Early 21st century cyclone climatology: a 3D perspective. Basic characterization

Article

Accepted Version

Lakkis, S. G., Canziani, P., Rodriguez, J., Yuchechen, A., O ´Neill, A., Albers, K. and Hodges, K. ORCID: https://orcid.org/0000-0003-0894-229X (2021) Early 21st century cyclone climatology: a 3D perspective. Basic characterization. Climate Dynamics, 41 (7). pp. 4019-4046. ISSN 0930-7575 doi: https://doi.org/10.1002/joc.7056 Available at https://centaur.reading.ac.uk/94778/

To link to this article DOI: http://dx.doi.org/10.1002/joc.7056

Publisher: Springer

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

S. G.Lakkis [a,b] , Pablo Canziani [b,c] , Joaquín Rodriguez[c], Adrián Yuchechen [b,c],

Alan O´Neill[d], Kim Albers[e], Kevin Hodges[d]

a. Facultad de Ingeniería y Ciencias Agrarias, Pontifica Universidad Católica Argentina, Buenos Aires, Argentina
b. Unidad de Investigación y Desarrollo de las Ingenierías, Facultad Regional Buenos Aires, Universidad Tecnológica Nacional, Buenos Aires, Argentina
c. Consejo Nacional de Investigaciones Científicas y Técnicas, CONICET, Buenos Aires, Argentina
d. Department of Meteorology, University of Reading, Reading, U.K.
e. Institute of Meteorology and Climate Research, Karlsruhe Institute of Technology, Karlsruhe, Germany.

Contact:

Dr. Gabriela Lakkis

Facultad de Ingeniería y Ciencias Agrarias, UCA

Alicia Moreau de Justo 1500. Tel +54 11 4349-0200

UIDI, Secretaría de Ciencia, Tecnología e Innovación Productiva, FRBA-UTN

Medrano 951, C1179AAQ Capital Federal

República Argentina

Email: gabylakkisetul@gmail.com

https://orcid.org/0000-0001- 7562-8204

Abstract

Extratropical cyclones are a relevant feature in the climate at middle and high latitudes. Despite their relevance, most of studies typically focus 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 cyclone events based on the multilevel cyclone tracking algorithm STACKER. The algorithm, using relative vorticity, detects the raw tracks at single levels and objectively combine them to provide the 3D events and their evolutionary timeline. As result, 3D cyclone climatology, based on ECMWF Reanalysis ERA-I data from 12 pressure levels in the troposphere and lowermost stratosphere is presented. To the best of our knowledge this is the first analysis carried out throughout the troposphere and the lowermost extratropical/subpolar stratosphere in order to give a comprehensive picture of the cyclone events as physical entities throughout their lifetime. Cyclone properties analysed are track densities, translational velocity, vorticity and lifetimes. For the subtropical and extrattropical SH, results support many previous ideas about cyclone characteristics, but new insights are also obtained. A total of 58231 multilevel cyclone events lasting 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 shows that the lowermost level of cyclones are most frequently detected at 925 and 700 hPa, Considering that cyclonic systems can be grouped into families, results per month on average, show that shallow systems are the most frequent events with approximately 248 systems detected, followed by 43 intermediates and 11 deep events. Shallow and deep systems have a large percentage of events with genesis at 925 and 700hPa. Density statistics show that shallow events are present at all latitude ranges mostly poleward 30ºS with high and medium intensities, while intermediate ones are mostly restricted to mid-latitudes and deep events are mostly confined to sub-polar and polar latitudes. Cyclones over Antarctica seems to be mostly intermediates and deeps, with longer lifetimes and lower velocities.

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

1. Introduction

Cyclone activity represents an important feature of the general circulation of the atmosphere. Because they transport large amounts of energy, momentum and moisture, the passage of cyclones is linked to rainfall, snowstorms and strong winds (Sinclair, 2020), and hence with severe weather and climate variability. In a climate that is expected to become warmer, with more frequent severe events, understanding changing cyclone behaviour is a particularly complex and important challenge, especially considering their potential economic and human impact (IPCC, 2007, 2014). At mid-latitudes, cyclones are known to be linked with storm tracks (Catto,2018). As Valsangkar et al. (2018) pointed out with regards to future climate change and associated changes in storm tracks, understanding the genesis and life-cycle of extratropical cyclones is an issue of great relevance. The analysis of the cyclones must include not only their characteristics, location and frequency but also identify and track their path, origin and evolution.

Many studies have addressed the topic since van Bebber (1882) studied cyclones with 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).

Most methods used to detect and track cyclones are based on some variant of the neighbour point tracking (NPT) method, which consists of a two steps approach: first, the cyclonic system centres, defined as a local maximum or minimum value of a climatic variable, are detected at one time step; and secondly the track based on the nearest neighbour concept (Kelemen et al., 2015) is obtained through the temporal connection between cyclone centres (Murray and Simmonds, 1991 a,b; Satake et al., 2013; Flaounas, 2014). Currently available algorithms mostly track atmospheric events broadly across the globe using mean sea level pressure (MSLP), MSLP gradients, geopotential heights, potential and 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, 2002; Flocas et al, 2010; Kouroutzoglou, et al., 20 12)even though the most frequent variables used are local minima in MSLP or maxima in vorticity at a single geopotential height or pressure level (Pepler and Dowdy, 2020; Walker et al., 2020).

An efficient algorithm implies the use of a decision tree formulated around constraints on cyclone properties in order to able to identify feature values (typically values above or below a prescribed value), the link between the detected centres at different times and therefore the paths of particular cyclones over time, as well as their life-cycle. The algorithm also has to deal with the fact that cyclones may split or merge with other cyclones. Because cyclones can have diverse characteristics and evolution at various levels, single-level will affect the climate analysis derived from such algorithms. On the basis that most cyclones are typically detected on or near surface levels, and despite the fact that the vertical structure of a system is known to play a major role 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.

