

Relationships between cut-off lows and the semiannual and southern oscillations

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Abstract The characteristics of Southern Cut-off Lows (CoLs) are studied for the period 1979–2008. The systematic identification of CoLs is realized by applying an original automated scheme using mean daily geopotential height and air temperature at 500 hPa NCEP-DOE II Reanalysis data. From closed lows' trajectories established from the Equator to the polar jet stream, extratropical lows are analyzed and the stage of cut-off is defined as a secluded low presenting a cold core. From 4,843 cases the general CoL features are presented and confirm several previous results such as the geographic distribution which shows that they are more frequent in the latitudinal band contained between 20°S and 45°S and in close proximity to the continents. On a seasonal time scale, CoLs are more numerous from late summer to autumn, with a maximum of frequency in March/April. In winter (June–July–August), they are fewer but deeper than during the rest of the year. In the median domain ($\sim 32.5^\circ\text{S}$), the annual cycle of the frequency is bimodal and present two peaks during transitional seasons. In this zone, the seasonal cycle varies in accordance with the Semiannual Oscillation. Thereby, when the meridional gradient of temperature/pressure is reinforced between mid and high latitudes, CoLs are more frequent in the median domain. Over the period 1979–2008, the annual CoLs' frequency exhibits a positive trend of about 25%.

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This increase is associated with a widening of the latitudinal domain of occurrence equatorward as well as poleward. The trend is linked with an abrupt positive shift in the number of CoLs' generation between 1998 and 1999. The geographical distribution of CoLs frequency varies significantly in accordance with El Niño Southern Oscillation with more CoL's at lower (higher) latitudes during La Niña (El Niño) events, principally in the Southern Pacific.

Keywords Cut-off low · Southern hemisphere ·
Semiannual oscillation · ENSO

1 Introduction

Cut-off Lows (CoLs) are hazardous atmospheric systems that have significant impact on society because of their association with tempestuous weather. They are defined as mid and upper tropospheric cold lows, which generate and develop in the westerlies. A split of the westerlies and a breaking of mid and upper level jet stream appear simultaneously with the generation of the closed low (e.g. Ndarana and Waugh 2010). At the mature stage, the low is clearly separated from the main flow typically by a cut-off high, i.e. a warm anticyclonic pressure system located at higher latitudes. Thus, typical CoLs represent an atmospheric blocking situation (e.g. Trenberth and Mo 1985). Consequently, they adopt a slow displacement with a non-preferential direction, and their quasi stationary character associated with their potential instability can induce heavy rainfall over two or three consecutive days.

The Intergovernmental Panel on Climate Change assessment (IPCC 2007) reports that many uncertainties persist in observed low features in sub-tropical latitudes due to divergences of the different Reanalysis data and

specifically for the Southern Hemisphere (Wang et al. 2006). Uncertainties also exist about blocking events and as CoLs are typically subtropical lows associated with blocking events, it is essential therefore to have a comprehensive baseline climatology to explore the regional implications of variability and climate change.

Fuenzalida et al. (2005, here after F2005) generated a general climatology of southern CoL features from NCEP-NCAR Reanalysis data (Kalnay et al. 1996; Kistler et al. 2001) over the period 1969–1999. This study has been recently updated by Reboita et al. (2010) and Ndarana and Waugh (2010) using ERA 40 and NCEP-NCAR Reanalysis datasets. These analyses highlight the climatology of CoL features and confirm several points of the knowledge on the subject, such as their geographical distribution in the Southern Hemisphere (SH) CoLs are typically located in subtropical latitudes and surrounding the three continents. Nevertheless, Reboita et al. (2010) show, using the same detection method, that the mean CoL features at hemispheric scale diverge significantly in accordance with the reanalysis data source, the period covered and the level of geopotential height used for the identification of the systems. Notable changes appear in the geographical distribution of CoLs from 1979 with the advent of satellite observations in the Reanalysis. These differences are significant over the South Atlantic, Southern Africa and the Indian Ocean. Despite these differences, they did establish that the CoLs are more frequent at higher troposphere levels in summer and in the lower troposphere in winter, a result observed in both Reanalyses (ERA40 and NCEP-NCAR).

This present study considers the link between CoLs and both the Semiannual Oscillation (SAO) and El Niño Southern Oscillation (ENSO). Our objective is to establish the relationship between CoLs' occurrence and large-scale modes which characterize the seasonal and inter-annual variation of the mean SH circulation.

Section 2 presents the data and the methodology developed to identify CoLs over the period 1979–2008. The method follows an original automated scheme including a tracking algorithm. Some complementary analysis and verifications have been performed to estimate the reliability of our CoLs dataset (Sect. 3). Section 4 addresses the link between CoLs' and the SAO. The relationship with ENSO and long term trends are presented in Sect. 5. Finally, the summary and discussion of the results are included in the Sect. 6.

2 Data and methodology: establishment of cut-off low trajectories

Within the extra-tropical latitudes, there are two types of secluded cyclone. The first type is the occlusion, when the warm sector of a cyclone is cut by cold air (cold air from

the rear joins the cold front of the cyclone, Bjercknes and Solberg 1922). These cyclones are located poleward of the polar jet-stream. The second type, commonly called cut-off low, is when cold sector is cut by warm air associated with a ridge of pressure. This study focuses on the latter.

2.1 Description of the typical CoLs' development

In mid-troposphere, a CoL typically begins as a cold trough in the upper-air flow, which becomes a closed circulation and then extends down to the surface but does not always achieve a surface expression. Previous studies have defined the different steps of the CoLs' development in the mid and high troposphere (e.g. Winkler and Zwatz-Meise 2001; Nieto et al. 2005; Porcù et al. 2007). Four major stages characterize the life cycle of these systems (see supplementary material, part A). The first stage is the formation of a trough in the upper air flow. Next, the trough becomes elongated and a cyclonic circulation forms on the equator side of the trough. This second stage is called Tear-off, meaning a closed low which is embedded in a trough. When the closed low is well developed and detached from the trough, it is qualified as a cut-off. At this stage the CoL is out of the main westerly flow and presents an equivalent barotropic structure with a cold core. Finally, the low weakens and dissipates, decaying completely or, in some cases, the system merges again with the westerly flow.

2.2 Data

Several regional and hemispheric studies on the climatology of CoLs in the SH have used NCEP-NCAR (NCEP1) Reanalysis data. Since 2002, NCEP-DOE¹ Reanalysis (NCEP2) data (Kanamitsu et al. 2002) are available extending from 1979 to present. In this new version, the known errors of NCEP1 were fixed, thereby producing better Reanalysis for many parameters. Hines et al. (2000) and Kanamitsu et al. (2002) recommend using the second version of these Reanalysis data, specifically for the study of transients in the SH.

The subsequent goal of this study will be to quantify the contribution of CoLs on precipitation in South Africa using the NCEP2 Reanalysis to identify these systems lower in the troposphere, at the 500-hPa level, for the following reasons: CoLs at 200 hPa do not always correspond to CoLs at 500 hPa level (e.g. Zhao and Sun 2007; Reboita et al. (2010) because they are sometimes associated with anticyclonic circulation in the lower troposphere; CoLs at 500 hPa often develop into the lower troposphere (e.g.

¹ <http://www.cdc.noaa.gov>; <http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm>.

Hoskins et al. 1985; McInnes et al. 1992; Katzfey and McInnes 1996), a situation more favorable for widespread precipitation.

