Climatological features of cutoff low systems in the Southern Hemisphere

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[1] Cutoff lows (COLs) pressure systems climatology for the Southern Hemisphere (SH), between 10°S and 50°S, using the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) and the ERA-40 European Centre for Medium Range Weather Forecast (ECMWF) reanalyses are analyzed for the period 1979–1999. COLs were identified at three pressure levels (200, 300, and 500 hPa) using an objective method that considers the main physical characteristics of the conceptual model of COLs. Independently of the pressure level analyzed, the climatology from the ERA-40 reanalysis has more COLs systems than the NCEP-NCAR. However, both reanalyses present a large frequency of COLs at 300 hPa, followed by 500 and 200 hPa. The seasonality of COLs differs at each pressure level, but it is similar between the reanalyses. COLs are more frequent during summer, autumn, and winter at 200, 300, and 500 hPa, respectively. At these levels, they tend to occur around the continents, preferentially from southeastern Australia to New Zealand, the south of South America, and the south of Africa. To study the COLs at 200 and 300 hPa from a regional perspective, the SH was divided in three regions: Australia–New Zealand (60°E–130°W), South America (130°W–20°W), and southern Africa (20°W–60°E). The common COLs features in these sectors for both reanalyses are a short lifetime (~80.0% and ~70.0% of COLs at 200 and 300 hPa, respectively, persisting for up to 3 days), mobility (~70.0% and ~50% of COLs at 200 and 300 hPa, respectively, traveling distances of up to 1200 km), and an eastward propagation.

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1. Introduction

[2] Closed lows in the upper troposphere are called cutoff low pressure systems (COLs) if they are completely detached from the westerly current in the jet stream [*Palmén and Newton*, 1969]. These systems usually move toward the equator off the main belt westerlies, and are more intense in the upper troposphere and weaker or absent in the low levels of the atmosphere. COLs were initially identified using isobaric maps at higher tropospheric levels [*Palmén and Newton*, 1969]. More recent studies have also used the potential vorticity (PV) on isentropic surfaces to detect them [e.g., *Wernli and Sprenger*, 2007; *Nieto et al.*, 2008]. The genesis of COLs can be seen as the displacement of a region of high PV from its polar reservoir to lower latitudes, leading to the detachment of a discrete cutoff low [*Hoskins et al.*, 1985; *Nieto et al.*, 2008].

[3] *Nieto et al.* [2005, 2008] present a complete review of the lifecycle of COLs and their characteristics for the Northern Hemisphere (NH). According to these authors, a COL presents four stages: (1) initially there is a trough in the middle and upper troposphere, after (2) it evolves to the tear-off stage, when the geopotential contours assume an omega form in the Southern Hemisphere (SH) and an inverted omega in the Northern Hemisphere (NH), and to (3) the cutoff stage; finally, (4) the decay is characterized by a merging with a large trough in the zonal flow.

[4] COLs have been extensively studied in the NH [*Nieto et al.*, 2008 and references therein], but much less attention has been paid to those occurring in the SH. *Fuenzalida et al.* [2005], hereafter F05, determined a climatology of COLs over the SH at 500 hPa from 1969 to 1999 using the National Center for Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis [*Kalnay et al.*, 1996; *Kistler et al.*, 2001]. It was found that the COLs tend to occur around three main continental areas: Australia, southern Africa, and South America, with greater

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seasonality (the maximum being in the austral winter) in these last two regions. Analyzing only South America and its adjacent oceans (100°W–20°W and 15°S–50°S) at 250 hPa from 1979 to 1988, *Campetella and Possia* [2007, hereafter CP07], found a higher frequency of COLs during the austral autumn. *Singleton and Reason* [2007, hereafter SR07], also found a higher frequency of COLs in the autumn over southern Africa (10°E–40°E and 20°S–40°S) at 300 hPa from 1973 to 2002.

[5] The difference in the seasonality of COLs between the results of (1) F05 and (2) CP07 and SR07 could be associated with the methodology and/or the pressure level used to detect COLs. For example, F05 identified COLs using a method that merged objective and subjective analysis. After identifying a geopotential minimum at 500 hPa, using an automatic method, they completed the identification of COLs by visually inspecting the geopotential and temperature fields at 500 hPa and isotachs at 200 hPa. The COLs were identified when they (1) are separated equatorward from the main westerlies having in their upstream side a split jet stream and (2) if they have a cold core. CP07 selected the COLs events partially following the methodology described by *Nieto et al.* [2005], but using different levels to impose the geopotential minimum and the equivalent thickness criteria (250 hPa and 250–500 hPa instead of 200 hPa and 200–300 hPa, respectively). After these steps, the authors used a subjective analysis to include the additional conditions of the cutoff circulation and the lower temperature within the core.

[6] Although F05 provided a COLs climatology for the SH, they did not use an objective method to identify these systems and used only the middle level of the troposphere in their analysis. The present study will carry out an objective climatological characterization of COLs at different pressure levels (200, 300 and 500 hPa) over the SH, from 1979 to 1999, following for the three levels the same methodology used by *Nieto et al.* [2005]. Based on our results, it will be possible to discuss whether the differences found in the seasonality of COLs in the previous studies is due to the atmospheric level analyzed or the different methods that were used to identify the COLs. We will also compare the COLs climatology obtained from two different reanalyses: the NCEP-NCAR and the ERA-40 (European Centre for Medium Range Weather Forecast). Details of the data and methodology are presented in section 2. The results are presented in section 3. Section 4 concludes.

2. Data and Methodology

2.1. Data

[7] The climatology of the COLs was obtained using the NCEP-NCAR [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] and ERA-40 [*Uppala et al.*, 2005] reanalyses. The periods covered by the reanalyses are not the same. The NCEP-NCAR data is from January 1948 to the present and the ERA-40 is from January 1958 to the August 2002. COLs climatologies were built using the 6-hourly data from both reanalyses with a 2.5° × 2.5° horizontal resolution. While the NCEP-NCAR data has 17 vertical pressure levels from 1000 to 10 hPa, the ERA-40 has 23, from 1000 to 1 hPa. For the objective identification of COLs we used geopotential and zonal wind from 200, 300, 500 hPa and to air temperature more two levels were included (400 and 600 hPa).

2.2. Algorithm for Identifying and Tracking COLs

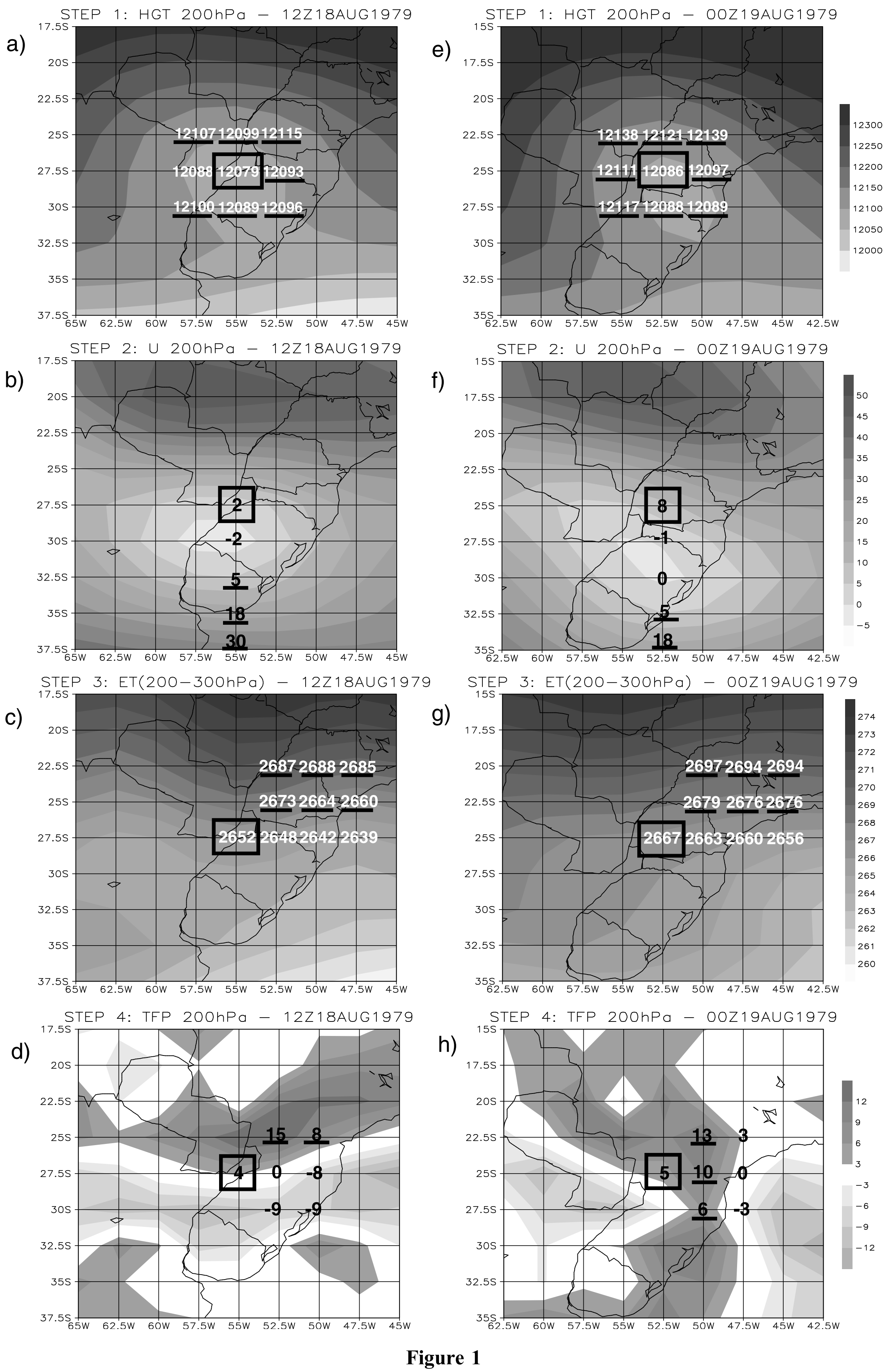
[8] COLs were identified using the objective method proposed by *Nieto et al.* [2005 hereafter NAL05], which follows four consecutive and restrictive steps based on the main physical characteristics of the conceptual model of COLs: (1) closed cyclonic circulation, (2) cutoff circulation from the westerlies, (3) equivalent thickness (thickness of the atmospheric layer between two pressure levels), which characterizes a ridge downstream of the COL, and (4) the presence of baroclinic zones, where one of those is situated downstream of the COL (see Manual of Synoptic Satellite Meteorology, available at http://www.zamg.ac.at/docu/Manual/start.htm). This last characteristic is identified via the thermal front parameter (TFP) [*Renard and Clarke*, 1965]. To clarify NAL05's procedure, Figure 1 illustrates the steps performed by their objective method for a real case of a COL during 18 and 19 of August 1979.

