mid latitudes over both ocean basins.

421 Similar to Figure 6, Figure 7 shows the pattern of the lysis behaviour of the cyclone activity throughout the 422 year and seasonally disaggregated, for all events. The plot for all events over SH during 2001-2017 (Fig. 7a) 423 shows that most of the lysis events appear to be concentrated between 30°S-80°S with maximum values 424 between 5°-10° west of the Andes, over the Pacific Ocean. This major lysis region remains active throughout 425 the year, but is particularly noticeable in the summer and spring (Fig. 7b, 7d). It also coincides with a relative maximum in cyclone density all year round. Moreover, this region displays genesis of shallow and 426 427 intermediate events, larger than the lysis (Fig 6), which could suggest that systems do not disappear and reappear over the lee side of the Andes. In L4DC a case study shows how a cyclone starts moving along the 428 429 N-S axis when it moves close to the Andes, in the vicinity of the highest peaks north of 40°S. Note the lysis 430 minimum surrounding the coast of South Africa is surrounded on the Atlantic side by a somewhat higher density of lysis events. Genesis and density values remain relatively constant and low throughout the period. 431 Again the South African Plateau appears to impact cyclone displacements, as by Inatsu and Hoskins (2004) 432 pointed out for storm tracks. Overall, it should be noted that the highest density region in terms of number 433 of events does not have a direct correspondence with the more active genesis and lysis zones. Although the 434 belt between 45°- 75°S has a high density of events and high genesis values, the highest lysis values 435 correspond to a narrower portion of this ring detected between 50°-65°S, with the exception of West 436 Antarctica, which retains high values in all three features. 437

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- 439 **3.2.3** Cyclone intensity

Figure 8 shows the relative vorticity scaled by  $-1 \times 10^{-5}$ , corresponding to cyclone centres, used here to identify cyclone intensity. The higher relative vorticity values (Fig. 8a), considering the whole period of analysis, can be found in the ring 50-80°S where high system densities are detected with values ranging between 2.5 and 4.5. An outer ring that spans most of the subtropics with intermediate values is located between 50-25°S. Note that near the coast of Chile, close to the Andes, a small wedge of higher vorticity extends north into the subtropics, while a wedge of lower values coincident with the area of maximum lysis and lower genesis values, further out in the Pacific, extends south from the subtropics.

- 447 These values are relatively constant throughout the year, with almost no noteworthy seasonal spatial 448 variability. During the MAM and JJA, West and East Antarctica shows slightly higher vorticity values. Over the South Atlantic most of the cyclones display somewhat higher values in MAM and JJA. During the spring, 449 450 results (Fig. 8e) show that in general vorticity values are lower compared to the other seasons. In general 451 terms, the vorticity values are in agreement with those reported by Gramcianinov et al. (2019). They 452 observed that vorticity for the southeast coast of Brazil (SE-BR in their work) and north eastern Argentina and the Uruguay region, close to the La Plata river (LA PLATA, in their work) areas, display a peak between 453 454 -2 and -3 in the summer. In the winter, SE-BR cyclones present initial vorticity between -4 and -6. Moreover, the majority of the South Atlantic cyclones have weaker vorticity in summer than winter. 455
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### 457 **3.2.4 Lifetime and translational velocity**

Figures 9 and 10 show, respectively, cyclone mean lifetime and translational velocity for all the systems 458 detected. Annually (Fig. 9a) the longest cyclone lifetime is found over East Antarctica with 4 to 6-day 459 460 lifetimes, coincident with the area of highest vorticity. During the whole period of analysis, the other regions show lifetimes between 3-4 days, decreasing from mid-latitudes towards the subtropics. Seasonally, the 461 longest lived events occur during the summer (Fig. 9b), with lifetimes up to 11 days. Many of these longer 462 lasting systems occur over and around Antarctica, where intermediate and deep events are more frequently 463 464 present. The remaining areas in this season show a fairly homogeneous behaviour with lifetime values between 3 and 6 days. The filament-like pattern, i.e., narrow extended regions, of somewhat longer lived 465 events in the subtropics, may suggest that events along or close to the subtropical jet may have slightly longer 466

lifetimes. Argentina, southern Brazil and Uruguay regions have lifetime values in agreement with those
reported by Gramcianinov et al (2019). According to Figures 9 b, c, d and e, the season with the highest
density of events with the longest mean lifetime is winter. Lifetime values range between 7-10 days over
Antarctica, spanning some hotspots in the Pacific and Atlantic Oceans.