Following Hu et al. (2010) we have used geopotential height and temperature at 500 hPa (Z500 and T500) (spatial resolution of $2.5^\circ \times 2.5^\circ$) data but instead of a 6 hourly time step, CoLs are defined in the time mean daily fields. Because they are slow moving and possibly intrude into the low latitudes, the “foot print” of CoLs in mean daily fields presents a more suitable structure, their features are less noisy along their life-time in comparison with a 6 hourly time step and for a 2.5 grid-resolution. This facilitates their detection and consequently the construction of their trajectories especially in lower latitudes where the space resolution is coarse compared to with higher latitudes (see supplementary material, part B). Furthermore, daily mean information of CoL features facilitates comparisons with other mean daily datasets, e.g. the outgoing longwave radiation data (OLR, Liebmann and Smith 1996,² space resolution: $2.5^\circ \text{lon} \times 2.5^\circ \text{lat}$).

To verify that the algorithm reasonably captures the CoLs, verifications have been realized computing different regional composites of the OLR and T500. The composites give an estimate of the coherence of the CoLs’ mean structure in terms of cloud pattern and horizontal thermal gradients, as well as the mean circulation associated at hemispheric scale. Note that these composites are built from daily anomalies (the seasonal cycle was removed from the daily data) instead of daily means (as in Ndarana and Waugh 2010), which allows the comparison of CoL structures to be independent of the season.

2.3 Automated scheme

Sophisticated algorithms have been developed and applied to track low pressure systems at different altitudes in the SH (e.g. Simmonds et al. 1999; Hoskins and Hodges 2005). Our scheme is built around a simple tracking algorithm presented and used in Favre and Gershunov (2006) and (2009) but adjusted to the conceptual description of CoLs structure in Z500 fields as presented in Sect. 2.1. The methodology follows six consecutive steps.

1. Firstly, the local minima positions are determined computing the local partial derivatives in the mean daily Z500 fields (step 1). The coordinates of points presenting a change in the derivative signs (\mp North–South and East–West directions) are retained.
2. With the double objective of eliminating local minima associated with small variations of pressure in space and to capture the tear-off stage (i.e. closed lows not strongly marked because of embedding in a lower

Z500 area), all local minima (and only local minima) are compared and those presenting the lowest height in a radius of 1,000 km are retained (step 2).

3. The third step is to localize the daily position of the polar jet stream to remove the local minima associated with polar lows. In the Z500 daily fields, the strongest meridional gradient is associated with the polar jet stream (the sub-tropical jet is usually more marked at the 200 hPa level and is not presently considered). Using a sliding centered window of 22.5° and beginning from the South Pole, for each longitude, the latitude of the strongest mean gradient in the geopotential is localized. All local minima situated on the polar side of the jet stream are eliminated (step 3).
4. The fourth step is the establishment of closed low trajectories using a tracking algorithm. This tool was initially developed to track extra-tropical low and high pressure systems in mean daily sea level pressure fields. It includes multi-criteria permitting the local minima connection from one time to the next one. All the criteria (e.g. the velocity, time variation of the central pressure, preferential directions for the propagation, convergence or split) can be used. For this study we have imposed one major threshold. Local minima are connected each day considering their proximity: within a radius less than or equal to 1,000 km (the mean daily velocity should be less than ~ 42 km/h) the connection is realized with the closest local minima the day after. On the other hand, lows can not split but are permitted to merge even if no merging has been detected for the CoLs. They are able to propagate in all directions and no threshold for the variation of the central pressure has been imposed.

At this stage, the trajectories of closed lows are established between the equator and the jet stream. To guarantee their extra-tropical origin, all systems generated further south than 20°S are retained. For each trajectory, the daily position (longitude and latitude) and central Z500 are recorded for the period 1979–2008. From this database, all the closed lows that have reached the cut-off stage during at least one day are extracted. The CoL stage is identified, as follows.

5. At the mature stage of development, a CoL represents a mid-tropospheric lows detached from a trough. Each day of each trajectory is analyzed and when the center of a closed low corresponds to the absolute lowest height in a radius of 1,200 km, the mature stage of CoL is considered probable and the trajectory is validated (step 5).
6. To guarantee the exclusive restriction of lows representing a cold core and showing an equivalent barotropic structure, mean daily T500 data is used.

² http://www.esrl.noaa.gov/psd/data/gridded/data.interp_OLR.html.

To define cold cores, all local minima of air temperature presenting the absolute lowest temperature in a radius of 600 km are recorded. In T500 fields, the structure of closed lows is not as marked as in Z500. This criterion (radius = 600 km) also permits the consideration of simultaneous small cores. Finally, all trajectories presenting a closed low associated with a cold core within 600 km of the center during the same day as step 5 are retained. These 2 last steps guarantee that the low is clearly marked (step 5) with a cold core (step 6).

According to the definition and to summarize the method, CoLs are mid-tropospheric closed lows (steps 1 and 2) travelling on the equator side of the jet stream (steps 3 and 4), clearly detached from the main flow, with a cold core and showing an horizontal equivalent barotropic structure at the mature stage (steps 5 and 6). All trajectories are recorded over the period and no restriction a posteriori is imposed for the systems: lifetime, intensity (central height/depth) and geographical domain of occurrence. Consequently, non persistent and weak CoLs are included in all latitudinal bands, within the limit of the criteria used in the automated scheme and the space–time resolution of the data. All systems that have not reached the stage of maturity (i.e. Tear-off having not developed to CoL) are not considered in this work. This choice can be problematic because both Tear-off and Cut-off Lows present similar features (extra-tropical cold lows) and are potentially associated with heavy precipitation (e.g. Delgado et al. 2007). Nevertheless, contrary to CoLs, the Tear-off Lows' structure is baroclinic. In order to be able to compare our results with previous studies, we decided to conserve a relative strict definition of CoL as presented above. Please note that this method optimizes the capture of CoLs at 500 hPa mainly because of the “cold core” criterion as presented in step 6. For example, at 200 hPa, the CoLs' structure in temperature fields does not systematically show a local minimum (see supplementary material, part C).

3 Verifications: statistics, geographical distribution and OLR pattern

3.1 General statistics and geographical distribution

For the period 1979–2008, the total number of CoL trajectories in the SH is 4,843 (around 161 systems per year, Fig. 1). Their lifetime, from generation to decay of the closed low, is about 4 days (Fig. 2a) and around 10% of cases last more than 7 days. They cover a total distance of 1,376 km in average (Fig. 2b), with a mean velocity of 12.6 km/h (Fig. 2c). They have a slow displacement as

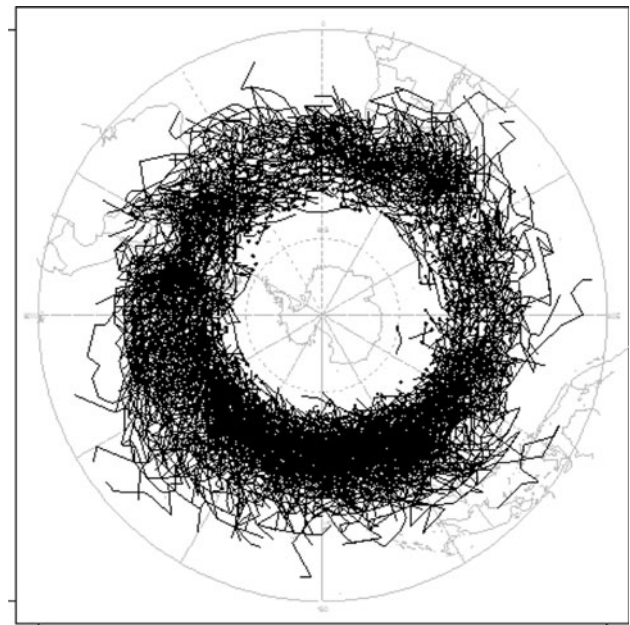


Fig. 1 4,843 CoL trajectories from 1979 to 2008 (black points = generation)

well as a short covered distance in comparison with other extra-tropical lows, and are consequently quasi-stationary. They tend to generate and decay in the same region (distance between generation and decay = ~ 925 km in average, not shown). More precisely, the stage of cut-off lasts about 2 days and 10% of cases exceed 4 days (Fig. 2d). In comparison with all southern extra-tropical cyclones detected at the 500 hPa level (Simmonds and Keay 2000), the lows that reach the stage of cut-off have on average a longer total lifetime (~ 4 days against ~ 3 days), they cover a shorter distance ($\sim 1,376$ km against more than 2,000 km) and present a weaker velocity. These differences are mainly due to the geographical domain of occurrence: CoLs form and displaced mainly in sub-tropical latitudes, out-side the main westerly flow. The central height during the cut-off stage is about 5,631 gpm (Fig. 2e) and 10% are detected at altitudes lower than 5,410 gpm.