There are very few analyses that consider multilevel events and usually spanning levels up to 500 hPa. Lim and Simmonds (2007) compared cyclone tracks at six levels, between MSLP and 500hPa, to assess the vertical climatology of SH cyclones for the austral winter months (JJA), for the period 1979-2001. The analysis was based on cyclone tracks defined in terms of multiple-level events, by considering their variations in height, or sequences of multilevel overlaps only, defined for track points at different contiguous levels at a given timestep, i.e., in an immediate upper level, whose coordinates fall within a 4° latitude radius (≈444 km) of the track point being considered at the lower level. This is carried out at each time step, 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 showed that cyclones are frequently detected at the surface and at 500 hPa, with a minimum frequency value at 700 hPa, while about 52% of SH winter events have a vertically well-organized structure, extending 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 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 southeastern 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 midlatitudes. 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 cyclones, and they also have higher maximum rain rates and wind speeds than shallow surface cyclones, resulting in significantly larger total rainfall accumulations. Therefore, their findings clearly highlight the need and benefits from examining cyclones over multiple levels of the troposphere due to the importance of 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 algorithm is needed. Including a greater number of atmospheric levels in the algorithm will allow us not only to delve into more detailed information of each level, but also to analyse from a new perspective the systems, giving to the cyclones a certain sense of wholeness, i.e., a 3D entity, throughout their entire lifetime.

Hodges (1999) proposed a detecting and tracking algorithm TRACK with a method that starts by building all potential tracks using NPT. The algorithm uses relative vorticity rather than pressure/geopotential anomalies computed from MSLP and geopotential as in Lim and Simmonds (2007). By using Hodges´s initial algorithm and the starting point provided by Lim and Simmonds (2007) for the implementation, we have developed a comprehensive, fully automated 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 which cyclone events independently tracked at different levels are to be combined into single event, preserving all the track features detected at each level. The STACKER was built using a Smoothness 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). STACKER was applied to track events for the 2015 winter (JJA) in the SH, using tracks determined at 7 levels between the surface and the vicinity of the tropopause. For algorithm validation, three multilevel events developing 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 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 21st century using the STACKER algorithm, including both single-level and multilevel analysis. This climatology is based on 17 years (2001-2017) of ECMWF Reanalysis ERA-I data from 12 pressure levels in the troposphere and lowermost stratosphere. Considering the vertical tracking, cyclones are categorized into families defined by their vertical extent given by the maximum number of levels present in each cyclone event (shallow, intermediate and deep) and height of occurrence, respectively. In section 2, we present the ERA dataset and the analysis techniques used. Results are presented in Section 3, focusing on the analysis of the density, intensity, lysis and genesis region as well as translational velocity. This first coherent picture provides the raw materials to develop a more comprehensive analysis of specific family and subtype characteristics as well as the cyclone dynamics in a later paper (Canziani et al., 2020, manuscript in preparation). 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 such a large number of atmospheric levels in the lifetime of the cyclone systems, viewing them as physical entities, rather than sample slices at specific pressure levels.

2. Data and Methodology

This study follows closely in methodology the previous SH cyclone tracking study of Lakkis et al (2019, 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 thickness more completely and to provide insights of the cyclonic events throughout their entire life cycle, the analysis explores a wider range of pressure fields for cyclone track activity between 925hPa and 100hPa than in our previous work (12 levels vs. 7 levels in L4DC). The study area spans the latitude band 14°S to 78°S. The tracking is performed using the STACKER algorithm (L4DC) involving single level cyclone tracks obtained with the TRACK algorithm used by Hodges (1995, 1999) for the following twelve pressure levels: 100, 125, 150, 200, 250, 300, 400, 500, 600, 700, 850 and 925 hPa. Potential cyclone centres at a given level are identified by comparing the relative vorticity values of each grid point to its neighbouring grid points. Following the criteria applied by Hodges (1999) in TRACK, the tracks are formed using the minimization of a Smoothness Cost Function (SMF) (L4DC) which is based in Segmentation, Feature Point Detection and Tracking steps (Hoskins and Hodges, 2005). In order to expand the analysis including more pressure levels to improve the space resolution and time evolution of cyclones, with respect to L4DC, the STACKER algorithm, designed so as to associate all tracks obtained from a given feature-tracking algorithm that represent the same synoptic event at different vertical levels , is used to combine an enhanced number of TRACK outputs from an increased number of pressure levels at a time, and then to link them according to an objective function criterion, as in L4DC. The process is sequentially repeated with the next adjacent pressure level 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 higher level tracks in the latter case), capturing such features as upper level troughs or cut off lows. Following the criteria adopted in L4DC, the relative vorticity threshold used is $-1.0 \times 10-5$ s -1, for all levels, without height nor latitude dependence. This is set at a comparatively low value to capture as much of the cyclone life cycle as possible during any season. A more restrictive threshold will reduce the number of systems identified but will also shorten the life cycles of those that are identified, even more so for the weaker summer systems. Further details of the STACKER algorithm, that includes the relative vorticity choice, parameterization criteria, event validation and preliminary statistics can be found in L4DC.

The data used in this study are from the ERA-I reanalysis products, 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 1.5º × 1.5º. 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.

In terms of the choice of data, an extensive discussion about the impact on the results of using different climate variables for the event identification, different databases and methods, can be found in recent literature. As mentioned in L4DC, Hodges et al. (2003), using four different analyses (Japanese JR25, ERA-Interim, National Aeronautics and Space Administration Modern Era Retrospective – analysis for Research and Applications (NASA MERRA) reanalysis and the National Center for Environmental Prediction Climate Forecast System Reanalysis (NCEP CFSR)) for composite cyclone diagnostics, showed that the detected cyclones, in terms of numbers, location and spatial distribution, compared well between each other. Slight uncertainties may arise primarily in the cyclone intensities and they are greater in the SH, in regions of growth or decay. Ulbrich et al. (2009) also found some disagreements between results using different reanalysis for both hemispheres, being the differences noteworthy in summer months. According to them, the differences when comparing reanalysis datasets are mostly linked to different spatial resolutions.