471 Translational velocity results (Fig. 10) show three well-defined areas with distinguishable velocity values. The first ring is over and around Antarctica, except the tip of the Antarctic Peninsula (Fig. 10a), with systems 472 473 moving with velocities between 4-6 m/s, surrounded by a higher velocity annular structure located 30-50°S, 474 with the highest values reaching up to 15 m/s over the Indian Ocean sector. According to Figures 6 to 9 this 475 area includes the higher vorticity, genesis, lysis and lifetimes values. There are some N-S anomalies to the 476 west of both the Andes and South Africa, where cyclones undergo significant lysis and high density values, 477 in the process changing from a predominantly zonal displacement to a meridional one, e.g. cf. L4DC. There are also some regions of somewhat higher velocities off the coast of Uruguay and southern Brazil. In certain 478 479 areas such as the central zone of Argentina, there are lower values of the order of 6 m/s. The overall pattern does not vary significantly from one season to the next. Velocities increase towards Antarctica in JJA and 480 481 peak velocities of the order of 20m/s are found over the Indian ocean during this period, Over the subtropics 482 velocities are of the order of 12m/s on average. Somewhat higher speeds appear to occur in the vicinity of 483 the subtropical jet from MAM through SON. The lowest translational velocities over the extratropics are observed in JJA. If the velocities of the systems are analysed considering the families, the results show that 484 the shallow and intermediate events are faster, while the deep ones, mostly located in the polar area, have 485 lower speeds. 486

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## 3.3 Lower and upper troposphere: 925 and 250 hPa "non family" cyclone results

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In order to have a preliminary look at height dependent cyclone behavior, results for 925 and 250 hPa are
introduced. For the present purpose all events present at each of these two levels will be considered together,
independent of their family classification, i.e., a "non family" approach. Note that no single level events are
included in this analysis, only multi-level events present at each of these pressure levels. A more detailed

- 494 analysis on the height behavior of families and subfamilies will be provided in Canziani et al. (2020,
  495 manuscript in preparation)
- 496
- 497 **3.3.1 Lower troposphere: 925 hPa**

Figure 11 shows monthly mean seasonal track density at 925hPa. Present results show large densities over 498 499 and to the east of the Rio de la Plata and southern Argentina, close to Ushuaia. Higher values can be found close to the Andes over the Pacific Ocean, where high lysis values are also observed, and in areas over East 500 Antarctica with hotspots extending from Dronning Maud Land to Oates Land mixed with areas of minimums 501 values. Overall, the higher density of events can be observed between 35°-75°S. The values throughout the 502 503 year show limited seasonal variability, although same differences can be noted. During SON, higher densities appear between Australia and New Zealand. In JJA present results show less cyclone activity over the eastern 504 505 South Atlantic and western Indian Oceans. Lim and Simmonds (2007), using the Melbourne University tracking algorithm in their 3D climatology for the period 1979-2001, found at sea-level results close to the 506 507 present study, for JJA. They also noted higher cyclone density near the Antarctic Peninsula's tip, i.e., to the 508 north of the high density region reported here, although their results did not find higher densities at 509 subtropical/midlatitudes as observed here. Results are also in agreement with Simmonds et al. (2003) and 510 Pepler and Dowdy (2020), though the maximum near the Antarctic Peninsula is to the west of the peninsula in their analysis. 511