Note that the space–time resolution of the data and the methodology influence the statistics. For example, the choice of daily mean data tends to increase the stationary character of CoLs, thereby presenting less erratic displacements in comparison with a 6-hourly time step. Secondly, in daily mean Z500 fields, low pressure systems following a fast and non erratic displacement present an over-estimation of the central height in comparison with an instantaneous snapshot and the statistics in Fig. 2e may be affected. Finally, the criterion of velocity used in the automated scheme (step 4, Sect. 2.3) may affect the number of generation, the total distance covered and the total duration of CoLs, prematurely interrupting some

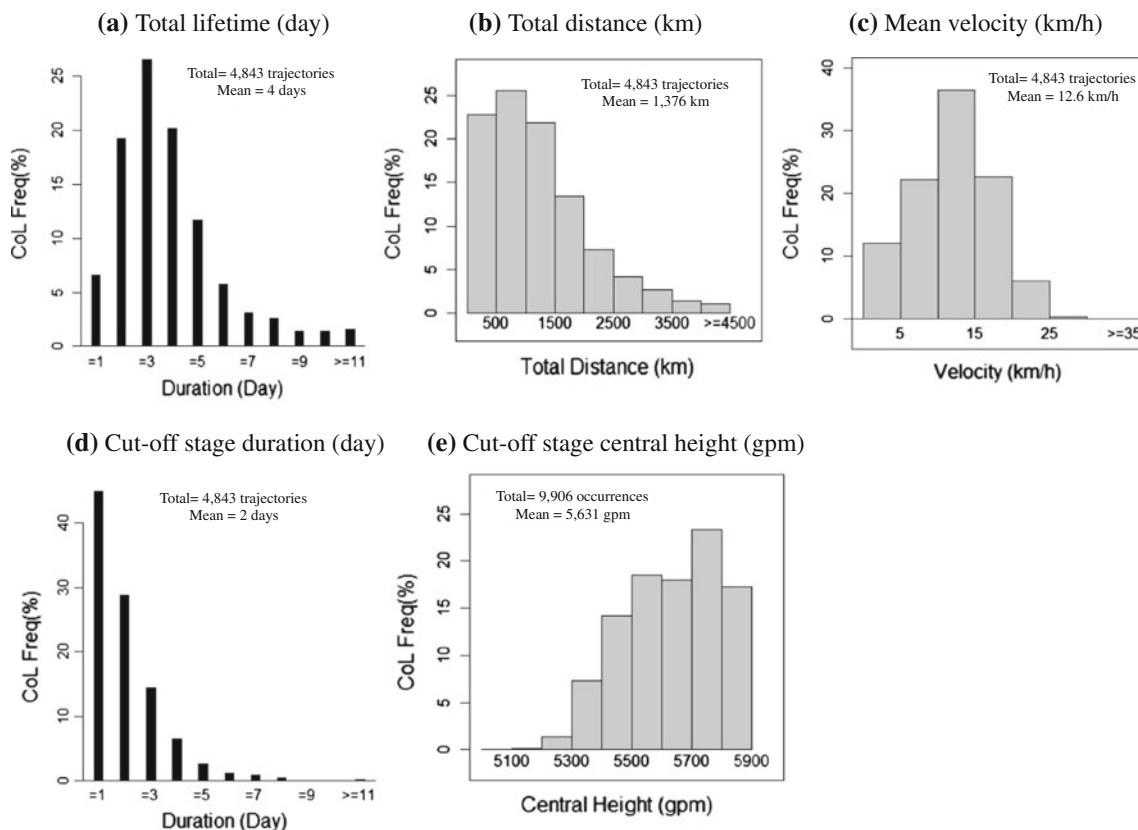


Fig. 2 Statistics on 4,843 CoL trajectories from the generation of the closed low (tear-off stage) to the decay and for the entire Southern Hemisphere: **a** total lifetime, **b** total covered distance, **c** mean velocity, **d** Cut-off stage duration, **e** central height during the cut-off stage

trajectories at the stage when the low system merges with the westerlies (before the demise) for example. However, in this case, the lows do not exhibit cut-off characteristics and are removed from the following analysis. If during the stage of cut-off stage, the low's displacement exceeds the threshold of velocity (which is unlikely), the trajectory is cut and a new generation is recorded. Consequently, the threshold of velocity may also directly affect the total number of systems (this last point is discussed in Sect. 5.1).

Nevertheless, these statistics are generally consistent with previous studies and more specifically with Reboita et al. 2010. Over the period 1979–1999 and at 500 hPa (NCEP1), they found an average of 141 CoLs per year against 154 per year in our study, for the same period. Note that the total number of local minima at 500 hPa (step 1 of the method in Sect. 2.3) derived from NCEP1 is about 4% underestimated in comparison with the NCEP2 Reanalysis data (not shown).

Regarding the geographical distribution (Fig. 3), CoLs are more frequent in the zonal belt between 20°S and 45°S and on the margins of the continents and this is consistent with previous studies. CoLs are generally more numerous over the Southern Pacific and cover a larger latitudinal band between approximately 20°S and 50°S, while over the

Atlantic and Indian Ocean domains CoLs concern mainly the 20°S–40°S band. Nevertheless there are some noteworthy differences with F2005. Firstly, we found a maximum of density at 32.5°S (median) against 38°S in F2005. This difference can be due to the fact that in NCEP2, the jet-stream and mid-latitude circulation, is in general slightly displaced equatorward³ compared to NCEP1. Secondly, using the same regional sub-division as in F2005 we found the most active area (in term of number of generations) is located over the Australia/New Zealand sector (80°E–140°W/10°S–60°S, in F2005) which accounts of approximately 49% of the total CoL generation (against 48% in F2005); the American sector (140°W–0°/10°S–60°S) contributes to 35% (against 42%); finally, the African sector (0°–80°E/10°S–60°S) is the least active region and counts for around 16% (against 10%) of the total CoL generation. We have detected more cases in the African sector especially over the South of the Mozambique Channel (F2005 study does not present CoL in this area) and this could explain the difference in this last sector. Keable et al. (2002), in their climatology of 500 hPa

³ <http://www.cpc.ncep.noaa.gov/products/wesley/reanalysis2/kana/reanl2-1.htm>.

cyclones in the SH, have also shown a regional maximum density in the Southern Mozambique Channel in all seasons.

3.2 Regional OLR patterns

Previous studies have shown that CoLs present convective clouds along their east flank drawing a comma pattern (e.g. Caruso and Businger 2006). This characteristic is verified by a targeted analysis of OLR daily anomalies. We have selected eight regional maxima of the CoLs' frequency through the hemisphere (see Fig. 3). Figure 4 presents the composites of OLR daily anomalies associated with the occurrence of CoLs for eight grid-points. The composites are not all built with the same number of CoL days (e.g. West America = 37 days (Fig. 4a), East America = 12 days (Fig. 4b). This difference affects partially the magnitude of the anomalies and the structure. Consequently, the patterns are not exactly similar for each location (e.g. Fig. 4b, c) but generally confirm the presence of negative OLR anomalies eastward of the mean position of CoLs. In addition, it can be mentioned that a band of positive OLR anomaly stretches to the south of CoL centers and is well defined for the eight composites. The composites over Eastern America (Fig. 4b) and the West Pacific (Fig. 4h) properly represent the typical dry and wet structure of extra-tropical cyclones.