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 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 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 in 2x2° resolution for the full study area. In the case of track densities, at a given timestep the total number of events where there is a track position present at each 2°x2°area or pixel are computed and given as monthly mean seasonal values for each season. These are corrected for pixel 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 event. These values are then assigned to the pixels over which the cyclone event moved. All the lifetimes in each pixel were then vertical averaged. Translational velocity and vorticity, these calculated at each timestep and pressure level in a given event, averaged in height and assigned to the corresponding pixel at each timestep. All values for events in each pixel 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

3.1 An overview of family distribution

The annual and seasonal frequencies of cyclones over the SH were obtained between 14° and 78°S between 2001 and 2017. A total of 58231 multilevel events were detected corresponding to an average of 303 per month. This means approximately 248-249 shallow systems, 43 intermediate systems and 11-12 deep events each month on average. Note that, the percentage of shallow events is greater than that reported by Pepler and Dowdy (2020) and Lim and Simmonds (2007) and even in L4DC, note that the latter only considered a single winter season. Test carried out with the STACKER show that the greater the number of pressure levels included in the analysis, the greater percentage of shallows are detected, while intermediate and deeps number of events remains constant or even decrease. It is important to bear in mind that using different approaches in tracking and different dataset as input, can lead to variations in the output statistics. According to Raible et al. (2008), differences in the location and number of tracks could be due to the choice of variable used. Additionally, the difference in frequency and number of events of the results may also be linked to the criteria of minimum lifespan of the events included in the analysis. For example, Pepler and Dowdy (2020) included events without a minimum lifespan threshold.

A preliminary inspection of the frequency distribution of events per level indicates 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 minimum values at 700. A similar minimum was observed in both Lim and Simmonds (2007) and Pepler and Dowdy (2020). In the upper troposphere/lowermost stratosphere, 250 hPa was the level with most events detected (Table 1). The annual histograms for cyclone families at different levels for all the events (not shown), show the shallow family is the most populous with 47751 events, followed by 8235 intermediates family events and 2245 deep family events. When the frequency distribution is given in terms of the lowermost pressure level per event, i.e., constructed by assigning an event to the lowermost level present during its lifecycle as previously explained, it shows two maxima at 925 and 700 hPa, with close to 13000 and 9000 cyclonic systems respectively. In other words, we are counting events as units or entities defined by STACKER, not overall number of cyclone tracks obtained with TRACK. Above 700 hPa and up to 300 hPa the vertical distribution of events is approximately constant in height, with an average of 6000 events per level. When the lowermost level of a system is near the tropopause, and hence the system may extend into the lowermost stratosphere, the number of events decreases to 4000 or less per level. In general terms, minimum values are detected in 125, 200 and 850 hPa. Minimum values in the number of events are observed near the surface, at 850hPa. Overall, close to 40% of detected events thus occur near the surface, while about 50% of 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 that these systems are the most frequently detected throughout the entire period of analysis, with a large percentage of events 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 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 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 how that in average, per year, shallow system translational velocity values were found up to 8.8 m/s, with lifetime values up to 6.5 days, while the intermediate and deep systems display translational velocities of the order of 5.5 and 3.1 m/s respectively, with similar mean lifetime values of 8.9 and 8.3 days. Translational velocities for shallows systems reported here, are in good agreement with Lim and Simmonds who reported a translational velocity ranging between 8.7-9.8 m/s. However, lifetimes here appear to be somewhat longer, probably due to the use of relative vorticity tracking. In order to provide a more detailed overview of these mean values of each family, Table 2 shows the zonal mean average translational velocity, vorticity, lifetime and density values, where each latitude band spans 10º 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 50ºS-60ºS, while overall properties 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 45ºS-50ºS. Rudeva et al. (2015) focused on the global analysis of variability of frontal activity using the Interim ECMWF Re-Analysis (ERA-Interim) from 1979 to 2013, pointed out that in DFJ, a shift of atmospheric fronts to the high latitudes can be 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. On the other hand, Keable et al (2002) observed that cyclone systems in this region exhibit meridional tilts.

For intermediate and deep events, results also show increasing differences poleward, in particular for deep ones. Higher densities can be found around 60ºS-65ºS, 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.

3.2 2001-2017 Basic annual and seasonal cyclone spatial characteristics

3.2.1 Cyclone densities

Figure 3 shows the annual spatial distribution of cyclone density during 2001-2017 for all multilevel cyclones detected (Fig. 3a). Cyclones are broadly distributed from the subtropics (approx. 30°S) into polar regions. During this period, the highest cyclone density occurs in the extra-tropics, from mid-latitudes towards Antarctica. High cyclone densities occur over the South Pacific. Lower cyclone densities are observed at mid latitudes over the southern central Indian Ocean. Density variations, with maxima and 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, Argentina, and over the adjacent Atlantic Ocean. A secondary density maximum is also present over the eastern Ross Sea. In the subtropics note the relatively high event density extending from the eastern edge of the Central Andes (Mendoza and Neuquén provinces, Argentina) eastward over the Pampas region of 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 the Andes a few degrees off the coast of Chile, and the very low density region in between (cf. case studies in L4DC).

The density distribution changes significantly when the density by cyclone families is considered (please 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 90ºE, 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 50ºS. 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.

The deep cyclone family density distribution shows a core region of cyclone activity in a ring around Antarctica near 60ºS (Fig. 3d). The Weddell Sea once more is an area with higher cyclone activity. These family 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 increase poleward. (cf. Table 2 where the number of events increases while the latitude increases). From the results it is evident that most of the cyclones in the SH tend to develop over the oceans and their distribution show zonal features linked to each family. While shallow events can be detected almost at all the latitude ranges, intermediate cyclones mainly develop at midlatitudes, and deep system are mostly confined to the polar region in agreement with Table 2. The Andes mountain range and the South African plateau appear as significant 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 (not shown) show a different seasonal distribution. While the shallows are mostly detected in summer and the lowest counts occur in winter, intermediate and deeps events are more frequent in winter, with fewer systems observed in summer. This means that detected intermediate cyclones are approximately 12.7% of all events in summer and 15.9% in winter. Deep events have a seasonal distribution similar to intermediates, albeit with an enhanced seasonal variability. They represent close to 3% of all events in summer and 5% in winter. This last result could show a similar behaviour to that reported by Reboita et al (2014) and Simmonds and Keay (2000), who noted that at 980hPa pressure, the austral winter is the most cyclogenetic season, closely followed by autumn, spring and summer. Results show that in all seasons the 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 behaviour of cut-off lows (Reboita et al, 2010, and Pinheiro et al, 2017). Above 300hPa the number of events decrease rapidly. Figure 5 show the seasonal cyclones density for all the events. During the autumn (Fig. 5b), the cyclone activity shows high values over West Antarctica, with hotspots in the area of the eastern side of the Antarctica Peninsula, Weddell Sea, and the Filchner-Ronne Ice Shelf. Two other small high-density areas can be observed for Antarctica. The cyclone density shows a ring of high values around the hemisphere with maximum values near 50ºS 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 Atlantic. In the subtropics cyclonic activity is present over Central Argentina to the east of the Andes extending over the South Atlantic almost to South Africa. To the west of the Andes there is a minimum in activity along most of the coast of Chile and, a few degrees into the Pacific Ocean, a parallel ridge of higher density values. On the equatorward edge of the subtropics a secondary ridge of slightly higher density spirals across the Pacific into the ridge off the coast of Chile.