[9] The first imposed condition (closed cyclonic circulation, Step 1) involves detecting geopotential minima on the three proposed levels. Grid points that were lower than at least six of the eight surrounding grid points were selected. The grid point with a least 10 geopotential meters (gpm) of difference in the geopotential regarding the surrounding points was retained to the next step (Figures 1a and 1e). To fulfill the condition of a cyclonic vortex (cutoff, Step 2) isolated from the westerly current, the zonal wind was analyzed. The zonal wind needs to fulfill a change in the wind direction (westerly wind) at some of the four grid points southward of the geopotential minimum (Figures 1b and 1f). To check the equivalent thickness condition (Step 3), the difference in temperature between two pressure levels was computed (the levels compared were the three levels selected to perform the climatologies and the immediately low levels, at 300, 400 and 600 hPa, respectively). The grid point to the east of the selected geopotential minimum must have higher values of equivalent thickness. Once that this condition was satisfied, the TFP was analyzed to verify the COL baroclinic structure (Step 4). The TFP is defined as the change of the temperature gradient in the direction of the temperature gradient,

$$TFP = -\nabla|\nabla T| \cdot (\nabla T/|\nabla T|). \qquad (1)$$

[10] So to the east of the geopotential minimum, the TFP should be higher in order to consider the initial grid point that was detected as a COL system. Although the method-

Figure 1. Example of the objective method following a real case of a COL (18–19 August 1979) detected in our analysis. A square indicates the grid point with geopotential minimum and underlines mark the grid points that met the criteria used to identify COLs. (a and e) The geopotential (HGT in gpm) condition, (b and f) the zonal wind (U in ms^{-1}) condition, (c and g) the equivalent thickness (ET in gpm) condition and (d and h) the thermal front parameter (TFP × 10^{-11} K m^{-2}) condition are confirmed to have been fulfilled.



STEP 1: HGT 200hPa – 12Z18AUG1979
STEP 1: HGT 200hPa – 00Z19AUG1979
STEP 2: U 200hPa – 12Z18AUG1979
STEP 2: U 200hPa – 00Z19AUG1979
STEP 3: ET(200–300hPa) – 12Z18AUG1979
STEP 3: ET(200–300hPa) – 00Z19AUG1979
STEP 4: TFP 200hPa – 12Z18AUG1979
STEP 4: TFP 200hPa – 00Z19AUG1979
a)
b)
c)
d)
e)
f)
g)
h)

Figure 1

ology described is similar to NAL05, it was necessary to modify the Steps 3 and 4 in order to adapt the method for the SH. A visual inspection of the COLs in the SH shows that the axis of these systems has westward tilt greater than the axis of the systems in the NH. This implies that in the SH, the temperature gradient is oriented southwest-northeast in contraposition to the west-east orientation in the NH. As a consequence, the grid point to the east of the geopotential minimum does not usually present the higher values of equivalent thickness (Figures 1c and 1g) and TFP (Figure 1d) than that observed at the geopotential minimum. In these cases, the original version of the NAL05 algorithm underestimates the COLs in the SH. Therefore, the algorithm used in the present study was modified to compare a much larger number of points with the center of the geopotential minimum. For the equivalent thickness, the potential COL point is compared with 9 points to the northeast, as illustrated in Figures 1c and 1g and for the TFP it is compared with 6 points to the east (Figures 1d and 1h).

[11] It is important to note that the algorithm identifies the systems in the cutoff phase (Figure 1e) when the geopotential minimum is well defined. Sometimes, in the tear-off phase (Figure 1a), the minimum is also present because Step 1 is relaxed by considering 6 points to identify the geopotential minimum, and this also allows the identification of the systems.

[12] Once the grid points with COLs characteristics have been identified, it is necessary to detect those that form the same system in order to track the systems during their lifetime. The COLs trajectory shows the grid point from its first identification up to its disappearance, corresponding to a sequence of positions in the time [lon(t), lat(t)]. Even if a COL loses some of its features (Steps 1 to 4), the algorithm will still track this system if the changes occur in a period smaller than 24 h. The present study only analyzes COLs whose lifetime is greater than or equal to 24 h.

2.3. Validation of the Algorithm

[13] The accuracy of the algorithm was validated in two ways: (1) the COLs outputs for 2 years were visually compared with the geopotential field at 200 hPa, and (2) the results (at 200 hPa from 1979 to 1988) with the previous climatology of CP07 (at 250 hPa).

[14] Following a visual inspection, the outputs of the algorithm (hour, day, month, year, latitude, and longitude) for each COL system were compared with geopotential maps at 200 hPa using the NCEP-NCAR reanalysis for the years 1981 and 1990. The area chosen for this validation was 15°S–50°S and 130°E–160°W, from southeastern Australia to New Zealand, which includes the region of greater frequency of COLs in the SH (see section 3.1.1). The identification considered the COLs lifecycle characteristics: the initial trough intensification, the tear-off, and the cutoff phase. Two problems were found during this validation: (1) the algorithm combines two different systems in one trajectory when the systems are very close to each other, which implies that the number of COLs will be underestimated, and (2) if during the track the COLs lose some of their features (Steps 1 to 4) and only return to their original form after 24 h, the algorithm will consider two different systems and the number of COLs will be overestimated. Therefore, the outputs of the algorithm usually have around ±10%–15% of error when compared to the visual inspection.

[15] Figure 2 shows the distribution of COLs at 200 hPa detected by our method and that found by CP07 at 250 hPa from 1979 to 1988 in the region between 15°S–50°S and 100°W–20°W. It is important to remember that CP07 only consider systems with lifetime greater than or equal to 48 h, which is double the period used in the present study. Figure 2a shows that the interannual variability of COLs is similar in both studies, even with respect to the higher frequency of COLs that was observed in 1979. However, for the 10 years studied, CP07 found 171 events, while we found 126. The difference between these two values is probably related to the different pressure levels used in the two analyses (see section 3.1.1). Figure 2b presents the geographical distribution of the COLs. Note that in CP07, COLs were plotted when they presented their greatest depth, whereas in our climatology it was considered the initial position of the COLs. In general terms, there is a good agreement between the results of the two studies. Both studies located the COLs in similar areas and recorded a higher frequency of occurrence near the coast of Chile, the center of Argentina, and southern Brazil. In summary, the results found with the algorithm are robust. Therefore it gives confidence in the analyses that will be presented in the following sessions.

2.4. COLs Climatology at 200, 300, and 500 hPa

[16] The COLs climatology, between 10°S and 50°S, at three different pressure levels (200, 300, and 500 hPa) was determined. The lower latitudes were excluded because there is only a small probability that COLs occur northward of 10°S [F05; CP07]. However, the higher latitudes were excluded in order to avoid the mid high level cyclonic vortices that developed near the southern pole [*Berbery and Vera*, 1996]. These cyclonic vortices do not necessarily form due to their detachment from westerly flow and enhanced cold air advection, as discussed in NAL05.

[17] The seasonal variability of COLs at 200, 300, and 500 hPa and their geographical distribution will be presented here. Only the density of the first position of the COLs is shown. The density was calculated by adding the COL systems in 2.5° × 2.5° boxes with respect to latitude-longitude and normalized by their areas. In this study, the austral seasons are defined as follows: December–February (summer), March–May (autumn), June–August (winter), and September–November (spring).