Figure 12 shows the cyclone translational velocity field at 925hPa. A quick inspection of the figure shows 512 that the area with the highest density of events is the one that shows the greatest range of speeds with 513 514 exception of East Antarctica were velocities appear to be the lowest. Though maximum observed velocities reach values of the order of 20m/s year round, there are some seasonal variations in their distribution. During 515 DJF peak translational velocities near 18m/s are observed over the South Atlantic and 20m/s over the Indian 516 Oceans between 40 and 60°S. During MAM maximum translational velocities in the vicinity of 20m/s 517 518 maximize mainly over the Indian Ocean, extending into the higher subtropics. Higher velocities are also 519 found over the South Pacific. During JJA translational velocity maximize in the vicinity of 20m/s over the Indian Ocean primarily between 35 and 60°. Translational velocities between 12 and 15m/s extend well into 520

the subtropics over the South Atlantic and Central South Pacific Oceans, appearing as a spiraling pattern
similar to the subtropical jet. A similar behavior is observed for SON.

523 Although there are fewer studies presenting seasonal translational velocities, Hoskins and Hodges (2005) show that JJA velocities at 850hPa maximize around 18m/s, with an overall distribution similar to present 524 525 results, even when the velocities over the subtropical latitudes are somewhat lower in their study. Similarly, translational velocities at MSLP for DJF and JJA in Sinclair (1994) are also in very good agreement with 526 527 present 925hPa results. Figure 13 shows the seasonal intensity distribution at 925hPa given in terms of relative vorticity distribution. Relative vorticity and cyclone depth, given in terms of the pressure or pressure 528 anomaly at the centre of the cyclone event, are most commonly used to show the intensity of cyclone events. 529 The highest relative vorticity values which match with higher velocities, are found in a broad band in the 530 531 extratropics and subpolar latitudes, with some seasonal variations in maximum values and distribution. During DJF, relative vorticity values of the order of  $4x10^{-5}s^{-1}$  are observed in the western south Pacific near 532 the Rio de la Plata and the coast of southern Patagonia and Malvinas (Falkland) sector, which merge towards 533 the central South Atlantic. Values between 3 and 4 x  $10^{-5}$ s<sup>-1</sup> extend in a latitudinally narrowing belt over the 534 535 Indian Ocean all the way to Australia. This relative vorticity belt expands into the subtropics and onto the 536 Antarctic coast on the western half of the South Pacific. During MAM somewhat lower relative vorticity values are observed with maximum values of the order of  $3.5 \times 10^{-5}$  with a broader, more homogeneous 537 distribution throughout the southern extratropics. During winter months, relative vorticity in the extratropics 538 539 can reach values close to 5x10-5s<sup>-1</sup> over the eastern South Atlantic and south of New Zealand. The latitudinal 540 distribution shows a minimum over the Indian Ocean around 90°E. During SON the current analysis, in 541 agreement with Hoskins and Hodges (2005), yields a broad latitudinal band from the subtropics into subpolar latitudes with values in the vicinity of  $3.5 \times 10^{-5} \text{s}^{-1}$ . Broadly speaking the overall depth patterns found here 542 543 are in agreement with the relative vorticity patterns described by Lim and Simmonds (2007) and Eichler and Gottschalck (2013). It is important to note, however, that maxima for the different reanalyses may differ as 544 much as 30% in a given region. 545

546

547 **3.3.2 Upper troposphere: 250 hPa** 

548 Figure 14 shows that during DJF high densities are still observed close to Antarctica. In the subtropics there is a weak density maximum similar to the one in Hoskins and Hodges (2005). During autumn there is a better 549 overall agreement in the density distribution between both studies. A double spiraling structure can be 550 observed, one in the subtropics and another at higher extratropical latitudes, extending from Australia well 551 552 into the South Pacific Ocean. During JJA the maximum values are higher in the present analysis spiraling 553 from the subtropics into the extratropics and extending all the way to Antarctica except in the vicinity of the 554 Ross Sea. There is only a very weak evidence of subtropical densities at this time of year. The higher latitude 555 distribution is observed during the spring in fairly good agreement with Hoskins and Hodges (2005) and Pinheiro et al (2017). The higher density region, when compared to the winter behavior, also broadens 556 557 towards midlatitudes. There is also some evidence of activity at subtropical latitudes, particularly over and 558 around southern Africa, the Indian Ocean between Madagascar and Australia, and over the South Pacific east of Australia. These results show the influence of the jet structure in the observed distribution of the 559 560 upper tropospheric cyclone families. Spatially the 250 hPa lows densities tend to be uniform around and over the continents, during most of the year, but with higher density observed over the Indian Ocean and the South 561 Pacific during summer. 562