This overall pattern prevails during all 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 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) but only for JJA. According to their study and Inatsu and Hoskins (2004), the spiralling structure in the lower level of activity can be related with the stronger SST gradient of the oceans, particularly in winter as well as the topography of South America and Africa. For all the cyclone systems identified, as would be expected, the seasons that displays the lowest and highest densities are respectively the summer and the winter/spring. It is interesting to note that throughout the entire period, for all seasons the highest cyclonic density values, except for some specific hotspot that occur with variations, are detected in the belt between 45-70ºS. 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 behaviour was also reported by Lim and Simmonds (2007) and more extensively addressed by Nakamura and Shimpo (2004) in their description of the seasonal variation of the eddies, pointing out that in the middle and upper troposphere, strong westerly winds can act forcing eddies to migrate away from the baroclinic zones, interacting in their growth or even leading to the suppression of their activity.

3.2.2 Cyclone Genesis and Lysis

Figure 6 shows the genesis of cyclone activity throughout the year and seasonally disaggregated for all events. Note that genesis is defined as the first appearance of the cyclone event, i.e., the first point identified by the algorithm (hence sparse plots). Other researchers, by contrast, have defined genesis as a developing stage (Grise et al; 2013). Most of the SH activity develops between 30ºS and 70ºS. There are three areas of 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 30ºS and 55ºS; southern New Zealand; and a broad band over the oceans, between Africa and New Zealand at 45-50ºS (Fig.6a). According to Figure 3, the largest number of events detected in these areas corresponds to shallows and intermediates systems. Over South America can be found the two most active genesis regions in the hemisphere: 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.

Hoskins and Hodges (2005) noted that the Patagonian genesis maximum is located along the downslope side of the Andes. This region is located to the east of the Pacific stormtrack. The other maximum genesis region on the lee side of the Central Argentina Andes, with an average height close to 6000 m a.s.l., which Hoskins and Hodges (2005) suggest is most probably linked to "the shallow but strong systems on the subtropical jet that cross the Andes" in agreement with Figure 3(b). The Ross Sea coast, is an intermediate genesis region throughout the year, maximising in winter. These regions, together with the genesis area in the 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 Antarctic Peninsula, i.e., along the main orographic barrier of the SH with its only break in the Drake Strait. These cyclogenesis areas are yield weaker activity in the SH summer than in in the other seasons.

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 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 spring. The high activity area near Oates Land on the Ross Sea is observed throughout the year but especially 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 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 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 Brazil and Uruguay. Over open ocean regions, cyclogenesis is weak during summer and mostly limited to the Indian Ocean near 40-45ºS. During autumn this region broadens poleward and extends into the Pacific. Such broadening extends towards the subtropics during winter and spring. It finally becomes a ring spanning southern mid latitudes. Also during this period over the Pacific Ocean, and to a lesser extent the Atlantic Ocean, subtropics, weakly enhanced cyclogenesis areas can be observed spiralling from west to east towards mid latitudes over both ocean basins.

Similar to Figure 6, Figure 7 shows the pattern of the lysis behaviour of the cyclone activity throughout the year and seasonally disaggregated, for all events. The plot for all events over SH during 2001-2017 (Fig. 7a) shows that most of the lysis events appear to be concentrated between 30ºS-80ºS with maximum values between 5°-10° west of the Andes, over the Pacific Ocean. This major lysis region remains active throughout 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 shallows and intermediate events, larger than the lysis (Fig 6), which could suggest that systems do not disappear and reappear over the lee side side of the Andes. In L4DC a case study shows how a cyclone starts moving along the N-S axis when it moves close to the Andes, in the vicinity of the highest peaks north of 40°S. Note the lysis minimum surrounding the coast of South Africa, is surrounded on the Atlantic side by a somewhat higher density of lysis events with genesis and density values that remain relatively constant and low throughout the period. Again the South African Plateau appears to impact cyclone displacements, as noted in storm tracks by Inatsu and Hoskins (2004). Overall, it should be noted that the highest density region in terms of number of events does not have a direct correspondence with the more active genesis and lysis zones. Although the belt between 45º- 75ºS has a high density of events and high genesis values, the highest lysis values correspond to a narrower portion of this ring detected between 50º-65ºS with the exception of West Antarctica that remains with high values in all three features.

3.2.3 Cyclone intensity

Figure 8 shows the relative vorticity scaled by 1×10^{-5}, corresponding to cyclone centres, used here to identify cyclone intensity. As Gramcianinov et al. (2019) pointed out, the vorticity of a cyclone may represent the event impacts on the continent, considering that “three main cyclogenesis regions of the domain are located near the coast and major cities” in Southern South America. The higher relative vorticity values

(Fig. 8a), considering the whole period of analysis, can be found in the ring 50-80ºS with values ranging between 2.5 and 4.5 x$10^{-5}s^{-1}$ where high system densities are detected. An outer ring that spans most of the subtropics with intermediate values is located between 50-25ºS. 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.