2.5. Data Inhomogeneity

[18] The quality of the reanalyses data for the SH is questionable before 1979, due to the sparse upper-air observation network over the oceans. After 1979, the satellite data were assimilated in the reanalyses; as a result, new features may have been introduced into the data [*Kistler et al.*, 2001]. For this reason, the COLs climatology at 200 hPa using the NCEP-NCAR and ERA-40 reanalyses for years before and after 1979 will be investigated (Figure 3). The NCEP data were divided in two periods, 1950–1978 and 1979–2007, and the density of the COLs frequency in their first position was determined (Figures 3a and 3b). Because the NCEP time series are larger than that the ERA-40, the NCEP data were divided into other two periods: 1958–1978 and 1979–1999, respectively (Figures 3d, 3e, 3g, and

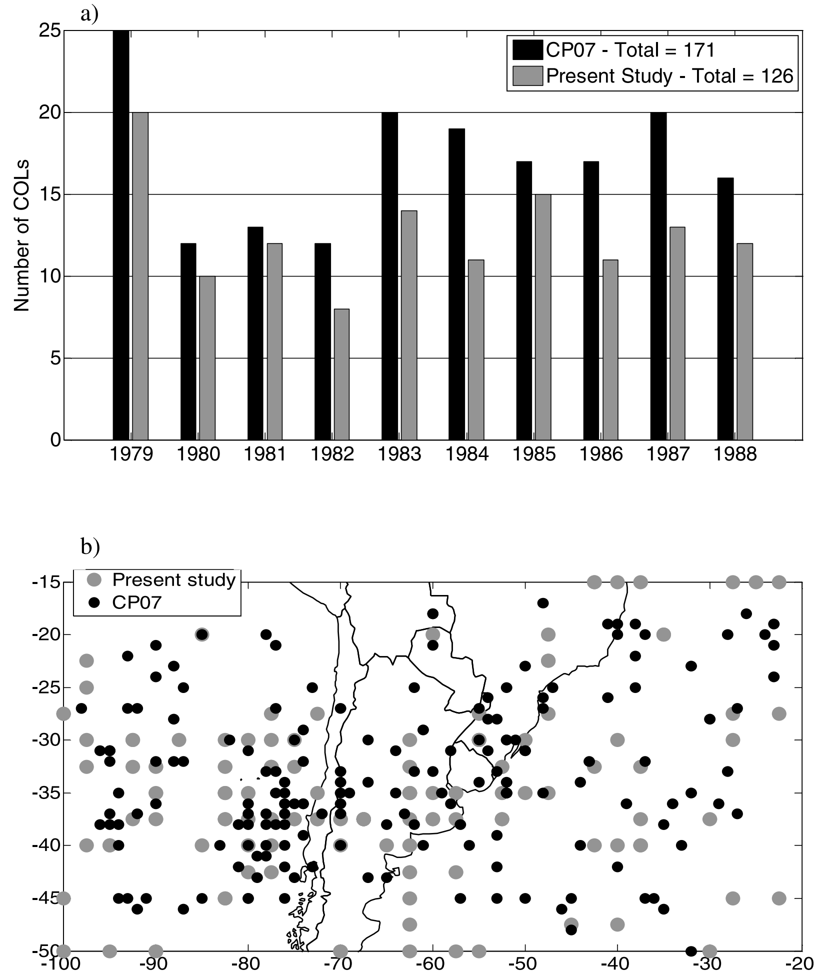


Figure 2. (a) The annual number of COLs at 250 hPa in CP07 (black bars) and at 200 hPa in the present study (gray bars) and (b) the spatial distribution of COLs from 1979 to 1988 in the region between 15°S–50°S and 100°W–20°W. In Figure 2b, gray circles indicate the first position of COLs detected by the method used in this study, and black circles represent the greatest depth of COLs detected by CP07.

3h), to allow the comparison with ERA-40. The density differences between the periods pre- and post-1979 (post-1979 minus pre-1979) are shown in Figures 3c, 3f, and 3i.

[19] It is clear from Figure 3 that COLs frequency increased in the period post 1979 being higher in the ERA-40 than in the NCEP. The maximum increase observed in both reanalyses coincides with regions identified by F05 as those in which COLs activity is higher, i.e., southern Africa, southern South America, and southeastern Australia. An increase in the COLs frequency is also observed in the oceans, particularly in the ERA-40 reanalysis (Figures 3c, 3f, and 3i). It is interesting that the density of COLs in the NCEP-NCAR decreased over large part of the Pacific Ocean in the period post-1979 (Figures 3c and 3f), whereas the ERA-40 shows an increase over this region (Figure 3i). These results agree with those of other studies, e.g., that of surface cyclones of *Wang et al.* [2006]. These authors also found that the frequency of cyclones is higher in the ERA-40 than in the NCEP-NCAR, both pre- and post-1979. In the NH, NAL05 also determined whether different periods of the reanalysis could affect the COLs climatology. They did not observe clear difference in the localization of COLs in the both periods analyzed (1958–1978 and 1979–1998). In the NH, the reanalyses were less affected by the assimilation of satellite data, due to the denser upper-air observation network that has been in place since 1950. *Nieto et al.* [2008] compared the seasonal distribution of all grid points that fulfilled the criteria to be a COL at 200 hPa in the NH, using the NCEP-NCAR and ERA-40 reanalyses. The period analyzed in the NCEP-NCAR was from 1948 to 2006 and in the ERA-40 from 1958 to 2002. They found that the geographical distribution of COLs is similar in both climatologies and it is coherent with that obtained in NAL05. They also noticed that though the ERA-40 time series is smaller than the NCEP-NCAR, it presents a larger number of COLs.

[20] The seasonal and annual average of COLs at 200 hPa in the SH, pre- and post-1979, were also compared (Table 1). The NCEP-NCAR and ERA-40 show the same seasonal variability for both periods, with COLs occurring with greater frequency in the summer, followed by autumn, spring, and winter. As mentioned before, the frequency with which COLs occur increases post-1979 and this increase is higher in the autumn (33% in the NCEP-NCAR and 137% in the ERA-40) and smaller in the summer (6% in the

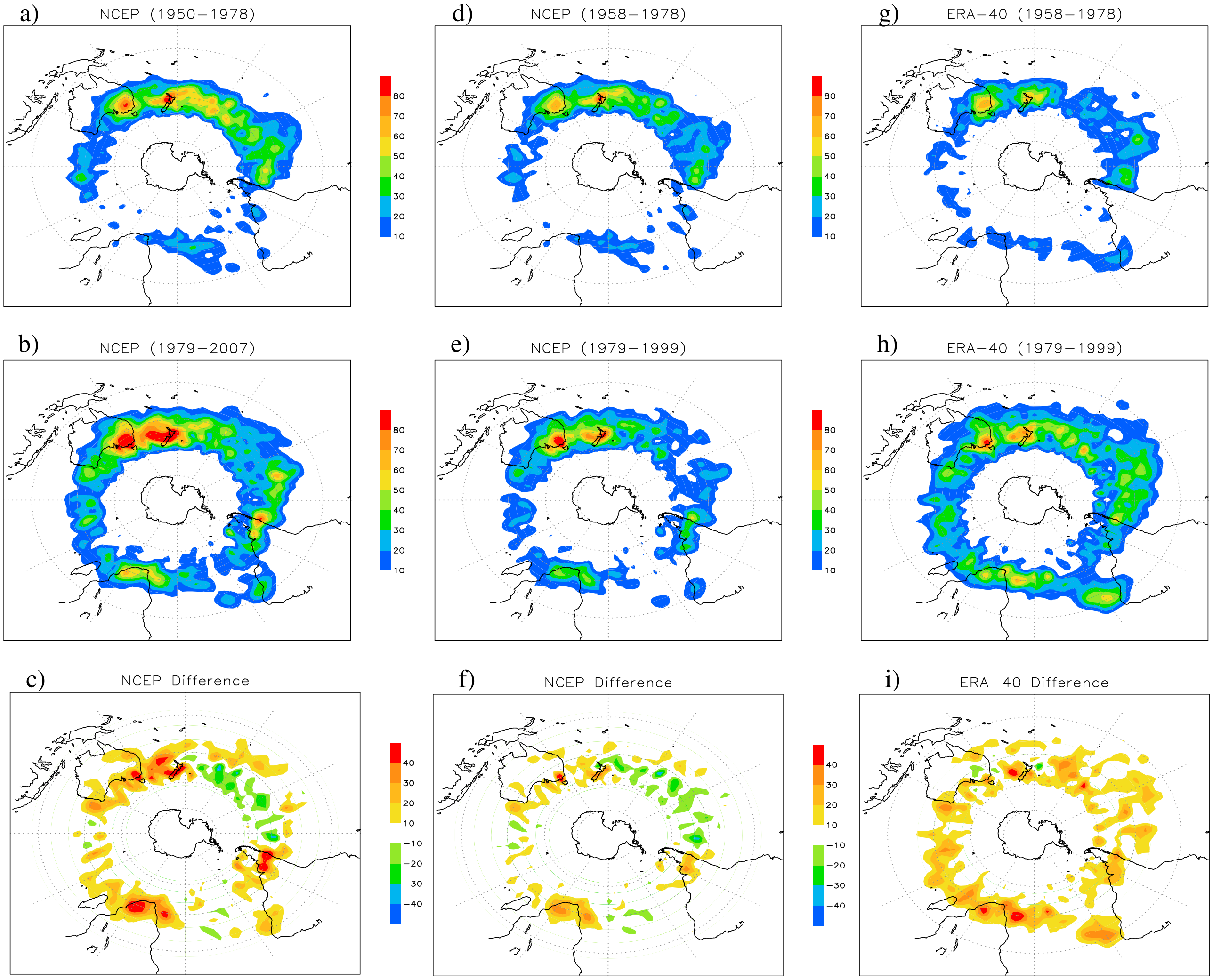


Figure 3. The total density (× 10^5 km^{-2}) of the occurrence of COLs in their initial position at 200 hPa in the (left and middle) NCEP-NCAR and (right) ERA-40 reanalyses for pre- and post-1979. (a) From 1950 to 1978, (b) from 1979 to 2007, and c) the difference between Figures 3a and 3b in the NCEP-NCAR. (d) From 1958 to 1978, (e) from 1979 to 1999, and (f) the difference between Figures 3d and 3e in the NCEP-NCAR. (g) From 1958 to 1978, (h) from 1979 to 1999 and (i) the difference between Figures 3g and 3h in the ERA-40. The density corresponds to the number of COLs in squares of 2.5° latitude × 2.5° longitude normalized by their areas and smoothed with a 9 × 9 point moving average.