563 The 250hPa translation velocity distribution is presented in Figure 15. During summer maximum velocities are mainly observed between 40 and 60°S with maximum velocities in the vicinity of 20m/s. These maxima 564 are observed primarily over the Indian Ocean and to the west of Chile, over the South Pacific. During MAM 565 566 the average speeds above 16ms<sup>-1</sup> are more evenly distributed over the SH subtropics and midlatitudes. Comparatively high translational velocities are also observed coincident with the subtropical poleward 567 568 spiraling branch previously mentioned. Winter velocities are also more evenly distributed and the spiraling structures are similar to the SH winter jet streams. Velocities in spring are similar to those in autumn and 569 570 winter, and also show the poleward spiraling pattern, which is also well-defined over the South Atlantic and Indian Ocean subtropics. The spatial distribution is in excellent agreement with that found by Pinheiro et al. 571 572 (2017),

573 Finally, Figure 16 shows the spatial distribution of event intensity in terms of relative vorticity. The seasonal 574 cycle appears to have somewhat limited seasonal changes: during DJF, MAM and JJA a broad ring of vorticity of the order of -6 to  $-8 \times 10^{-5} \, s^{-1}$  extends from the poleward edge of the subtropics into polar latitudes. There are some areas with values up to  $-10 \times 10^{-5} \, s^{-1}$  over the Indian Ocean near 55°S, during autumn. The latitudinal extent varies over the season, during DJF and MAM extending into the subtropics with areas with values between -6 and -8  $\times 10^{-5} \, s^{-1}$  near or above New Zealand, South America and southern Africa. During spring, the overall pattern is similar, but the relative vorticity values are all under -8  $\times 10^{-5} \, s^{-1}$ . There is a relative minimum spanning the ocean due south of South Africa extending towards Antarctica. The relative vorticity also shows higher values associated with the spiralling structure of the upper tropospheric jets.

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#### 583 **3.3.3 Stacked plots of the lower and upper troposphere**

In order to shed some light in the comparison between the 925 hPa and 250 hPa and attempt to further explore 584 the spatial patterns of the cyclonic events and their vertical distribution in the atmosphere, Figure 17 shows 585 the "stacked" plots of the two levels. Figure 17a presents the overlapped vorticity fields of the two levels. A 586 distinct stronger vorticity average value at 250 hPa can be observed with respect to 925 hPa values, 587 suggesting a strong vertical vorticity gradient, which more than doubles in the upper troposphere with respect 588 to the lower troposphere. The spatial pattern also shows that the values are more uniform in the upper 589 troposphere than near the surface, where events, mostly shallow ones, are observed to die in the vicinity of 590 591 the Andes. There is also a highlighted area over Argentina that displays low values of vorticity near the 592 surface, which in the upper troposphere become uniform. Velocity values show that events are faster at 250 593 hPa than at 925 hPa. Regarding the lifetime, a much more homogeneous spatial pattern can be appreciated, 594 with events lasting up to almost 8 days at both levels. However, it can be noted that while the events at 595 925hPa are more concentrated in middle latitudes, for the upper troposphere, the density of events with the same speed expands to middle and high latitudes (Figure 17 c). Finally, density patterns are shown in Figure 596 597 17 d. It can be noted that more surface lows are detected in subtropical regions, including near South America and between Australia and NZ. Another characteristic is that near Antarctica, events are stronger at 250 hPa, 598 and weaker near the surface. 599