These values are relatively constant throughout the year , with almost no noteworthy seasonal spatial 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, results (Fig. 8e) show that in general vorticity values are lower compared to the other seasons. In general terms, the vorticity values are in agreement with those reported by Gramcianinov et al. (2019). They observed that vorticity for the Southeast coast of Brazil (SE-BR in their work) and Northeastern Argentina and the Uruguay region, close to the La Plata river (LA PLATA, in their work) areas, display a peak between −2 and −3 × 10−5s−1 in the summer. In the winter, SE-BR cyclones present initial vorticity between −4 and −6 × 10−5s−1. Moreover, the majority of the South Atlantic cyclones have weaker vorticity in summer than winter.

3.2.4 Lifetime and translational velocity

Figures 9 and 10 show, respectively, cyclone mean lifetime and translational velocity for all the systems detected. Annually (Fig. 9a) the longest cyclone lifetime is found over East Antarctica with 4 to 6-day 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 longest lived events occur during the summer (Fig. 9b), with lifetimes up to 11 days. Many of these longer lasting systems occur over and around Antarctica, where intermediate and deep events are more frequently 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 events in the subtropics may suggest that events along or close to the subtropical jet may have slightly longer 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, with lifetime values ranging between 7-10 days over Antarctica and spanning some hotspots in the Pacific and Atlantic Oceans.

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 moving with velocities between 4-6 m/s, surrounded by a higher velocity annular structure located 30-50ºS, with the highest values reaching up to 15 m/s over the Indian Ocean sector. According to Figures 6 to 9 this area includes the higher vorticity, genesis, lysis and lifetimes values. There are some N-S anomalies to the west of both the Andes and South Africa, where cyclones undergo significant lysis and high density values, 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 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 peak velocities are found over the Indian ocean during this period, of the order of 20m/s. Over the subtropics velocities are of the order of 12m/s on average. Somewhat higher speeds appear to occur in the vicinity of the subtropical jet from MAM through SON. The lowest translational velocities over the extratropics are observed in JJA. If the velocities of the systems is analysed considering the families, the results show that the shallow and intermediate events are faster, while the deep ones, mostly located in the polar area, have lower speeds.

3.3 Lower and upper troposphere: 925 and 250 hPa “non family” cyclone results

In order to introduced 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 analysis on the height behavior of families and subfamilies will be provided in Canziani et al. (2020, manuscript in preparation)

3.3.1 Lower troposphere: 925 hPa

Figure 11 shows monthly mean seasonal track density at 925hPa. Present results show large densities over 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, are and in areas over East Antarctica with hotspots extending from Dronning Maud Land to Oates Land mixed with areas of minimums values. Overall, the higher density of events can be observed between 35º-75ºS. The values throughout the year show limited seasonal variability, although it can be noted same differences. During SON, higher densities appears between Australia and New Zealand. In JJA present results show less cyclone activity over the eastern 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 present study, for JJA, and they did note higher cyclone density near the Antarctic Peninsula´s tip, i.e., to the north of the high density region reported here, although their results did not find higher densities at subtropical/midlatitudes as observed here. Results are also in agreement with Simmonds et al. (2003) and Pepler and Dowdy (2020), though the maximum near the Antarctic Peninsula is to the west of the peninsula in their analysis.

Figure 12 shows the cyclone translational velocity field at 925hPa. A quick inspection of the figure shows that the area with the highest density of events is the one that shows the greatest range of speeds with 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 DJF peak translational velocities near 18m/s are observed over the South Atlantic and 20m/s over the Indian Oceans between 40 and 60°S. During MAM maximum translational velocities in the vicinity of 20m/s maximize mainly over the Indian Ocean, extending into the higher subtropics. Higher velocities are also 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 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. 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 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 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 anomaly at the centre of the cyclone event, are most commonly used to show the intensity of cyclone events. The highest relative vorticity values which match with higher velocities, are found in a broad band in the 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 the Rio de la Plata and the coast of southern Patagonia and Malvinas (Falkland) sector, which merge towards the central South Atlantic. Values between 3 and $4 \times 10^{-5}s^{-1}$ extend in a latitudinally narrowing belt over the Indian Ocean all the way to Australia. This relative vorticity belt expands into the subtropics and onto the 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 3.5x10-5s-1, with a broader, more homogeneous distribution throughout the southern extratropics. During winter months, relative vorticity in the extratropics can reach values close to 5x10-5s-1 over the eastern South Atlantic and south of New Zealand. The latitudinal distribution shows a minimum over the Indian Ocean around 90°E. During SON the current analysis in agreement with Hoskins and Hodges (2005), yields a broad latitudinal band from the subtropics into subpolar latitudes with values in the vicinity of 3.5x10-5s-1. Broadly speaking the overall depth patterns find here are in agreement with the relative vorticity patterns described by Lim and Simmonds (2007) and Eichler and Gottschalck (2013). It is important to note that maxima for the different reanalyses may differ as much as 30% in a given region.

3.3.2 Upper troposphere: 250 hPa

There are fewer studies tracking cyclonic activity in the upper troposphere and they also define certain criteria to classify TRACK results as cut-off lows (COLs). Pinheiro et al. (2017) noted that there are differences between cut-off low results and unfiltered TRACK outputs. 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 overall agreement in the density distribution between both studies. A double spiraling structure can be observed, one in the subtropics and another at higher extratropical latitudes, extending from Australia well into the South Pacific Ocean. During JJA the maximum values are higher in the present analysis spiraling from the subtropics into the extratropics and extending all the way to Antarctica except in the vicinity of the Ross Sea. There is only a very weak evidence of subtropical densities at this time of year. The higher latitude 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 behaviour also broadens towards midlatitudes. There is also some evidence of activity at subtropical latitudes, particularly over and 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 upper tropospheric cyclone families. Spatially the higher COL densities tend to cluster around and over the continents in three regions, South America, Southern Africa and Australia, during most of the year. High densities are also observed over the Indian Ocean and the South Pacific during summer. Results are in agreement with Pinheiro et al. (2017) and Reboita et al. (2010), who pointed out that COLs over the Southern Hemisphere are subtropical and lower midlatitude phenomena.