4 Circulation patterns and the link with SAO

SAO quantifies the strength of the mid- and low tropospheric meridional gradient of pressure and/or temperature between the mid- and high latitudes ($\sim 50^{\circ}\text{S}$ – $\sim 65^{\circ}\text{S}$) at hemispheric scale (e.g. Van Loon 1967, Simmonds and

Jones 1998). In these latitudes, the long-term annual cycle of the gradient strength exhibits a half-yearly cycle with two peaks during transitional seasons and a weakening in winter and summer. In autumn and spring, the polar vortex is contracted and intensified, a situation linked with increasing warm air transport from the tropics towards extra-tropical latitudes, while in winter (summer) there is an expansion and a general strengthening (weakening) of the polar vortex. This feature, peculiar to the SH, is explained by the time lag of temperature seasonal cycles in response to heat storage in mid-latitude oceans and in Antarctica. Over the three oceans, the pressure and temperature gradients vary regionally on seasonal, inter-annual and decadal time scales (e.g. Van Loon and Rogers 1984; Hurrell and Van Loon 1994; Burnett and McNicoll 2000; Simmonds 2003) thereby modulating the space time variation of the SAO.

4.1 Links with the meridional gradients of pressure and temperature at daily time scale

On Fig. 5 two synthetic composites of the Z500 (Fig. 5a, since the structure in Z500 is similar to T500 was not include here) and SLP daily anomalies (Fig. 5b) associated with CoLs are presented. These figures are built as follows. Firstly, for each longitude (144 longitudes), all CoL days are retained and a composite is computed. Next, the 144 composites are averaged and centered on the longitude 0. Thus, on both figures, the x axis is expressed in relative longitudes while the y axis represents the statistical latitude (the mean latitude). Note that, this approach is the first step which will permit to show the relationship between CoLs and the SAO and the following description focuses mainly on horizontal pressure and thermal gradients.

In general, the CoLs' mean position corresponds to a secluded colder and a lower pressure area (Fig. 5a). The

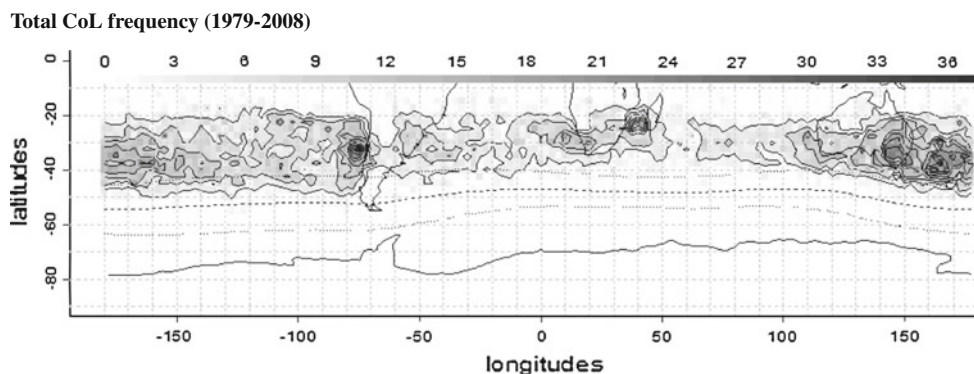


Fig. 3 Total CoL frequency (the frequency of cut-off stage is expressed in number of days per grid point) over the period 1979–2008 (resolution = $2.5^{\circ}\text{lon} \cdot 2.5^{\circ}\text{lat}$). *Shadings* represent the total frequency and *contours* (interval = 3) represent the frequency after smoothing (running median = 5°). For the period 1979–2008 the total frequency of CoLs is 9,906 (while the total number of

generations or the total number of trajectories is 4,843). *Black dashed line* and *dotted lines* represent the mean position of the maximum gradient in Z500 (see step 2 in Sect. 2.3, hemispheric mean = 50.2°S) and the standard deviation (hemispheric standard deviation = 8°), respectively

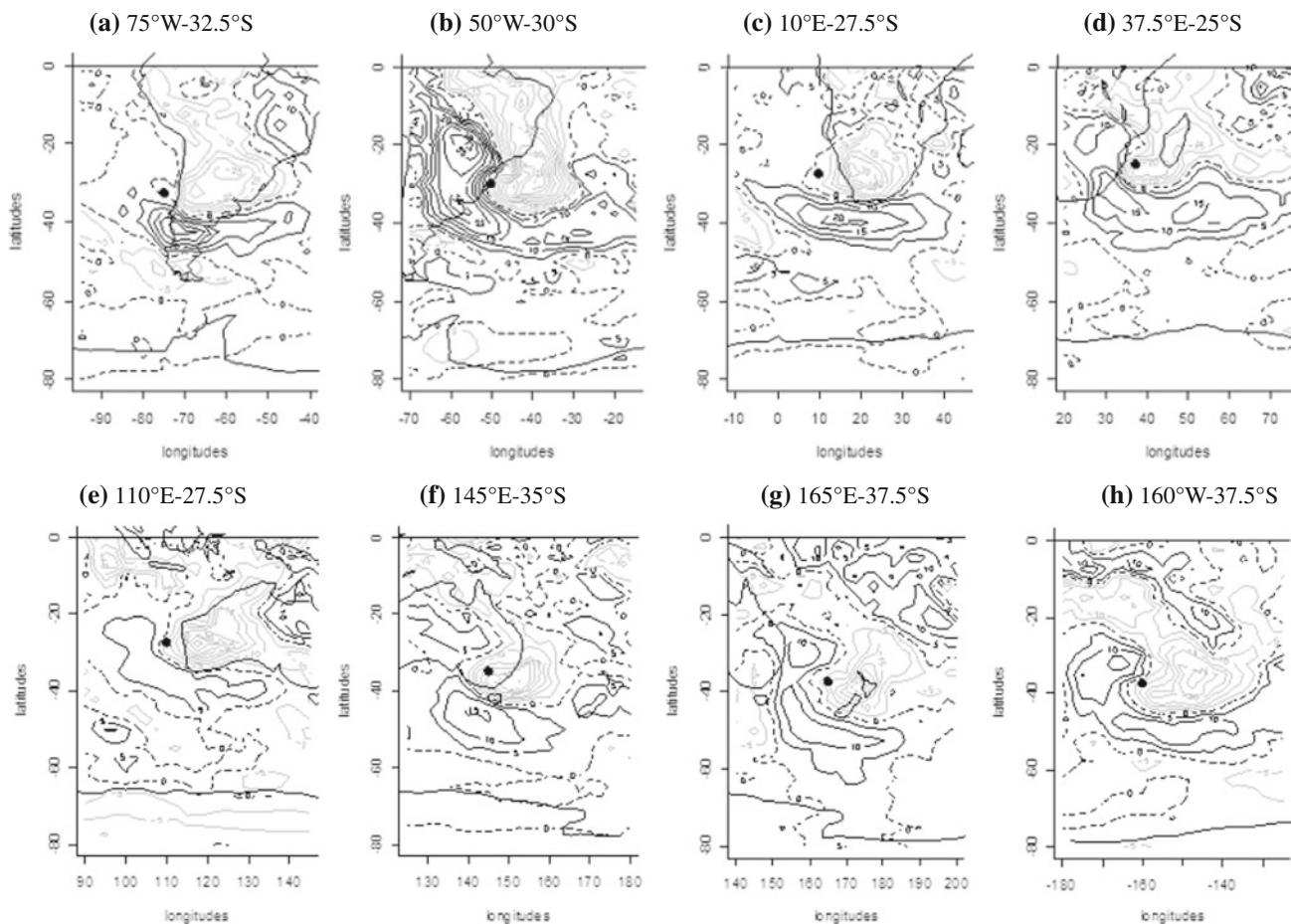


Fig. 4 Composites of OLR daily anomalies (interval contour = 5 W/m², black/grey = positive/negative anomalies) computed from CoL days for 8 grid-points (black point): **a** Western America (75°W–32.5°S = 37 days), **b** Eastern America (50°W–30°S = 12 days),