NCEP-NCAR and 85% in the ERA-40). For annual values, the NCEP-NCAR and ERA-40 present an increase of 19% and 105%, respectively. Therefore, Figure 3 and Table 1 indicate that there are questionable differences in the COLs climatology before and after the introduction of satellite data. Based on these results, the COLs at 200, 300, and 500 hPa from 1979 to 1999, a common period in the both reanalyzes, will be analyzed here.

3. Results

3.1. COLs at Different Atmospheric Levels

3.1.1. Spatial and Temporal Distribution

[21] Figures 4 and 5 show the seasonal and annual average density of the COLs at their initial position for the NCEP-NCAR and ERA-40 reanalyses at 200, 300 and 500 hPa. For both reanalyses, the density of COLs is greater

Table 1. Seasonal and Annual Averages of COLs at 200 hPa in the Southern Hemisphere in the NCEP-NCAR and ERA-40 Reanalyses for Pre- and Post-1979 and From 1958 to 1999[a]

	NCEP/NCAR			ERA-40		
	58/78	79/99	58/99	58/78	79/99	58/99
Summer	31.2	33.1 (6%)	32.5	29.3	54.2 (**85%**)	42.1
Autumn	23.3	31.1 (**33%**)	27.3	19.9	47.2 (**137%**)	33.6
Winter	8.28	9.7 (17%)	9.0	6.0	13.1 (**118%**)	9.6
Spring	12.9	16.5 (**28%**)	14.7	10.8	22.0 (**104%**)	16.4
Annual	76.5	91.0 (**19%**)	83.8	66.9	137.2 (**105%**)	101.7

[a]Values in parentheses correspond to the percentage increase in the number of COLs post-1979 compared to the pre-1979 period, and values in bold are those with a significance level of 0.05 (95% of confidence).

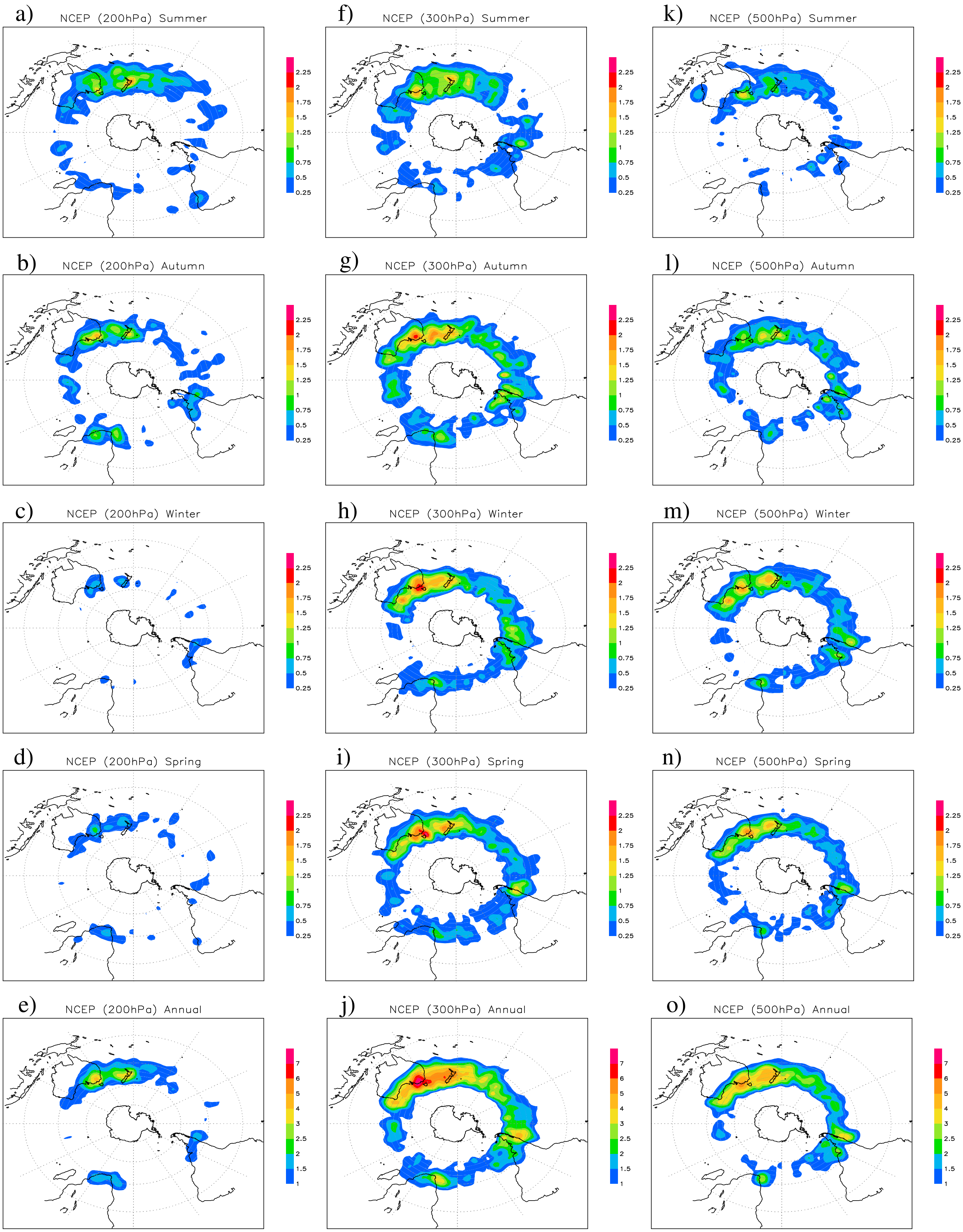


Figure 4. The seasonal and annual average density ($\times\ 10^5\ km^{-2}$) of the occurrence of COLs in their initial position in the NCEP-NCAR reanalysis at (a–e) 200 hPa, (f–j) 300 hPa, and (k–o) 500 hPa. The density corresponds to the number of COLs in squares of 2.5° latitude × 2.5° longitude, normalized by their areas, divided by the number of seasons and smoothed twice with a 9 × 9 point moving average.