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 are observed primarily over the Indian Ocean and to the west of Chile, over the South Pacific. During MAM the average speeds above 16ms^{-1} are more evenly distributed over the SH subtropics and midlatitudes. Comparatively high translational velocities are also observed coincident with the subtropical poleward 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 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. (2017),

Finally, Figure 16 shows the spatial distribution of event intensity in terms of relative vorticity. The seasonal cycle appears to have somewhat limited seasonal changes: during DJF, MAM and JJA a broad ring of vorticity of the order of -6 to -8x10^{-5} s^{-1} extends from the poleward edge of the subtropics into polar latitudes. There are some areas with values up to -10x10^{-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 x10^{-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 x10^{-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.

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 into the spatial patterns of the cyclonic events and their vertical distribution in the atmosphere, Figure 17 shows the “stacked” plots of the two levels. Figure 17a presents the overlapped vorticity fields of the two level. A distinct stronger vorticity average value at 250 hPa can be observed with respect to 925 hPa values, suggesting a strong vertical vorticity gradient, which more than doubles in the upper troposphere with respect to the lower troposphere. The spatial pattern also shows that the values are more uniform in the upper troposphere than near the surface, where events, mostly shallow ones, are observed to die in the vicinity of the Andes. There is also a highlighted area over Argentina that displays low values of vorticity near the surface, that in the upper troposphere become uniform. This behaviour seems to be directly opposite to that shown by the velocities compared at both levels (Figure 17 b), where faster systems near the surface are observed, slowing down into the upper troposphere. Note that, once again over Argentina and the vicinity of the Andes, events show decreasing values from 925 hPa to 250 hPa. Regarding the lifetime, a much more homogeneous spatial pattern can be appreciated, with events lasting up to almost 8 days at both levels.

However, it can be noted that while the events at 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 (Figure 17 d) appear to be similar in both levels, however events over South America are most frequently detected near the surface (more shallows) than in the upper troposphere. Another characteristic is that near Antarctica, events are stronger at 250 hPa, and weaker near the surface.

4. Discussion and summary

Cyclonic systems are one of the most widely studied topics from different perspectives based on theoretical, numerical analysis and observational data. However most observational studies are restricted to the surface or near surface. Those involving various levels of pressure are scarce and it is important to highlight that there are also 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 pressure levels in the troposphere and lowermost stratosphere. Cyclone events were categorized into shallows, intermediate and deeps 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, translational velocity, relative vorticity lifetime, genesis and lysis for event occurrences between 14° and 78°S, providing the raw material for ongoing research on cyclone dynamics.

Basic aspects of the characterization were presented, with 58231 multilevel cyclones being detected during the study period, an average of 303 events for all types per month, lasting at least 2 days with vertical 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. Intermediate cyclones extend from the extratropics into polar latitudes while deep cyclones are essentially sub-polar and polar. This does not mean the intermediate or deep events cannot extend into the subtropics, just that at lower latitudes they are comparatively rare events, in particular deep cyclones. Table 2 also provides information regarding lifetime and velocity and shows that, on average, shallows, are usually faster in contrast with deep events that tends to move more slowly but with longer lifetimes. As the results also highlight, an equatorward shift in the higher density frequency can be noted for shallow events. This may be linked to the nature of the shallow systems which apparently are usually elongated toward the Equator from the cyclone centre, but also with the shift in the SH circulation noted since the mid-1970s, as was pointed out by Pezza et al. (2007); Chen and Held (2007), among others.

For the 17-year sample from 2001 to 2017, results show that most of the events develop over oceans rather than over land, and the 700 hPa pressure level plays an important role in the analysis, regardless of the family or seasonality. Shallow and deep cyclones tend to have a large percentage of genesis with their lowermost level at 925 and 700hPa, while the intermediate ones have their genesis maxima near the surface 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 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 90ºE, 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 densities are respectively the summer and the winter/spring. It is interesting to note that throughout the entire period and for all seasons, the highest cyclonic density values can be observed in areas associated with the polar jet instead the subtropical jet, even when the latter is stronger in winter, when higher densities are regionally found. With respect to genesis and lysis it is important to highlight that the more dense regions in terms of number of events do not have a direct correspondence with the genesis and lysis high values zones. Although the belt between 45º- 75ºS has a high density of events and high genesis values, the highest lysis values correspond to a narrower portion of this ring detected between 50º-65ºS with the exception of West Antarctica. The extensive Andes region, coinciding with previous analyses, reappears 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 development of the systems. The area displays genesis of shallows and intermediate events, larger than the lysis which could suggest that systems do not disappear but reappear in the downstream side of the Andes, depending on latitude as discussed in L4DC. In terms of translational velocity, the analysis suggests that shallow and intermediate events are faster, while the deep ones, located in the vicinity of the polar areas, move at lower velocities.

In order to take the first steps toward 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, though 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 good agreement with translational velocities at MSLP for DJF and JJA in Sinclair (1994). The highest relative vorticity values are found in a broad band in the extratropics and subpolar latitudes, with some seasonal variations in maximum values and distribution. With respect of 250 hPa, high densities are observed close to Antarctica with a weak density maximum similar to the one in Hoskins and Hodges (2005) in the subtropics. There is also some evidence of activity at subtropical latitudes, particularly over and around southern Africa, the Indian Ocean between Madagascar and Australia, and over the South Pacific east of Australia, albeit weaker than in Hoskins and Hodges (2005). Results show the influence of the jet structure in the observed distribution of the upper tropospheric cyclone families. Spatially distribution of the COL show the higher densities tend to cluster around and over the continents in three regional groups (South America, Southern Africa and Australia) during most of the year. High densities are also observed over the Indian Ocean and the South Pacific during summer. Despite the density differences, current results over the subtropics agree with Pinheiro et al. (2017) and Reboita et al. (2010). 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.

In general terms, current bibliography usually provides results obtained in terms of agreement between studies. However, it should be noted that most of them are based on methods that usually involve either surface systems and/or single or few pressure levels. In this sense, we believe that the STACKER provides 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 highlight that features observed here were present in some studies but not in others, and none of the other studies were closer among themselves than with the present results if we consider a partial analysis. Local regional differences in the lower troposphere can be observed and can be attributed to different tracking methodologies, different study periods or reanalysis products used. As Walker et al (2020) pointed out, it is important to note that each 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.