c Western Africa (10°E–27.5°S = 28 days), **d** Eastern Africa (37.5°E–25°S = 25 days), **e** Western Australia (110°E–27.5°S = 20), **f** Eastern Australia (145°E–35°S = 25 days), **g** Tasman Sea (165°E–37.5°S = 18), **h** West Pacific (160°W–37.5°S = 20)

section south of the “cold pool” is surrounded by warmer temperatures. These warmer temperatures are associated with a cut-off high located in mid-latitudes. Over all sectors, this strong Z500 positive anomaly area is centered around 50°S and corresponds to a similar structure of the mean sea level pressure (Fig. 5b) and T500 (not shown). These observations confirm the typical synoptic scheme of the CoL/cut-off high blocking structure in the SH, presented by Coughlan (1983), Holland et al. (1987) and Katzfey and McInnes (1996). On each side of the cut-off, two large troughs are clearly distinct from each composite. At hemispheric scale, the zonal pattern in mid-latitudes associated with the CoLs occurrence describes mainly a zonal wave 3 [excepted for CoLs in the Tasman Sea, not shown (see supplementary material, part D)]. Trenberth and Mo (1985) have shown that the local wave 3 plays a significant role in the occurrence of blocking events in the SH.

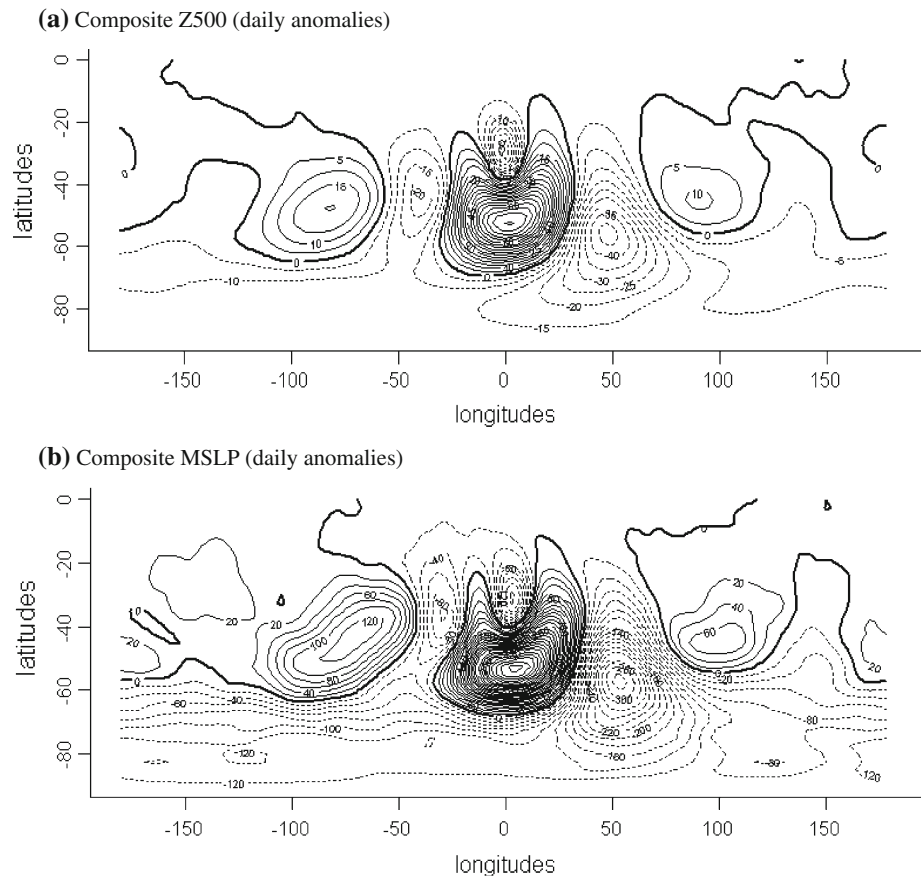
Along the longitude of the cut-off, the north–south gradient of temperature/pressure is reduced from the

tropics to about 50°S and reinforced between ~50°S and the South Pole. This configuration signifies that between ~30°S and ~50°S the westerly flow is reduced and the sub-tropical jet is weakened, while the gradient is reinforced between ~50°S and ~70°S, corresponding to a poleward displacement and strengthening of the polar jet-stream, which in the SH, is located on average at ~50°S.

4.2 Translation of the domain of occurrence at seasonal time-scale

Figure 6a shows the total number of CoL generations per month. CoLs form more frequently from the late summer until autumn (from February to May) with a maximum in March–April. A secondary peak is identified on September–October (spring). The mean total duration of trajectories (Fig. 6b) does not vary strongly, however, CoLs have a slightly longer lifetime from November to February (late spring and summer). As a result, the total frequency

Fig. 5 Composite of **a** Z500 daily anomalies (interval contour = 5 gpm) and **b** MSLP (interval contour = 20 Pascals) associated with CoLs (9,906 occurrences). The x axis is expressed in relative longitude and the y axis in mean latitude



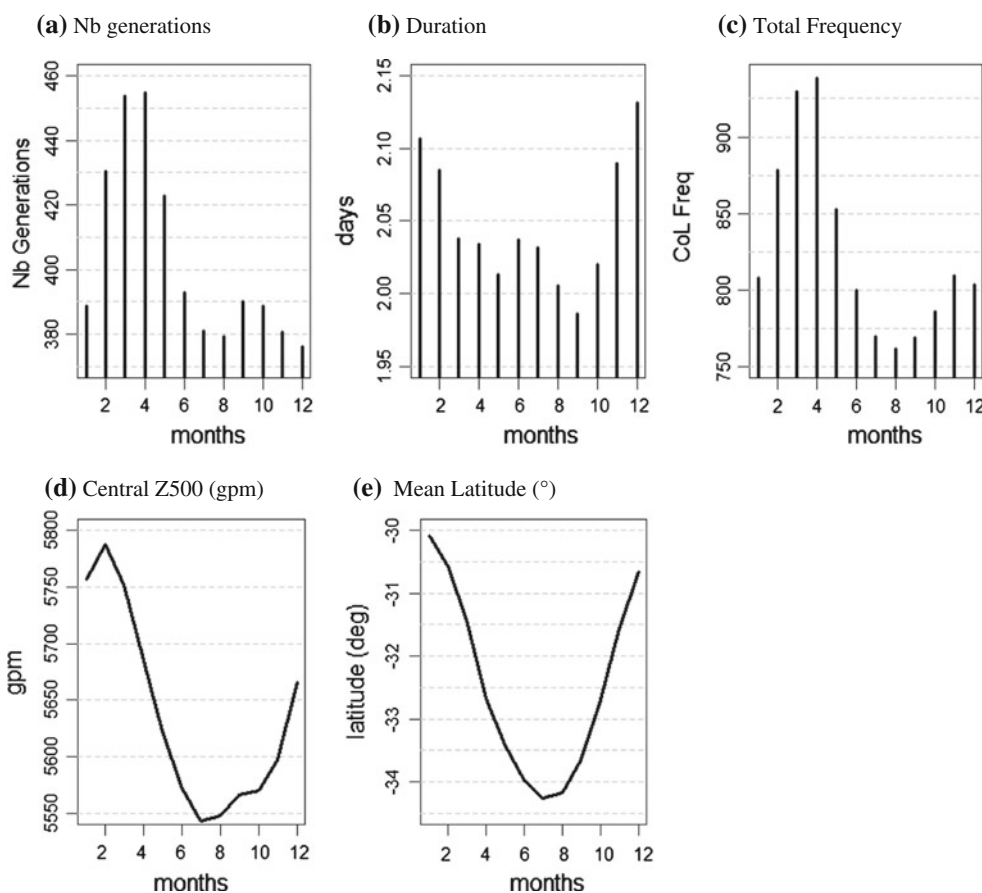
(Fig. 6c, total number of occurrence per grid-point) presents the same annual cycle as the number of generation but the secondary peak in spring is less marked because attenuated by the longer life time of the systems in summer which compensates the deficit of the number of generation. In winter, CoLs are generally less numerous but develop more often in lower altitudes (Fig. 6d) and reach the surface more frequently [not shown, (see supplementary material, part E)]. This result is in agreement with Reboita et al. (2010) and confirms that CoLs are more frequently detected in the upper troposphere during summer and in the lower troposphere during winter.