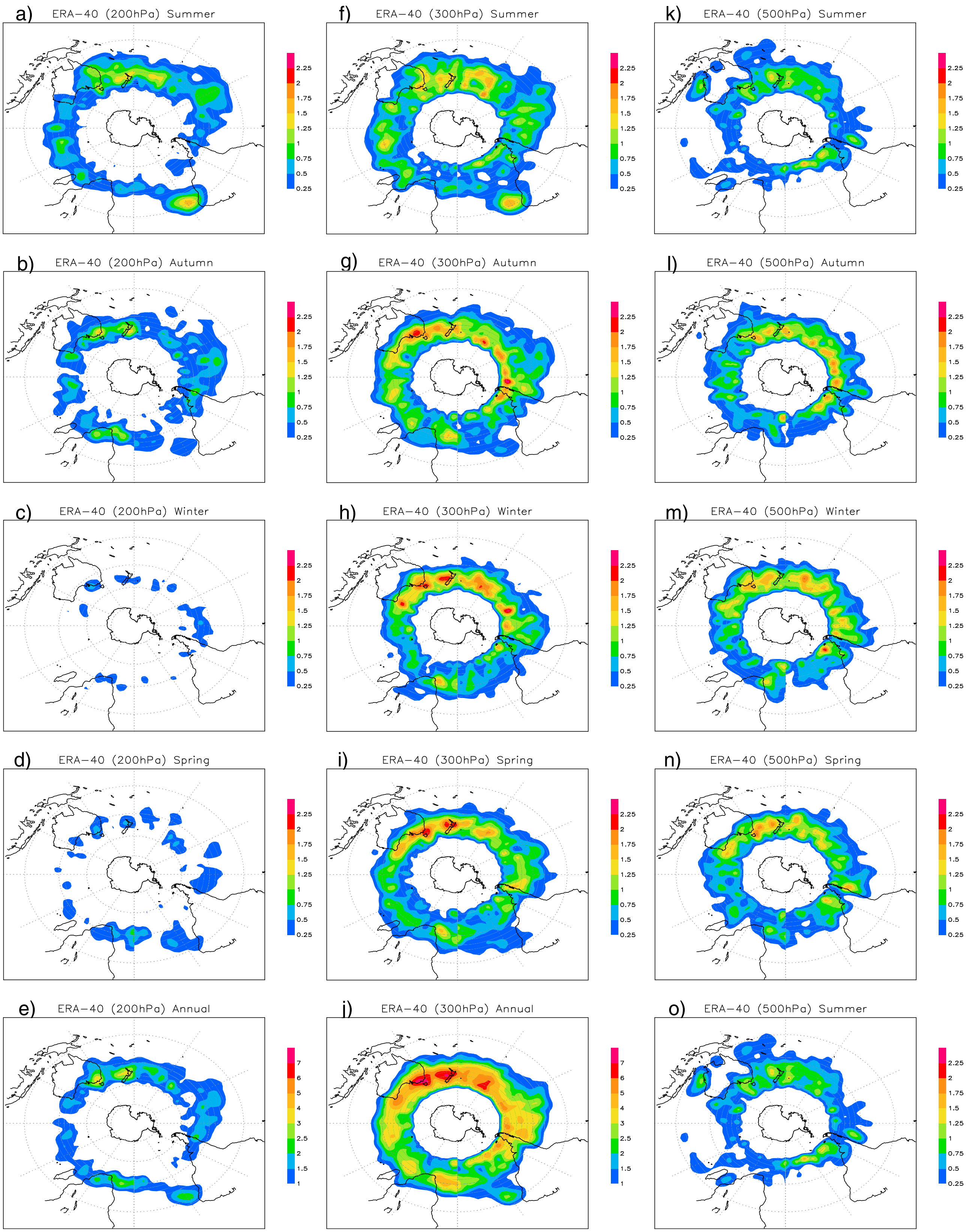


Figure 5. As in Figure 4, but for the ERA-40 reanalysis.

Table 2. Seasonal and Annual Averages of COLs at 200, 300, and 500 hPa in the Southern Hemisphere from 1979 to 1999 in the NCEP-NCAR and ERA-40 Reanalyses[a]

	200 hPa		300 hPa		500 hPa	
	NCEP	ERA-40	NCEP	ERA-40	NCEP	ERA-40
Summer	33.1	54.2 (63.7%)	43.5	87.0 (100.0%)	25.8	53.5 (107.4%)
Autumn	31.1	47.2 (51.8%)	55.6	94.0 (69.1%)	37.0	69.1 (86.8%)
Winter	9.7	13.1 (35.0%)	48.1	80.2 (66.7%)	40.9	73.9 (80.7%)
Spring	16.5	22.0 (33.3%)	49.2	85.9 (74.6%)	37.1	70.0 (88.7%)
Annual	91.0	137.2 (50.8%)	197.5	348.8 (76.6%)	141.4	267.5 (89.2%)

[a]Values in parentheses correspond to the percentage of COLs found in the ERA-40 in relation to the NCEP-NCAR. It was considered that the NCEP correspond to 100%; thus, the ERA-40 was evaluated in relation to the NCEP.

at 300 hPa, decreasing at 500 hPa, and reaching the minimum occurrence at 200 hPa. At all levels, the main regions in which COLs develop are southern Africa, southern South America, and from southeast Australia to New Zealand. These regions coincide with those found by F05 at 500 hPa from 1969 to 1999.

[22] It is important to mention that in the three pressure levels analyzed, the ERA-40 shows more COLs than in the NCEP-NCAR (Figures 4 and 5 and Table 2). This result is clear in the annual mean (Table 2), where the ERA-40 shows 50.8% (200 hPa), 76.6% (300 hPa), and 89.2% (500 hPa) more COLs than the NCEP. Therefore, there is an increase of differences from upper levels to midlevels. *Nieto et al.* [2008] also found a larger number of COLs in the ERA-40 over the NH in comparison with the NCEP-NCAR. According to *Wang et al.* [2006], the ERA-40 also contains a number of surface cyclones larger than the NCEP-NCAR reanalysis. These differences might be due to the resolution of the model, new data assimilation scheme, or more/improved observed data in the ERA-40. For the surface cyclones in particular, *Wang et al.* [2006] conclude that the resolution of the model affects small-scale dynamics and cyclogenesis, with could explain the differences in the climatology of the ERA-40 and NCEP-NCAR reanalyses.

[23] The seasonal variability of the COLs is the same in both reanalyses, but differs among pressure levels (Figures 4 and 5 and Table 2). At 200 hPa, most COLs occur in the summer, followed by autumn, spring, and winter (Figures 4a–4d and 5a–5d and Table 2). This seasonal distribution agrees with NAL05 for the NH. At 300 hPa, the maximum number of COLs occurs in the autumn (Figures 4f–4i and 5f–5i and Table 2), and for the others seasons the behavior is different between the ERA-40 and NCEP-NCAR; where COLs are much less common in the winter for ERA-40 and in the summer for NCEP-NCAR. A similar seasonal variation at 300 hPa was found by SR07 over subtropical southern Africa, with COLs occurring more in the autumn and less in the summer. As obtained by F05, the largest number of COLs occurs in the winter at 500 hPa, followed by autumn, spring, and summer (Figures 4k–4o and 5k–5o and Table 2).

[24] In a regional analysis of the seasonal variability, the NCEP-NCAR and ERA-40 at 200 hPa and the ERA-40 at 300 hPa present a well-defined COLs area over northeast Brazil in the summer (Figures 4a, 5a, and 5f), which is not apparent at 500 hPa and in the F05 study. Moreover, there is a reduction of COLs over the southwest of South America in summer. This may be related to the development of an upper level anticyclone, known as the Bolivian high, which inhibits the formation of COLs over this area. However, downstream of the Bolivian high, a trough develops over northeast Brazil [*Lenters and Cook*, 1997] and contributes to the formation of detached cold core cyclonic circulations [*Kousky and Gan*, 1981; *Ramirez*, 1996; *Ferreira et al.*, 2009], or in other words, the development of COLs. This process explains the higher frequency of COLs at upper tropospheric levels found in this region. Due to the fact that high-pressure systems in upper levels are a characteristic of the summer circulation [*Lenters and Cook*, 1997], an upper level high is also present in southern Africa (centered ~15°S), which could also explain the lower frequency of COLs there (Figures 4a, 5a, and 5f).

3.1.2. Comparison With Other Works

[25] The comparative analysis shows that the observed seasonality of COLs may depend on the pressure level that is studied. Therefore, the differences in seasonality obtained by NAL05, F05, and SR07 seem mainly related to the pressure levels that were considered, rather than the method used to identify the COLs.

[26] With respect to the annual mean (Figures 4 and 5), the number of COLs found at 500 hPa in the NCEP-NCAR (141 COLs/yr) was greater than that found in F05 (40 COLs/yr). The difference could be attributed to (1) the fact that the present study considered COLs with a lifetime greater than or equal to 24 h, whereas F05 used 36 h, meaning that more systems were included in the climatology of the present study and (2) the periods were also different: 1979–1999 for the present study and 1969–1999 for F05.

[27] Although the present study did not focus on the evaluation of the physical mechanisms that determines the seasonality of COLs at different atmospheric levels, some suggestions are presented. The jet streams at 200 hPa act as waveguides for Rossby wave propagation [*Hoskins and Ambrizzi*, 1993; *Ambrizzi et al.*, 1995]. The breaking of these waves in the upper troposphere allows the advection of stratospheric air toward the subtropical troposphere [*Hoskins et al.*, 1985], thereby helping in the formation of COLs. However, during the seasons with stronger jet streams it seems to be more difficult for Rossby wave breaking to occur. In the SH, the subtropical jet intensifies (weakens) during the winter (summer) [*Kållberg et al.*, 2005; *Gallego et al.*, 2005], which could inhibit (promote) the Rossby wave breaking and consequently reduce (increase) the development of COLs. This proposed mechanism is consistent with the results of *Postel and Hitchman* [1999] and T. Ndarana and D. W. Waugh (personal communication, 2010), where at 350 K isentropic level (~ 200 hPa) they found smaller

Table 3. The Seasonal and Annual Average of COLs at 200 and 300 hPa in the Three Regions of Occurrence in the Southern Hemisphere in the NCEP-NCAR and ERA-40 Reanalyses[a]

	200 hPa						300 hPa					
	A-NZ		SA		Africa		A-NZ		SA		Africa	
	NCEP	ERA	NCEP	ERA	NCEP	ERA	NCEP	ERA	NCEP	ERA	NCEP	ERA
Summer	**22.7**	**31.0**	6.6	15.4	3.8	7.8	27.8	**45.8**	10.1	27.3	5.6	14.0
Autumn	17.0	22.0	**8.0**	**15.8**	**6.0**	**9.5**	**30.8**	45.2	**15.9**	**30.8**	**8.9**	**18.0**
Winter	5.0	5.5	3.1	5.0	1.6	2.7	26.1	40.3	14.9	24.7	7.1	15.2
Spring	8.6	8.8	4.1	7.2	3.7	5.9	27.9	41.5	13.1	26.4	8.1	**18.0**
Annual	53.7	67.7	22.1	43.5	12.8	26.0	113.3	173.2	54.4	109.7	29.9	65.4

[a]The three regions are the Australia–New Zealand region (A-NZ), the South America region (SA), and the southern Africa region (Africa) from 1979 to 1999 in the NCEP-NCAR and ERA-40 reanalyses. The season with the greatest frequency of COLs is in bold.

(larger) number of Rossby wave breaking during the winter (summer).