600

### 601 **4. Discussion and summary**

602 Cyclonic systems are one of the most widely studied topics from different perspectives based on theoretical, 603 numerical analysis and observational data. However, most observational studies are restricted to the surface 604 or near surface. Those involving various levels of pressure are scarcer and it is also important to highlight 605 that there are differences in the characteristics analysed between them. The STACKER algorithm was used to build an initial 3D cyclone climatology, based on 18 years of ECMWF Reanalysis ERA-I data from 12 606 pressure levels in the troposphere and lowermost stratosphere. Cyclone events were categorized into shallow, 607 608 intermediate and deep families. This complex cyclone tracking scheme based on the methods of Hoskins and Hodges (2005), and applied over the Southern Hemisphere for 2001-2017 focused on density, 609 translational velocity, relative vorticity, lifetime, genesis and lysis for event occurrences between 14° and 610 78°S, provides much raw material for ongoing research on cyclone dynamics. 611

612 Basic aspects of the characterization were presented, with 58231 multilevel cyclones being detected during 613 the study period, an average of 303 events for all types per month, lasting at least 2 days with vertical 614 structures spanning two levels or more. In terms of families, there is a clear identification in the distribution of densities. The shallow family cyclones are observed from the subtropics well into polar latitudes. 615 Intermediate cyclones extend from the extratropics into polar latitudes, while deep cyclones are essentially 616 617 sub-polar and polar. This does not mean the intermediate or deep events cannot extend into the subtropics, 618 just that at lower latitudes they are comparatively rare events, in particular deep cyclones. Table 1 also provides information regarding lifetime and velocity and shows that, on average, shallow cyclones, are 619 620 usually faster in contrast with deep events which tend to move more slowly but with longer lifetimes. As the 621 results also highlight, an equatorward shift in the higher density frequency can be noted for shallow events. 622 For the 17-year sample from 2001 to 2017, results show that most of the events develop over the oceans 623 rather than over land, and the 700 hPa pressure level plays an important role in the analysis, regardless of 624 the family or seasonality. Shallow and deep cyclones tend to have a large percentage of genesis with their 625 lowermost level at 925 and 700hPa, while the intermediate ones have their genesis maxima near the surface 626 and at 500hPa. During the whole period, the highest cyclone density can be observed in the extratropics, from mid-latitudes towards Antarctica while high and low cyclone densities occur over the South Pacific 627

and over the southern central Indian Ocean respectively. Peak densities can be detected over the Antarctic Peninsula, Weddell sea and the east of the Southern Andes, over the Santa Cruz province, Argentina and the adjacent Atlantic Ocean. Family analysis also reveals that shallow events are predominant in the total distribution, with more than 81% systems detected per month throughout the entire period, with the largest cyclone activity confined to 90°E, over Kaiser Wilhelm II Land, near the Dome Argus on the Antarctic Plateau, and over Tierra del Fuego, Argentina.

Results also show that for all the detected cyclone events, the seasons that yield the lowest and highest 634 635 densities are respectively the winter and autumn. Throughout the entire period and for all seasons, the highest 636 cyclonic density values can be observed in areas associated with the polar jet instead of the subtropical jet. 637 even when the latter is stronger in winter, when higher densities are regionally found. With respect to genesis 638 and lysis, it is important to highlight that the more dense regions in terms of number of events do not have a 639 direct correspondence with the genesis and lysis high value zones. Although the belt between 45°-75°S has 640 a high density of events and high genesis values, the highest lysis values correspond to a narrower portion of this ring detected between 50°-65°S with the exception of West Antarctica. The latitudinally extended 641 642 Andes region, coinciding with previous analyses, is revealed again as a region of high hemispheric relevance in terms of genesis and lysis, showing that their unique orographic characteristic may play a key role in the 643 644 development of the systems. The area displays genesis of shallow and intermediate events, larger than the lysis. This suggests that systems do not necessarily die out but can reappear/redevelop in the downstream 645 side of the Andes, depending on latitude as discussed in L4DC. In terms of translational velocity, the analysis 646 suggests that shallow and intermediate events are faster, while the deep ones, mostly found in the vicinity of 647 the polar areas, move at lower velocities. 648