The mean latitudinal domain of circulation displaces equatorward from winter to summer (Fig. 6e). The meridional distribution confirms the apparent seasonal displacement of CoLs' domain of occurrence and shows that they are more frequent in lower (higher) latitudes during summer (winter, Fig. 7a). This result is in accordance with Keable et al. (2002) study which shows that southern 500 hPa closed lows are more numerous in summer than in winter in lower latitudes. However, the apparent southward displacement of the CoLs' domain in winter seems to be only induced by a depletion of the CoLs' occurrence to the North of 40°S–37.5°S. This depletion can be related to the winter reinforcement of the

sub-tropical jet. Consequently, the meridional displacement is mainly northward from spring to summer and southward from summer to autumn.

In the median latitudinal band ($\sim 32.5^\circ\text{S}$, Fig. 7a), the CoLs' frequency exhibits a half-yearly cycle with two peaks during the transitional seasons. This half-yearly cycle seems to coincide with the SAO. Singleton and Reason (2007) showed the statistical relationship between the CoLs' frequency over the Southern Africa and the SAO. At hemispheric scale, the seasonal variation of the CoLs' frequency appears to be related to the polar vortex features. On Fig. 4, we showed that on average, CoLs are associated with cut-off highs centered $\sim 50^\circ\text{S}$, a situation linked with a stronger meridional gradient between mid- and high latitudes. Thus, the statistical link between CoLs' frequency and SAO may be dynamically accomplished via cut-off highs which regionally reinforce the pressure and temperature gradient between $\sim 50^\circ\text{S}$ and polar latitudes. This hypothesis is verified on Fig. 8. A composite of Z500 has been constructed from all CoL days centered on 32.5°S , this latitude representing the median zone of occurrence. The CoLs' frequency along 32.5°S is associated with higher Z500 in mid-latitudes (along $\sim 47.5^\circ/50^\circ\text{S}$) and with lower Z500 in high latitudes (to the South of $\sim 60^\circ\text{S}$) meaning a reinforcement of the meridional

Fig. 6 **a** Total number of CoL generations per month, **b** mean duration of the cut-off stage, **c** CoL frequency (number of occurrence per grid-point), **d** mean central Z500 and **e** mean latitudinal position. (For all figures: smoothing = 3 months running mean)



gradient between mid and high latitudes. Consequently, the positive statistical relationship between SAO and the frequency of CoLs is confirmed on seasonal time scale.

The seasonal displacement of the CoLs' latitudinal domain interacts regionally with the continental features and with semi permanent sub-tropical highs. Figure 7b summarizes the zonal distribution of CoLs for each season. Generally, they are less (more) numerous during summer on the east (west) side of the ocean and the opposite happens in the winter. This geographic difference may be caused by the seasonal variation of the sub-tropical subsidence position. During summer, sub-tropical ridges are on average centered over the eastern part of the oceans, a situation less favorable for low pressure systems along the western coast of the continents. Inversely, in winter, the sub-tropical highs become displaced westward, into the center of the oceans, a situation more favorable for the occurrence of low pressure system along the western coast of the continents. Moreover, during the seasonal translation of the latitudinal domain, CoLs' interact regionally with different characteristics of the topography. The axis and the altitude of the mountains impose conditions associated with more or less cyclolysis, thereby affecting the duration of the lows and consequently the regional CoLs' frequency. For example, in the Tasman Sea sector, the Alps of New

Zealand (stretching between $\sim 35^{\circ}\text{S}$ and $\sim 45^{\circ}\text{S}$) hinder the eastward progression of lows in winter, but less so in summer because CoLs are more often located to the north of New Zealand and are more able to propagate eastward as F2005 has shown. It is also possible that topography blocks CoLs more frequently in winter because they are often developed in lower altitudes during this season. Garreaud and Fuenzalida (2007) have investigated the role of the Andes cordillera on an upper level CoL behavior located off the Pacific coast. They showed that the cordillera, situated downstream of the studied system, does not influence the generation and deepening of the low but delays the cyclolysis, hindering the inflow of warm and moister air coming from the north-east and consequently delaying the demise due to the diabatic heating. This situation may be more common during winter thereby increasing CoLs frequency along the west coasts.

In previous regional studies, the seasonal distribution of the CoLs number (number of generation and/or path), presents a maximum in autumn, a minimum in summer and a shallow secondary peak in spring in the American sector (100°W – $20^{\circ}\text{W}/15^{\circ}\text{S}$ – 50°S , Campetella and Possia 2006) and the African sector (20°E – $40^{\circ}\text{E}/20^{\circ}\text{S}$ – 40°S , Taljaard 1985; Singleton and Reason 2007). In these same sectors we found the same seasonal cycle in the number of CoLs.

Fig. 7 **a** Meridional and **b** zonal distribution of the total CoL frequency for each season (*black*: winter JJA; *black-dashed*: spring SON; *grey*: summer DJF; *grey-dashed*: autumn MAM). For the both figures smoothing = running mean, centered window = 12.5°)