[28] Over the SH, the seasonality of the westerly winds at 500 hPa is weak [*Kållberg et al.*, 2005]. Therefore, F05 suggests that the diabatic process may explain the greater (lower) frequency of COLs during the austral winter (summer). The atmosphere latent heating that is associated with cumulus convection (which is normally maximized in the midtroposphere) is an important mechanism for inhibiting the development of COLs or reducing their lifetime (*Hoskins et al.*, 1985]. Knowing that the convective activity is intense over subtropical latitudes of Africa and South America during the austral summer, F05 point out that this mechanism tends to produce COLs with short lifetimes and only a few meet the criteria of being strong and closed systems for long periods (longer than 24 or 36 h). In contrast, over the most part of Australia, summertime deep convection does not develop, which could explain the large number of COLs in this region.

3.2. Climatology for Different Sectors of SH

[29] This section presents the main climatological features of the COLs at 300 and 200 hPa, i.e., at the pressure levels that are representative of the upper troposphere. The 500 hPa level is not included, because a complete COLs climatology for this level has already been presented in F05.

3.2.1. Seasonal Climatology

[30] According to Figures 4 and 5, COLs have preferential regions of occurrence and seasonality. Most of the COLs occurs over three main regions: Australia–New Zealand (60°E–130°W), South America (130°W–20°W), and southern Africa (20°W–60°E), covering the 15°S–50°S latitude bands. The COLs annual and seasonal means at 200 and 300 hPa in each region selected are given in Table 3. From this table, one can see that (1) ERA-40 has more than twice the number of COLs than the NCEP-NCAR reanalysis in all regions, and that (2) the seasonality of the COLs is highly dependent on the region in which they occur.

[31] For southern Africa at 300 hPa, more COLs are found annually (29.9 systems in the NCEP-NCAR and 65.4 in the ERA-40) than in SR07 (11 systems). However, taking the same area (10°E–40°E and 20°E–40°S) and COLs lifetime (greater than 24 h) used by these authors, the annual mean obtained in the NCEP-NCAR is 10.5 COLs/yr, which is similar to their result of 11 COLs/yr, but the annual mean in the ERA-40 is 17.3 COLs/yr. Over South America, we also found more systems annually at 200 and 300 hPa than in CP07 (17 COLs/yr). If we consider the same area (100°W–20°W and 15°S–50°S) and COLs lifetime (greater than or equal to 48 h) studied in CP07, at 200 hPa and 300 hPa there are 6.5 and 22.2 COLs/yr, respectively, in the NCEP-NCAR, and 15.0 and 46 in the ERA-40. This indicates that the main difference between the present result and those of CP07 is probably related to the pressure level used.

[32] Considering the SH as a whole, the COLs at 200 hPa are more (less) frequent during austral summer (winter) in both reanalyses (Table 2). However, the seasonality of the COLs differs according to the different regions (Table 3). More COLs occur over Australia–New Zealand during the summer, whereas for South America and southern Africa the maximum occurs in the autumn. For the three regions, the fewest COLs occur during winter. The regional seasonal variability at 200 hPa is similar in the NCEP-NCAR and ERA-40 (Table 3). The smaller number of COLs over the southwest of South America and southern Africa in the summer (section 3.1.2) is probably related to the upper level monsoon anticyclones [*Lenters and Cook*, 1997]. There is also an anticyclone over Australia, however, it is located in the north of the continent and it appears does not influence the COLs over the southeast of Australia. Some mechanisms that might explain the seasonality of COLs at 200 hPa were discussed in section 3.1.2.

[33] The results show that at 300 hPa, COLs occur with greater frequency in the autumn than in the summer and winter (Table 2). In the three sectors, there are differences in the seasonality of COLs between the two reanalyses (Table 3). In the NCEP-NCAR and ERA-40, more COLs occur over Australia–New Zealand in the autumn and summer, respectively, but in both reanalyses the difference in the number of COLs between autumn and summer is small (~10%). Fewer COLs occur during the winter over Australia–New Zealand. Over the South America and southern Africa sectors, more COLs are observed in the autumn for both reanalyses and there are fewer COLs during summer (winter) in the NCEP-NCAR (ERA-40).

3.2.2. COLs Lifetime

[34] It is known that COLs last for only a couple of days [NAL05; F05; CP07]. This feature is also observed in Figure 6 that shows the relative frequency distributions of the lifetime of COLs at 200 hPa and 300 hPa. At 200 hPa, for the three sectors of occurrence the majority of COLs (about 80%) have a lifetime from 1 to 3 days. The number of COLs that last for more than 6 days is very small. The same pattern is observed for the COLs at 300 hPa, but there is

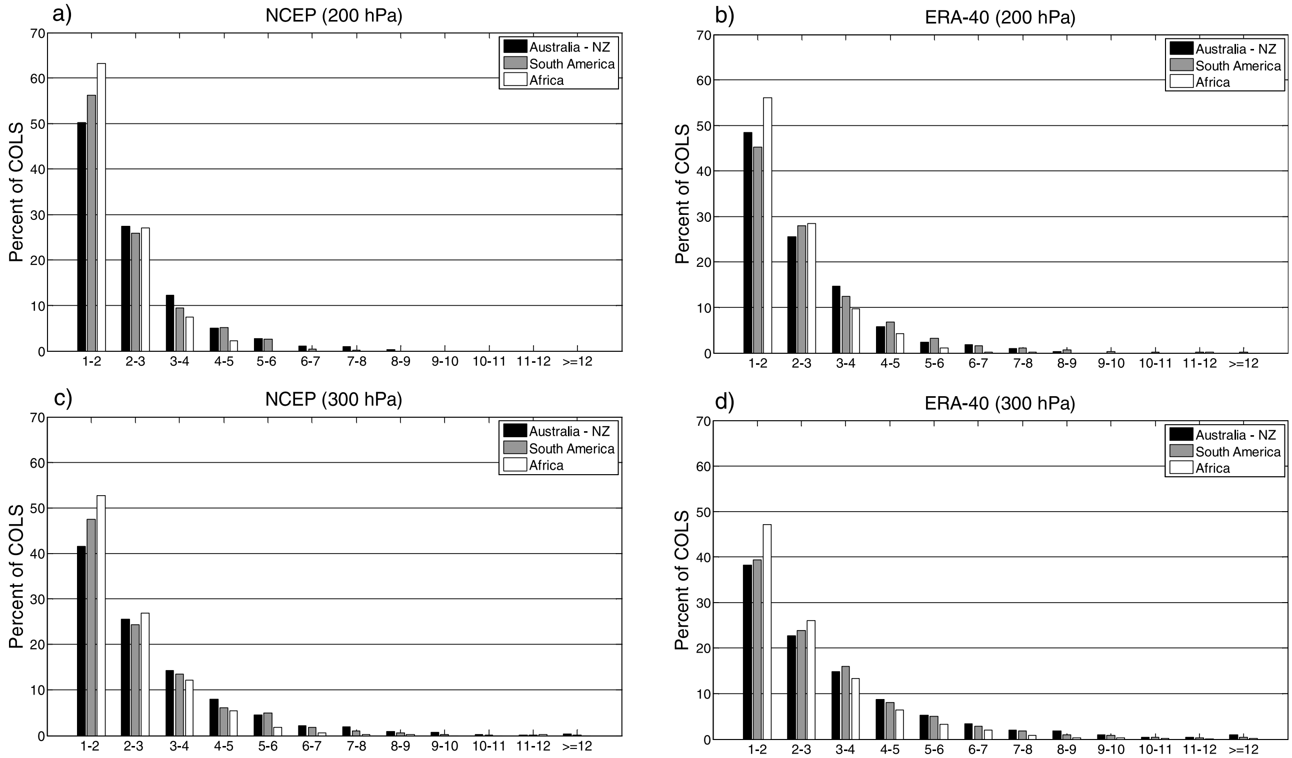


Figure 6. The frequency distribution with respect to the lifetime of COLs, in days, for the Australia–New Zealand (60°E–130°W), South America (130°W–20°W), and southern Africa (20°W–60°E). The frequency intervals do not include the last number.

a decrease in the number of COLs with shorter lifetimes (1–2 days) corresponding to ~40% of the cases when compared to the ~50% at 200 hPa. This implies a slight increase in the number of COLs that has longer lifetime, mostly in the ERA-40. The results obtained at 300 hPa over southern Africa confirm those of SR07, such that more than 50% of COLs last for only 1–2 days and fewer than 10% last more than 4 days.

3.2.3. COLs Movement

[35] It has been usually suggested that the regions of development and dissipation of COLs are close to each other [*Bell and Bosart*, 1989], which indicates that COLs are quasi-stationary systems. However, more recent studies have shown that COLs are mobile systems [*Kentarchos and Davies*, 1998; NAL05; F05]. The distance traveled and the mean velocity of the COLs for the SH were calculated for the three sectors analyzed. The mean velocity was determined as the ratio between the distance traveled, from the initial to the final position, by the time that it occurs. Ndarana and Waugh (personal communication) present the frequency distributions for mean velocity and distances traveled, respectively. In both reanalyses the modal value for the mean velocity is in an interval of 3–6 m s $^{-1}$ (Figure 7), with 3%5–40% at 200 hPa and 30%–35% at 300 hPa of the COLs presenting this velocity in each sector of the SH. For the whole hemisphere, at 200 hPa a considerable percentage (between 27% and 30%) of COLs have slow movement (between 0 and 3 m s^{-1}) in both NCEP-NCAR and ERA-40 (Figures 7a and 7b). On the other hand, at 300 hPa there is a clear increase in the number of COLs that move faster (greater than 9 m s^{-1}) in both reanalyses.