In order to take the first steps toward an analysis of the height dependence in cyclones systems behaviour, 925 and 250 hPa were analysed. In the lower troposphere, present results show large densities over and to the east of the Rio de la Plata basin and southern Argentina, as well as over the Weddell Sea, east of the Antarctic Peninsula. Regarding transitional velocity, although maximum observed velocities reach values of the order of 20m/s year round there are some seasonal variations in their distribution at this pressure level. There are fewer studies presenting seasonal translational velocities, but results presented here are in very 655good agreement with translational velocities at MSLP for DJF and JJA in Sinclair (1994). The highest656relative vorticity values are found in a broad band in the extratropics and subpolar latitudes, with some657seasonal variations in maximum values and distribution. With respect of 250 hPa, high densities are observed658close to Antarctica with a weak density maximum similar to the one noted in Hoskins and Hodges (2005) in659the subtropics. There is also some evidence of activity at subtropical latitudes, particularly over and around660southern Africa, the Indian Ocean between Madagascar and Australia, and over the South Pacific east of661Australia, albeit weaker than in Hoskins and Hodges (2005).

- 662 Results show the influence of the jet structure in the observed distribution of the upper tropospheric cyclone 663 families. Spatially the 250 hPa lows densities tend to be uniform around and over the continents, during most 664 of the year, but with higher density observed over the Indian Ocean and the South Pacific during summer.
- A novel way of presenting the results through the stacked plots between levels also revealed that there is a distinctly stronger vorticity at 250 hPa than 925 hPa, and that the translational velocity of the systems is faster close to the surface than in the upper troposphere/lowermost stratosphere.
- 668 In general terms, the current bibliography usually present results that focus areas of agreement between studies. However, it should be noted that most of them are based on methods that usually involve either 669 670 surface systems and/or single or few pressure levels. In this sense, we believe that the STACKER provides 671 a more complete perspective of the cyclone systems by involving 12 pressure levels, and therefore the comparison with previous results is at most partial, if not limited. Bearing that in mind, it is important to 672 highlight that features observed here were present in some studies but not in others, and none of the other 673 674 studies were closer among themselves than with the present results. Local and regional differences in the lower troposphere can be observed and can be attributed to different tracking methodologies, different study 675 676 periods or reanalysis products used. As Walker et al (2020) pointed out, it is important to note that each 677 method has its uncertainties and these differences, may result from differences in the data used or differences in the methodology of tracking or even in the way the properties are presented. 678
- Hence overall the STACKER seasonal climatology results, without including single level events, only family
  classified events, agree well with previous cyclone climatologies in the lower troposphere. Larger differences
  occur in the upper troposphere where, for example, generic multilevel cyclone events can be only primarily

682	compared with more selective studies with specific constraints of COLs (Pinheiro et al., 2017) determined					
683	from single surfaces studies. Some of the results have suggested linkages between major atmospheric					
684	features such as jets and probably, as argued by Gramcianinov et al (2019), SST gradients or with the main					
685	modes of atmospheric variability, in particular with the SAM and ENSO in the SH (Rudeva et al, 2015).					
686	Many of these features, however, are not well defined in the current analysis given that all cyclone families					
687	are considered together. A family analysis is necessary to highlight the details of such relationships (Canziani					
688	et al., 2020, manuscript in preparation).					
689						
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697	to publish the results.					
698						
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**Graphical Abstract** 

# Early 21st Century cyclone climatology: a 3D perspective . Basic Characterization

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A 3D Southern Hemisphere climatology for the 2001-2017 period was developed using the STACKER algorithm. Cyclones are analysed as 3D entities. The Andes Cordillera and the South African Plateau appear as significant orographic features impacting cyclone distribution, in agreement with Inatsu and Hoskins (2004). The plot suggests that at 925 hPa, systems undergo lysis near the Andes, but a fraction can move over the mountains at extratropical latitudes and even redevelop on the lee side of the Andes.