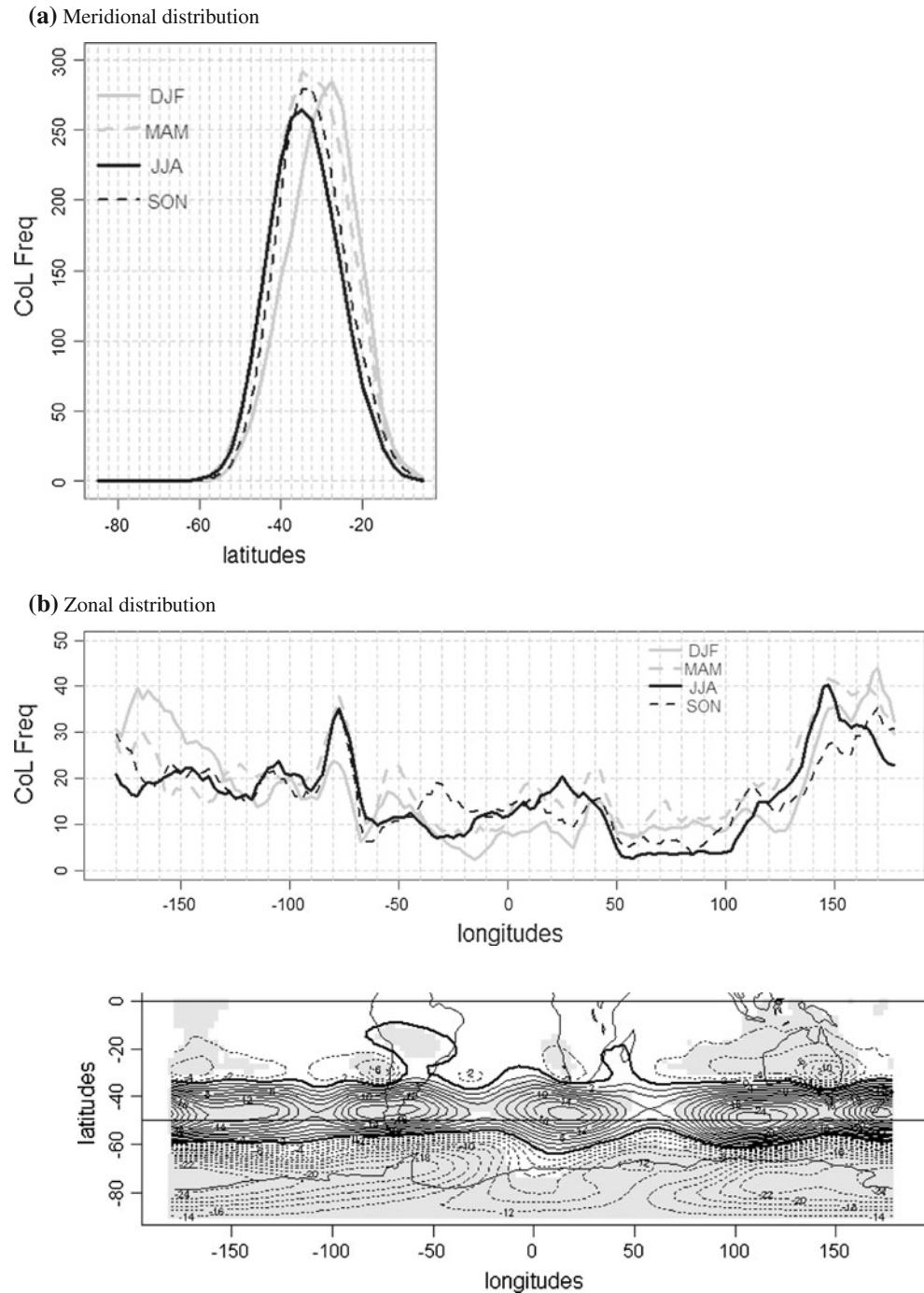
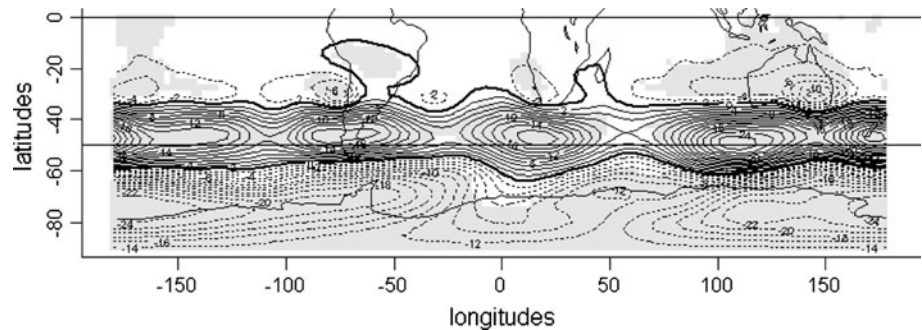


Fig. 8 Composite of Z500 daily anomalies (interval contour = 2 gpm) computed from CoL occurrences centered on 32.5°S (1,065 days). *Shadings*: sig. >99%; two tailed bootstrap test (length of sample = 1,065; number of samples = 100). The *horizontal black line* represents the 50°S latitude



Over the eastern Australia and the Tasman Sea (140°E–170°E/20°S–50°S), Katzfey and McInnes (1996) studied deep CoLs extending down to sea level and they found a half-yearly cycle with two maxima during transitional seasons and fewer CoLs during summer. We find the same cycle but with a weak secondary peak in October–November. Both regional and hemispheric distribution of the CoLs' frequency seems to be linked with SAO and more specifically with the strength of temperature and pressure meridional gradients between mid and high latitudes.

5 Interannual variations in the frequency of CoLs

5.1 Trends over the period 1979–2008

During the period 1979–2008, CoLs become more frequent at the hemispheric scale (Fig. 9a). The linear regression is highly significant and presents an increase of 27 CoLs per decade. The lowest annual number of recorded CoLs is in 1980 with 255 whereas 2001 is the most active year recording 438 CoLs. Three major peaks in the frequency

occur during 1995, 2001 and 2006, and three low points during 1980, 1981 and 1990. The linear regressions are significantly positive for each season excepted for spring (not shown). The differences in the magnitude of seasonal trends tend to modify the annual cycle of the CoLs' frequency (Fig. 9d and see Fig. 6c) over the studied period, thereby growing the major peak in autumn and reducing the secondary peak in spring.

CoLs have generally become more numerous throughout all the latitudinal bands (from 12.5°S to 65°S, Fig. 10a) but the linear trend is only significant in the 25°S–37.5°S and 55°S–60°S zones, signifying that the latitudinal domain has enlarged. The zonal distribution (Fig. 10b) shows that CoLs are significantly more numerous from the middle of the South Pacific to the Andes Cordillera, over South Atlantic and over the Indian Ocean. Nevertheless, in the Australian-New Zealand sector, the CoLs' frequency diminishes one side to the other of the Tasman Sea, with a weak but significant negative trend over New-Zealand. F2005 have also found that CoL frequency increases significantly in the American sector along the period 1969–1999 as well as in the African sector (but the trend is not significant for this period) but decreases over the Australian sector. It may be noted that CoL frequency increases in the middle of oceans and off the west coasts of the three continents but they show no trend or a slightly decreasing trend on the east-side of continents.

The inter-annual variation of CoLs frequency is largely determined by the number of generation of systems ($r = 0.8$, sig. > 99%, Fig. 9b; Table 1) and to a lesser extent by the duration ($r = 0.4$, sig. > 90%, Fig. 9c; Table 1). Although, the number of CoL generations shows a positive trend between 1979 and 2008, but also exhibits a significant positive shift between 1998 and 1999. From 1980 to 1998, the number of generations is lower than the long term annual mean but then abruptly, from 1999, it increases substantially. Considering separately the periods 1979–1998 and 1999–2008, the linear trends are not significant, consequently the increase in the number of generations mainly comes about as a result of the positive shift between 1998 and 1999. This shift is confirmed in Fig. 10c which shows that the positive trend in the number of generations is significant over the period 1979–2008 and for the larger part of the latitudinal bands but is not significant during the period 1979–1998.

On the other hand, the duration of the systems also shows a positive trend, although this is non-significant. In particular, CoLs show a longer life time during the period 1991–1996. Thus, this combination of changes of the number of generation and the duration of the systems leads to an overall significant trend of the CoLs' frequency for the entire period:

1. from 1980 to 1990, fewer CoLs are generated and their lifetime is shorter;
2. from 1991 to 1997, fewer CoLs are generated but their lifetime is longer;
3. from 1999, their lifetime is shorter but the number of formation is significantly higher.

(These previous results have been tested to verify if the threshold of velocity imposed by the method (see Sect. 2.3, step 4) does not introduce a significant bias in the inter-annual variability of the number of generations and the lifetime of the systems (see supplementary material, part F).

The period 1997 to 2001 is known for a phase shift of El Niño Southern Oscillation (ENSO), from a strong El Niño (1997–1998) to a strong and long La Niña event (1998–1999 to 2000–2001) and is associated with less and more frequent CoLs, respectively. The following section examines the link between ENSO and Southern CoL's frequency.