[36] Figures 8a and 8b show the distances traveled by COLs at 200 hPa. The results indicate that a small percentage of COLs (3.1% in the NCEP-NCAR and 2.7% in the ERA-40) are stationary, while the quasi-stationary systems, such as those moving less than 300 km, constitute 11.3% and 10.7% of COLs in the NCEP-NCAR and ERA-40, respectively. At 300 hPa (Figures 8c and 8d) there is a reduction of the both stationary (~1.3%) and quasi-stationary systems (between 5% and 6%) and a clear increase of the number of COLs traveling larger distances (>2400 km).

[37] For the three sectors and the SH as a whole, approximately 70.0% at 200 hPa and 50% at 300 hPa of the systems have a displacement of up to 1200 km in the NCEP-NCAR and ERA-40 reanalyses. Considering the seasonal means (figures not shown), for the three sectors studied and whole SH, both reanalyzes at 200 and 300 hPa show that COLs displacement is larger (smaller) during the winter (summer).

[38] To show the preferential direction of COLs movement, Figure 9 presents the trajectories of these systems at 200 hPa using the NCEP-NCAR for five selected years: 1979, 1980, 1981, 1990, and 1993 (neutral years, i.e., without El Niño or La Niña events). The trajectories in Figure 9 were obtained by jointing the first and last position of the COLs. The trajectories followed by the COLs are in general irregular, although eastward movement seems to be more common. This result is confirmed considering the period from 1979 to 1999 at 200 and 300 hPa as shown by the frequency distributions in Figure 10. In both levels (Figures 10a and 10b), a larger number of COLs moves to the east quadrant (east, southeast, or northeast). Although at both levels about 27–

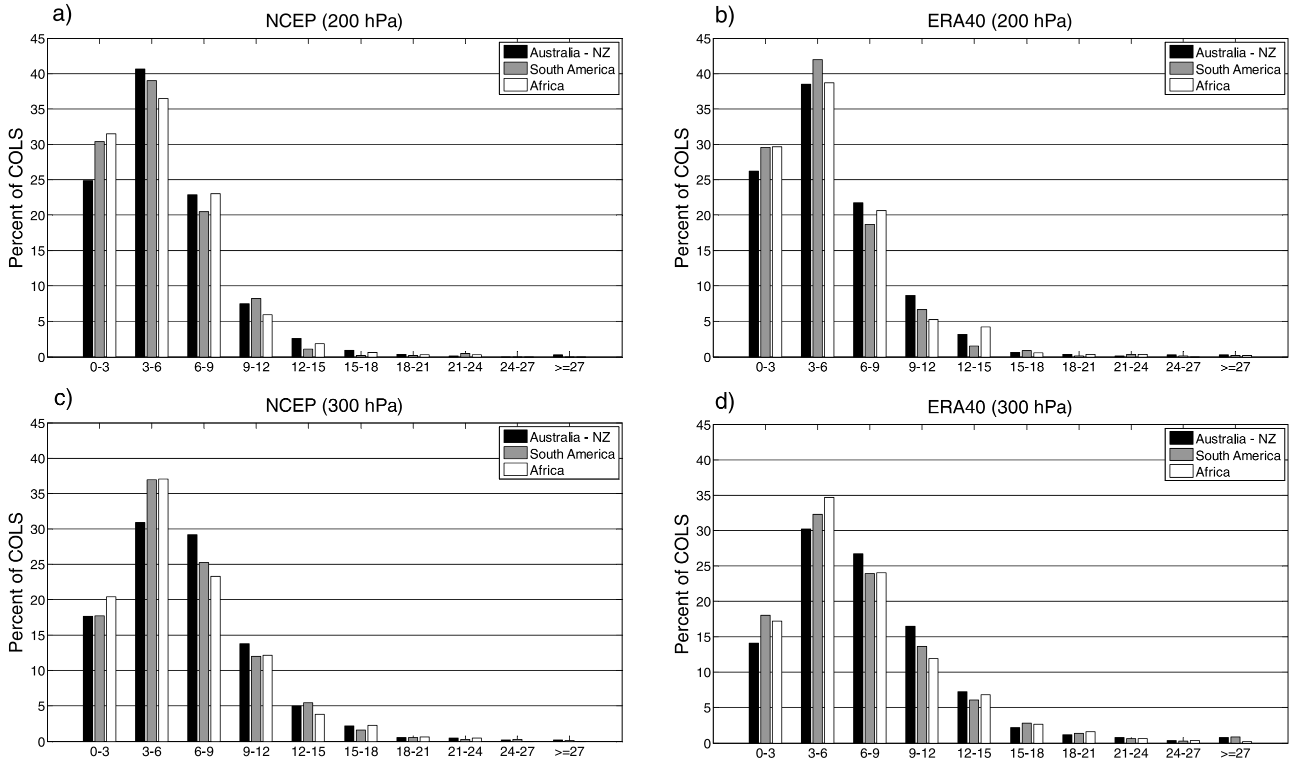


Figure 7. As in Figure 6, but for the mean velocity of COLs (m s^{-1}).

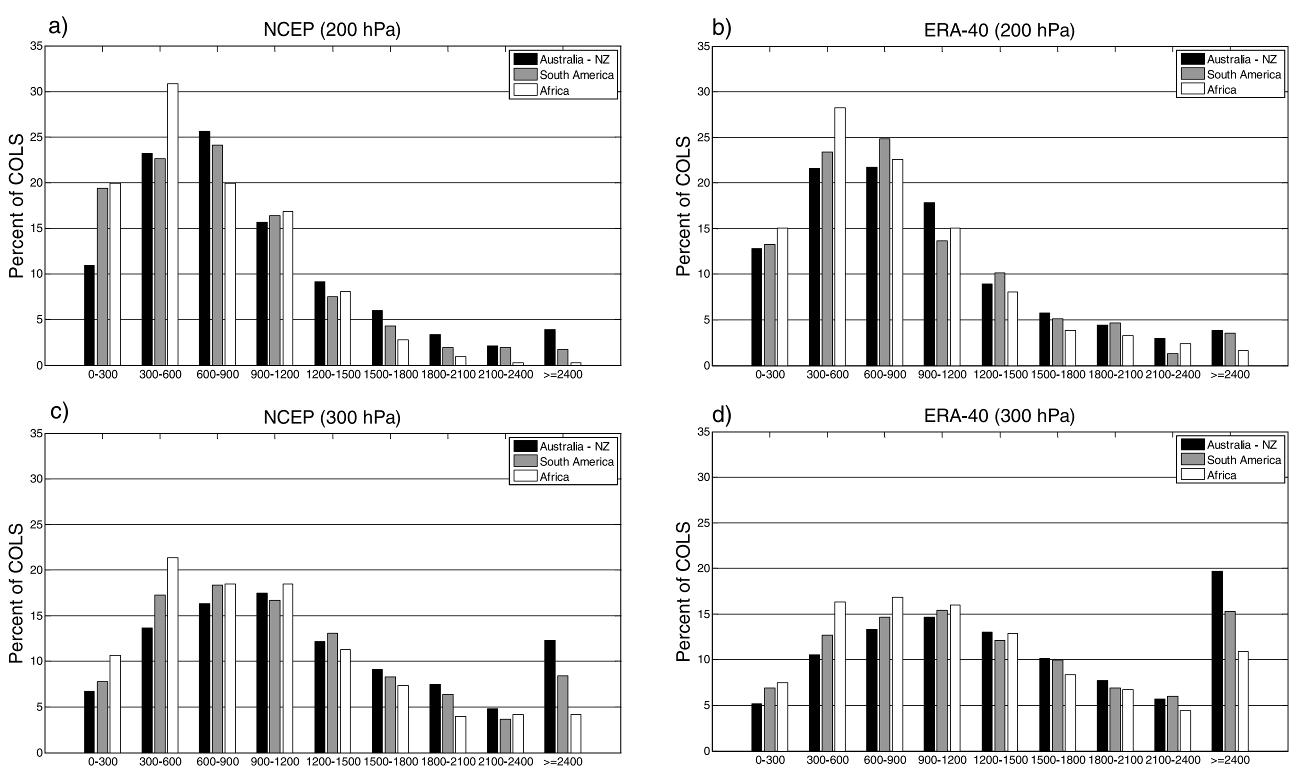


Figure 8. As in Figure 6, but for the distance traveled by the COLs (in km).

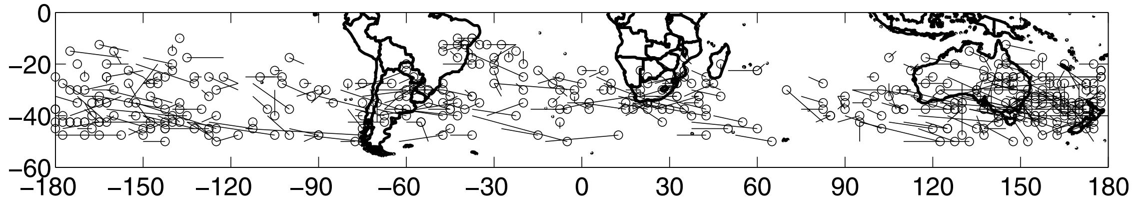


Figure 9. The trajectories of COLs at 200 hPa in the NCEP-NCAR reanalysis during 1979, 1980, 1981, 1990, and 1993 (neutral years, without El Niño or La Niña events). Circles indicate the final position of the COLs.