Hence overall the STACKER seasonal climatology results, without including single level events, only family classified events present, 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 compared with more selective studies with specific constraints of COLs (Pinheiro et al., 2017) determined from single surfaces studies. Some of the results have suggested linkages between major atmospheric features such as jets and probably, as argued by Gramcianinov et al (2019), SST gradients or with the main modes of atmospheric variability, in particular with the SAM and ENSO in the SH (Rudeva et al, 2015). Many of these features, however, are not well defined in the current analysis given that all cyclone families are considered together. A family analysis is necessary to highlight the details of such relationships (Canziani et al., 2020, manuscript in preparation).

5. Acknowledgments

The authors would like to thank CONICET, Universidad Tecnológica Nacional, Facultad Regional Buenos Aires, and Pontificia Universidad Católica Argentina. We would also like to thank UTN, PID 4787 and ECMWF for the ERAI reanalysis products. The authors wish to thank the reviewers for their valuable comments and insights.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

6. References

Bengtsson, L., Hodges, K.I. and Roeckner, E. (2006). Storm Tracks and Climate Change. Journal of Climate, 19(15), pp.3518–3543

Catto, J.L. (2018). A New Method to Objectively Classify Extratropical Cyclones for Climate Studies: Testing in the Southwest Pacific Region. Journal of Climate, 31(12), pp.4683–4704.

Chen, G., and I. M. Held. (2007). Phase speed spectra and the recent poleward shift of Southern Hemisphere surface westerlies. Geophys. Res. Lett., 34, L21805, doi:10.1029/2007GL031200.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balmaseda, M.A., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Hólm, E.V., Isaksen, L., Kållberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, [online] 137(656), pp.553–597. Available at: https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.828 [Accessed 15 Oct. 2019].

Eichler, T. and Gottschalck, J. (2013) A comparison of southern hemisphere cyclone track climatology and interannual variability in coarse-gridded reanalysis datasets. Advances in Meteorology, 2013,891260

Flaounas, E., Kotroni, V., Lagouvardos, K. and Flaounas, I. (2014). CycloTRACK (v1.0) – tracking winter extratropical cyclones based on relative vorticity: sensitivity to data filtering and other relevant parameters. Geoscientific Model Development, 7(4), pp.1841–1853.

Flocas, H. A., I. Simmonds, J. Kouroutzoglou, K. Keay, M. Hatzaki, V. Bricolas, and D. Asimakopoulos, 2010: On Cyclonic Tracks over the Eastern Mediterranean. J. Climate, 23, 5243–5257, https://doi.org/10.1175/2010JCLI3426.1.

Gramcianinov, C.B., Hodges, K.I. and Camargo, R. (2019). The properties and genesis environments of South Atlantic cyclones. Climate Dynamics, 53(7–8), pp.4115–4140.

Grieger, J., Leckebusch, G.C., Raible, C.C., Rudeva, I. and Simmonds, I. (2018). Subantarctic cyclones identified by 14 tracking methods, and their role for moisture transports into the continent. Tellus A, 70(1), 1–2. https://doi.org/10. 1080/16000870.2018.1454808.

Grise, K., Son, S. and Gyakum, J. (2013). Intraseasonal and Interannual Variability in North American Storm Tracks and Its Relationship to Equatorial Pacific Variability. Monthly Weather Review, 141(10), pp.3610-3625

Hanson, C., Palutikof, J. and Davies, T. (2004). Objective cyclone climatologies of the North Atlantic – a comparison between the ECMWF and NCEP Reanalyses. Climate Dynamics, 22(6-7), pp.757-769.

Hodges, K. I. (1995.*)* Feature tracking on the unit-sphere. Monthly Weather Review, 123 (12). pp. 3458-3465, ISSN 0027-0644 doi: https://doi.org/10.1175/1520-0493

Hodges, K. I. (1999). Adaptive constraints for feature tracking. Monthly Weather Review, 127 (6). pp. 1362-1373. ISSN 1520-0493 doi: https://doi.org/10.1175/1520-0493(1999)

Hoskins, B.J. and Hodges, K.I. (2002). New Perspectives on the Northern Hemisphere Winter Storm Tracks. Journal of the Atmospheric Sciences, 59(6), pp.1041–1061.

Hoskins, B.J. and Hodges, K.I. (2005). A New Perspective on Southern Hemisphere Storm Tracks. Journal of Climate, 18(20), pp.4108–4129.

Inatsu, M. and Hoskins, B.J. (2004). The Zonal Asymmetry of the Southern Hemisphere Winter Storm Track. Journal of Climate, 17(24), pp.4882–4892.

IPCC. (2007) In: Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (Eds.) Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC. (2014) In: Pachauri, R.K. and Meyer, L.A. (Eds.) Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. IPCC, Geneva, Switzerland, 151 pp

Jansa, A., Genoves, A., Picornell, M., Campins, J., Riosalido, R. and Carretero, O. (2001). Western Mediterranean cyclones and heavy rain. Part 2: Statistical approach. Meteorological Applications, 8(1), pp.43-56.

Keable, M., Simmonds, I. and Keay, K. (2002), Distribution and temporal variability of 500 hPa cyclone characteristics in the Southern Hemisphere. Int. J. Climatol., 22: 131-150. https://doi.org/10.1002/joc.728.

Kelemen FD, Bartholy J, Pongracz R (2015) Multivariable cyclone analysis in the Mediterranean region. Quarterly Journal of the Hungarian Meteorological Service, 119(2):159–184

Kouroutzoglou, J., Flocas, H.A., Keay, K. et al. On the vertical structure of Mediterranean explosive cyclones. Theor Appl Climatol 110, 155–176 (2012). https://doi.org/10.1007/s00704-012-0620-3

Lakkis, S., Canziani, P., Yuchechen, A., Rocamora, L., Caferri, A., Hodges, K. and O'Neill, A. (2019). A 4D feature-tracking algorithm: A multidimensional view of cyclone systems. Quarterly Journal of the Royal Meteorological Society, 145(719), pp.395-417.

Lim, E. and Simmonds, I. (2007). Southern Hemisphere Winter Extratropical Cyclone Characteristics and Vertical Organization Observed with the ERA-40 Data in 1979–2001. Journal of Climate, 20(11), pp.2675-2690.