CYCLONE EVENT CLASSIFICATION

Figure 1. Event classification: Shallow cyclones are cyclone events containing at some stage in their evolution tracks in 2 or 3 pressure level and subsequently separated into 3 sub-families or types spanning the low and mid troposphere and the upper troposphere/lowermost stratosphere pressure levels (925 to 600hPa, 500 to 250hPa and 200 to 100hPa); Intermediate includes intermediate events with cyclone events spanning 4/5 pressure levels at some stage in their lifecycle with the corresponding subtypes located in the lower and mid troposphere up to 500hPa and in the upper mid troposphere above 500hPa and potentially extending into the lowermost stratosphere. Finally, vertically well-organized or deep cyclones span at least 6 of the levels without sub-families since they cover much of the atmospheric thickness under study







(a)

Event Lowermost Level Count





Figure 2. Histogram of the lowermost level distribution per family (a) Shallows, (b) Intermediate and (c) Deep events. The histograms are constructed by assigning an event to the lowermost level present during its lifecycle.



Figure 3. Annual density cyclones distribution from 2001-2017 for (a) all the events over SH, (b) shallow, (c) intermediate (d) deep. Note that different scales are used in the panels. Density is calculated as the total number of events at a given timestep where there is a track position present at each  $2^{\circ}x2^{\circ}$ .

(b)

(a)





**Event Lowermost Level Count** 



**Event Lowermost Level Count** 

Figure 4. Seasonal distribution of lowermost pressure level of all events over SH along 2001-2017 for (a) DJF, (b) MAM, (c) JJA and (d) SON. Histograms are built in the same way as Figure 3



Figure 5. Seasonal cyclones density for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON. Density values as Figure 3, but as monthly mean seasonal values for each season.



Figure 6. Genesis of (a) all the events, (b) DJF, (C) MAM, (d) JJA and (e) SON.

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Figure 7. Lysis for (a) all the events, (b) DJF, (C) MAM, (d) JJA and (e) SON

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Figure 8. Vorticity for (a) all events, (b) DJF, (c) MAM, (d) JJA and (d) SON

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Figure 9. Lifetime for (a) all the events, (b) DJF, (c) MAM, (d) JJA and (d) SON  $\,$ 

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Figure 10. Speed for systems for (a) all the events, (b) DJF, (c) MAM, (d) JJA and (e) SON

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Figure 11. 925 hPa seasonally density for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 12. 925 hPa seasonally velocity for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 13. 925 hPa Vorticity for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 14. 250hPa seasonal density for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 15. 250 hPa Seasonal velocity for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 16. 250 hPa vorticity for all the events over the SH from 2001-2017, (a) DJF, (b) MAM, (c) JJA and (d) SON



Figure 17. Stacked plots for 925 hPa (below) and 250 (above) for (a): vorticity, (b) speed, (c) lifetime and (d) density.

Latitudinal band		-74,-66	-66,-58	-58,-50	-50,-42	-42,-34	-34,-26	-26,-18
Family	Property							
Shallows	Lifetime	4.37	4.12	4.02	4.01	4.03	3.97	3.95
	Vorticity ( $\times$ 10 <sup>-5</sup> )	3,41	3,50	3,57	3,27	2,74	2,32	2,04
	Speed	7.31	10.14	11.84	11.64	10.45	9.32	8.31
	Density	30.87	34.44	39.74	38.27	28.66	19.52	11.95
Intermediate	Lifetime	5.42	5.24	5.11	5.17	5.13	5.04	4.48
	Vorticity ( $\times$ 10 <sup>-5</sup> )	3,78	3,75	3,68	3,34	2,82	2,31	1,88
	Speed	6.41	9.58	11.64	11.31	8.39	5.08	1.64
	Density	18.21	20.59	19.08	13.07	6.63	2.43	0.82
Deep	Lifetime	6.18	5.93	5.89	6.11	6.20	3.92	1.09
	Vorticity ( $\times$ 10 <sup>-5</sup> )	3,72	3,63	3,56	3,16	2,54	1,23	3.20
	Speed	3.75	6.66	7.66	6.02	1.92	0.93	0.77
	Density	11.09	12.61	9.52	4.56	1.25	0.23	0.03

Table 1. Mean 8°- latitudinal band average values of the cyclone properties per family. Lifetime is expressed in days; speed in m/s, and vorticity in s<sup>-1</sup>; lifetime is calculated as the average of lifetime of

each pixel in the band.

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