30% of the COLs have a southeast displacement, at 300 hPa there is also a large percentage of COLS (~30%) moving to the northeast.

[39] It is interesting to note from Figure 9 that over the northeast Brazil the COLs seem to have a preference to move westward. In section 3.1.1, it was mentioned that COLs in this region are associated with the trough downstream of the Bolivian high during the summer. According to *de Calbete et al.* [1996], the COLs in this area are more frequent in summer and displace westward, but some of them can also move eastward. To confirm this hypothesis, the movement of COLs in this particular region (from 10°S to 25°S, 20°W to 55°W) was evaluated. According to Figure 11a, at 200 hPa, 54.5% (55.5%) of the COLs in the NCEP-NCAR (ERA-40) move to the west quadrant (west, southwest, or northwest) and 18.1% (35.0%) to the east quadrant (east, southeast, or northeast). At 300 hPa, a large percentage of COLs moves to the west quadrant (52.9% and 40.8% in the NCEP-NCAR and ERA-40, respectively) and more COLs than at 200 hPa move to the east quadrant (35.3% and 41.4% in the NCEP-NCAR and ERA-40, respectively). At 200 hPa, there are more stationary COLs in the NCEP-NCAR than in the ERA-40 (Figure 11a) and at 300 hPa there is no southward movement of COLs in the ERA-40 (Figure 11b).

4. Conclusions

[40] A climatology of COLs for the SH was presented. COLs were identified at three atmospheric levels (200, 300, and 500 hPa) using NCEP-NCAR and ERA-40 reanalyses. Because of the questionable quality of the reanalyses before 1979 in the SH, the analyses were carried out for the period 1979 to 1999.

[41] COLs were identified using the objective method developed in NAL05, which is based on four main physical characteristics of these systems. The method was adapted for studying COLs in the SH. This was necessary because in the austral hemisphere COLs have greater westward tilting than in the NH. As a consequence, the grid point to the east of the geopotential minimum does not usually present higher value of equivalent thickness and TFP (thermal frontal parameter). The main modification was to increase the number of the grid points eastward of the geopotential minimum to make the comparisons of equivalent thickness and TPF.

[42] The spatial distribution of COLs over the SH shows higher density at 300 hPa, decreasing at 500 and 200 hPa levels and the number of COLs is larger in the ERA-40. In general, these results are in good agreement with previous studies.

[43] The long databases built of COLs revealed that there are three preferential regions of these systems: from southeastern Australia extending to New Zealand (60°E–130°W), southern South America (130°W–20°W), and southern Africa (20°W–60°E). The annual mean number of COLs at 200 hPa in the NCEP-NCAR (ERA-40) is 53.7 (67.7), 22.1 (43.5) and 12.8 (26.0) in the three regions, respectively. These numbers are more than double at 300 hPa in both reanalyses, where the Australia–New Zealand contributes for most of the total number of COLs over the SH at 200 and 300 hPa. This large number of COLs could be

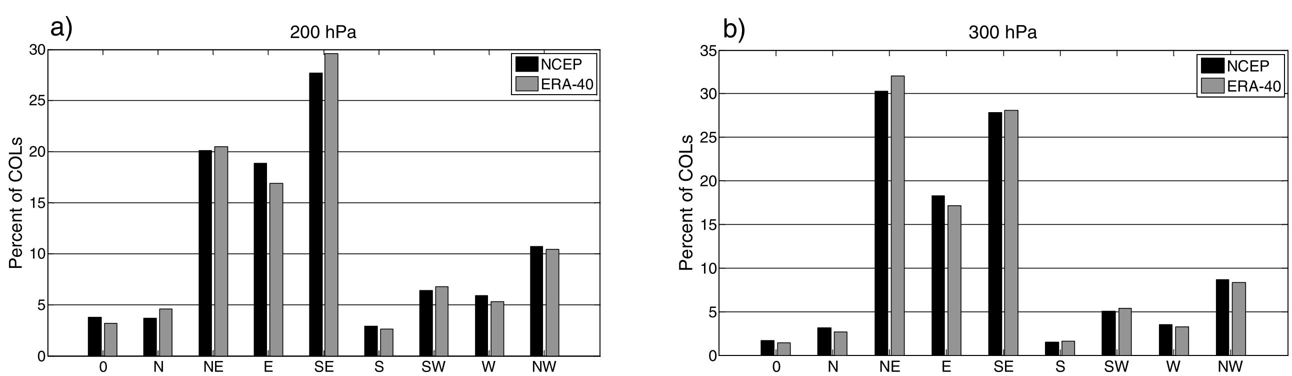


Figure 10. The direction of displacement of the COLs in the SH from 1979 to 1999 in the NCEP-NCAR and ERA-40 at (a) 200 hPa and (b) 300 hPa. The horizontal axis shows the direction of movement directions; stationary COLs are represented by 0.

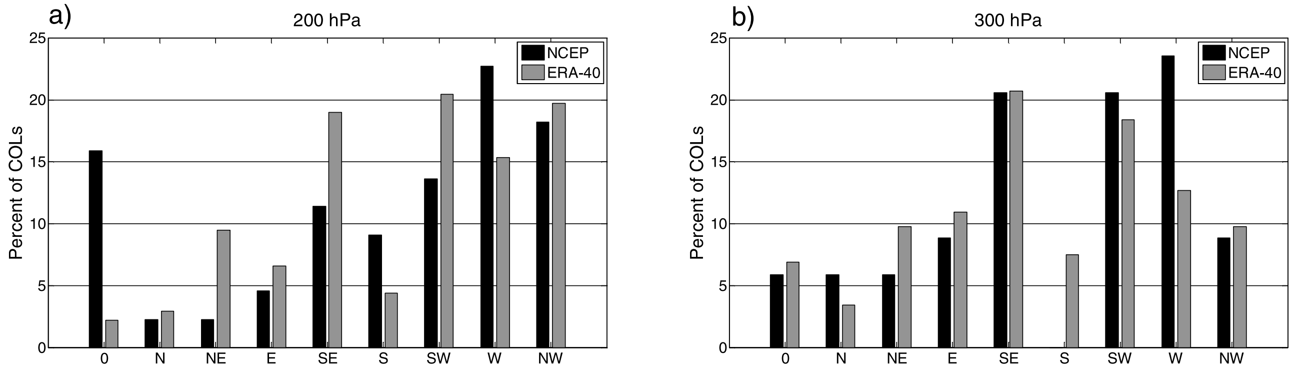


Figure 11. Similar to Figure 10, but for the displacement of COLs over the northeast of Brazil (10°S–25°S, 20°W–55°W).

attributed to the high frequency of blocking events in the eastern side of this region [*Trenberth and Mo*, 1985; *Mendes et al.*, 2008]. F05 also suggests that the mid upper level blocking can generate COLs in their northern sector. Moreover, the COLs region over Australia seems to be not affected by the monsoon anticyclone that usually inhibits the COLs development in the other two regions of the SH.

[44] Considering the whole SH, the seasonal variability of COLs is similar in the NCEP-NCAR and ERA-40 reanalyses, but differs among the atmospheric levels. At 200 hPa, COLs occur with greater frequency in summer, whereas at 300 hPa they are more frequent in autumn, as suggested by SR07. At 500 hPa, COLs frequency is large in winter, which is in agreement with the COLs climatology reported in F05 for the SH. Based on these results, it is clear that the seasonality of COLs is related to the pressure level used to search them and not because of the different methods used to identify them. As suggested by some studies, this variability could also be linked to Rossby wave breaking events or with the jet intensity at upper atmospheric levels. It lies beyond the scope of this study to draw conclusions to the physical mechanisms associated with the seasonal variability of COLs and the difference in the frequency of COLs in the two reanalyses used here.

[45] A more exhaustive analysis of the three areas of occurrence showed different seasonal behavior. At 200 hPa, COLs form more often in summer over the Australia–New Zealand region, whereas they are more common in autumn over the South America and southern Africa regions. During winter, fewer COLs form over the three areas. This seasonal feature is observed in the NCEP-NCAR and ERA-40 reanalyses. The lower frequency of COLs over South America and southern Africa in the summer may be due to the upper level monsoon anticyclones that inhibit the formation of COLs in the southwest of South America and southern Africa. At 200 and 300 hPa, the presence of COLs over northeast Brazil is clearly observed in the NCEP-NCAR and ERA-40. These COLs form in the trough downstream of the South America upper-level monsoon anticyclone [*Kousky and Gan*, 1981]. In the three sectors, COLs formation is higher during autumn at 300 hPa.

[46] Over the SH, a large proportion of the COLs lasted for 1–3 days. In general, the COLs were found to be mobile, with the preferential direction of movement being to the east. At 300 hPa, the COLs tend to be faster, travel greater distances, and live for longer than at 200 hPa.

[47] This study has demonstrated that some features of the COLs climatology may depend on the atmospheric level that is calculated and the method used to identify COLs seems to be of less importance. In a regional analysis, some interesting characteristics of COLs were found, particularly related to the differences in the frequency and seasonality. The physical mechanisms associated with these results were not evaluated here. However, they are being investigated and the findings will be presented elsewhere.

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