Murray, R.J. and Simmonds, I. (1991a). A numerical scheme for tracking cyclone centres from digital data. Part I: Development and operation of the scheme. Australian Meteorological Magazine, 39, 155–166.

Murray, R.J. and Simmonds, I. (1991b). A numerical scheme for tracking cyclone centres from digital data. Part II: Application to January and July GCM simulations. Australian Meteorological Magazine, 39, 167–180

Nakamura, H. and Shimpo, A. (2004). Seasonal Variations in the Southern Hemisphere Storm Tracks and Jet Streams as Revealed in a Reanalysis Dataset. Journal of Climate, 17(9), pp.1828-1844.

Neu, U., Akperov, M., Bellenbaum, N., Benestad, R., Blender, R., Caballero, R., Cocozza, A., Dacre, H., Feng, Y., Fraedrich, K., Grieger, J., Gulev, S., Hanley, J., Hewson, T., Inatsu, M., Keay, K., Kew, S., Kindem, I., Leckebusch, G., Liberato, M., Lionello, P., Mokhov, I., Pinto, J., Raible, C., Reale, M., Rudeva, I., Schuster, M., Simmonds, I., Sinclair, M., Sprenger, M., Tilinina, N., Trigo, I., Ulbrich, S., Ulbrich, U., Wang, X. and Wernli, H. (2013). IMILAST: A Community Effort to Intercompare Extratropical Cyclone Detection and Tracking Algorithms. Bulletin of the American Meteorological Society, 94(4), pp.529-547.

Pepler, A. and Dowdy, A. (2020). A Three-Dimensional Perspective on Extratropical Cyclone Impacts. Journal of Climate, 33(13), pp.5635-5649.

Pezza, A. B., I. Simmonds, and J. A. Renwick. (2007). Southern Hemisphere cyclones and anticyclones: Recent trends and links with decadal variability in the Pacific Ocean. Int. J. Climatol., 27, 1403–1419, doi:10.1002/joc.1477.

Picornell, M., Jansà, A., Genovés, A. and Campins, J. (2001). Automated database of mesocyclones from the HIRLAM(INM)-0.5° analyses in the western Mediterranean. International Journal of Climatology, 21(3), pp.335-354.

Pinheiro, H. R., Hodges, K. I., Gan, M. A. and Ferreira, N. J. (2017) A new perspective of the climatological features of upper-level cut-off lows in the Southern Hemisphere. Climate Dynamics, 48 (1). pp. 541-559.

Raible CC, Della-Marta PM, Schwierz C et al. (2008). Northern Hemisphere extratropical cyclones: a comparison of detection and tracking methods and different reanalyses. Mon. Weather Rev. 136: 880–897.

Reboita, M.S, Ambrizzi, T. and da Rocha, R.P, (2009). Relationship between the southern annular mode and southern hemisphere atmospheric systems. Revista Brasileira de Meteorologia, 24(1), pp.48-55.

Reboita, MS, da Rocha R.P, Ambrizzi, T, Sugahara, S. (2010). South Atlantic Ocean cyclogenesis climatology simulated by regional climate model (RegCM3). Climate Dynamics, 35(7):1331–1347. https://doi.org/10.1007/s00382-009-0668-7.

Reboita, M.S., da Rocha, R.P., Dias, C.G. and Ynoue, R.Y. (2014). Climate Projections for South America: RegCM3 Driven by HadCM3 and ECHAM5. Advances in Meteorology, 2014, pp.1–17

Reboita, M.S., da Rocha, R.P., Ambrizzi, T. and Gouveia, C.D. (2014). Trend and teleconnection patterns in the climatology of extratropical cyclones over the Southern Hemisphere. Climate Dynamics, 45(7–8), pp.1929–1944..

Simmonds, I. and Keay, K. (2000). Variability of Southern Hemisphere Extratropical Cyclone Behavior, 1958–97. Journal of Climate, 13(3), pp.550–561.

Simmonds, I., K. Keay, and E. Lim, 2003: Synoptic Activity in the Seas around Antarctica. Mon. Wea. Rev., 131, 272–288, https://doi.org/10.1175/1520-0493(2003)131<0272:SAITSA>2.0.CO;2.

Satake, Y., Inatsu, M., Mori, M. and Hasegawa, A., 2013. Tropical Cyclone Tracking Using a Neighbor Enclosed Area Tracking Algorithm. Monthly Weather Review, 141(10), pp.3539-3555.

Sinclair, M.R (1994). An Objective Cyclone Climatology for the Southern Hemisphere. Monthly Weather Review, 122(10), pp.2239-2256.

Sinclair, M.R., (1995). A Climatology of Cyclogenesis for the Southern Hemisphere. Monthly Weather Review, 123(6), pp.1601-1619.

Sinclair, M.R, (1997). Objective Identification of Cyclones and Their Circulation Intensity, and Climatology. Weather and Forecasting, 12(3), pp.595-612.

Sinclair, V., Rantanen, M., Haapanala, P., Räisänen, J. and Järvinen, H., (2020). The characteristics and structure of extra-tropical cyclones in a warmer climate. Weather and Climate Dynamics, 1(1), pp.1-25.

Trigo, I., Davies, T. and Bigg, G., (1999). Objective Climatology of Cyclones in the Mediterranean Region. Journal of Climate, 12(6), pp.1685-1696.

Ulbrich U, Leckebusch GC, Pinto JG. (2009). Extra-tropical cyclones in the present and future climate: a review. Theor. Appl. Climatol. 96: 117–131

Valsangkar, A.A., Monteiro, J.M., Narayanan, V., Hotz, I. and Natarajan, V. (2019). An Exploratory Framework for Cyclone Identification and Tracking. IEEE Transactions on Visualization and Computer Graphics, 25(3), pp.1460–1473.

van Bebber, W.J. (1891) Die Zugstrassen der barometrischen Minima nach den Bahnenkarten der Deutschen Seewarte für den Zeitraum von 1870–1890. Meteorologische Zeitschrift, 8, 361–366.

Walker, E., Mitchell, D. and Seviour, W. (2020), The numerous approaches to tracking extratropical cyclones and the challenges they present. Weather, 75: 336-341. https://doi.org/10.1002/wea.3861