5.2 Relationships with ENSO

Previous studies investigated the potential link between ENSO and regional CoLs' frequency. Over the period 1969–1999, F2005 did not find a link with ENSO for the American (140°W–0°/10°S–60°S), Australian-New-Zealand (80°E–140°W/10°S–60°S) and African sectors (0°–80°E/10°S–60°S). Nevertheless, over the period 1979–2002 for Southern Africa (10°E–40°E/20°S–40°S), Singleton and Reason (2007) showed a weak but significant statistical relationship; during La Niña events CoLs are found to be more frequent (although during El Niño events they are not systematically less numerous). Here we have also investigated the link between ENSO and the inter-annual variation of CoL's frequency over the SH.

At the hemispheric scale, CoLs are more frequent than the long term average during La Niña events but not notably less frequent during El Niño events. For the five strongest La Niña years (from July to June: 1988/1989; 1998/1999; 1999/2000; 2000/2001; 2007/2008), the annual frequency is approximately 350 (174 generations) while for El Niño years (from July to June 1982/1983; 1986/1987; 1991/1992; 1994/1995; 1997/1998) the frequency is approximately 331 (156 generations). Figure 11a presents the meridional distribution of CoLs frequency during La Niña, El Niño and neutral years and Fig. 11b represents the composite of La Niña versus neutral and La Niña versus El Niño of the CoLs' frequency. The difference between the cold and warm events is significant in the 20°S–30°S zone and the 42.5°S–50°S zone and shows that during La Niña, the CoLs' frequency is higher in the lower latitudes and lower in the higher latitude band than during El Niño. This means that the CoL's domain displaces equatorward during

Fig. 9 **a** CoL total frequency, **b** number of generations, **c** mean duration per year from 1979 to 2008. The significance of the linear trends is estimated computing the Pearson correlation coefficient between the original time series and the linear regressions (same for Fig. 10). “sd” means standard deviation. **d** Monthly distribution of the CoL frequency per decade: the *black line* represents the period 1979–1988, the *grey line* the period 1989–1998 and the *dashed black line* the period 1999–2008 (smoothing = 3 months running mean)

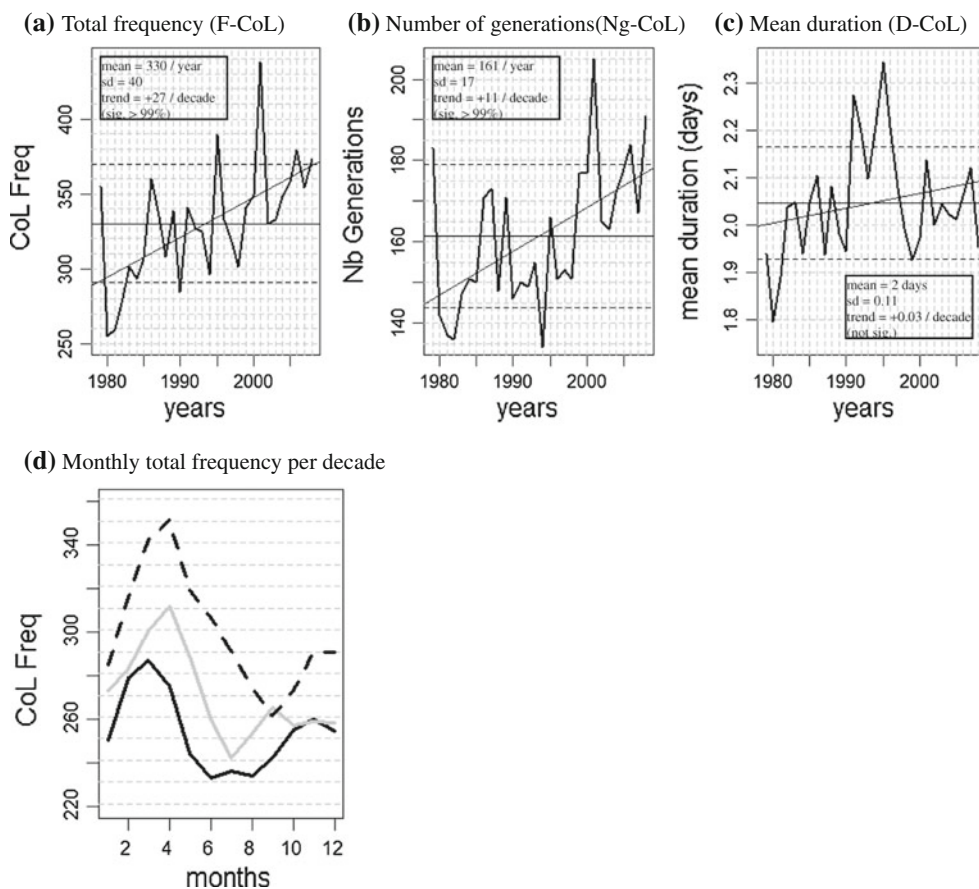


Fig. 10 Linear regression coefficients per decade of CoL frequency for each latitude (**a**), and **b** for each longitude over the period 1979–2008. **c** Linear regression coefficients per decade of CoLs’ number of generations for each latitude over the period 1979–2008 (*black line*) and over the period 1979–1998 (*grey line*). For all figures, *grey/black points* = sig. >90%/>95%

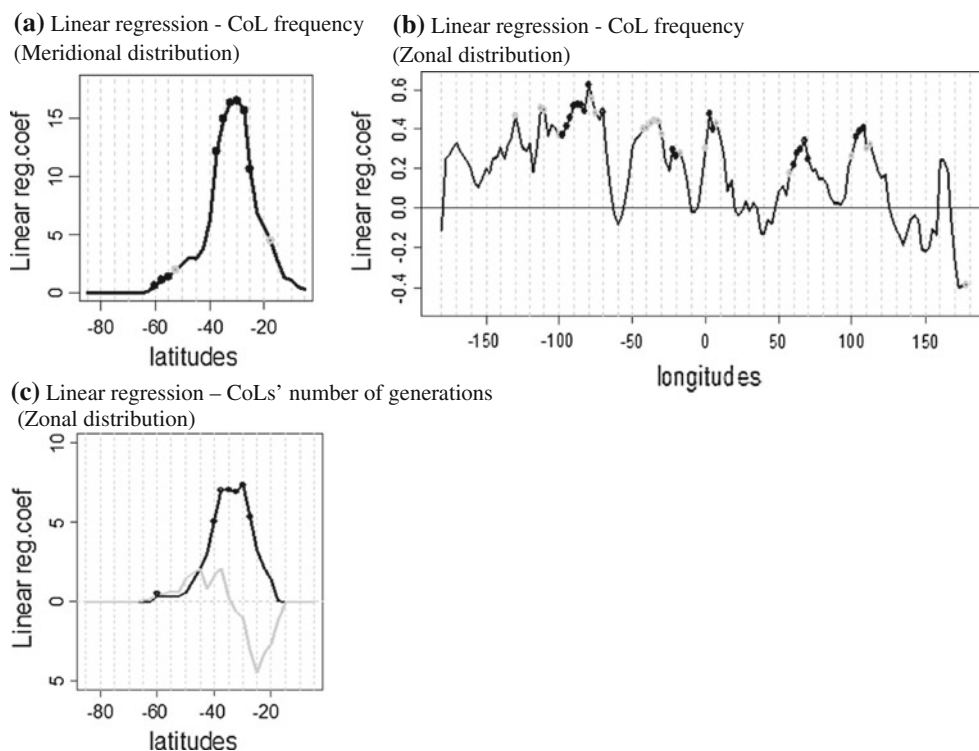


Table 1 Linear temporal correlation coefficients between the total frequency (F-CoL), the number of generation (Ng-CoL) and the mean duration (D-CoL) of CoLs, for the period 1979–2008

	F-CoL	Ng-CoL	D-CoL
F-CoL	1		
Ng-CoL	0.88 (0.83)	1	
D-CoL	<u>0.41 (0.35)</u>	-0.06 (-0.23)	1

Underlined/bold values are significant at the 90%/99% level and italic coefficients are computed from detrended times series

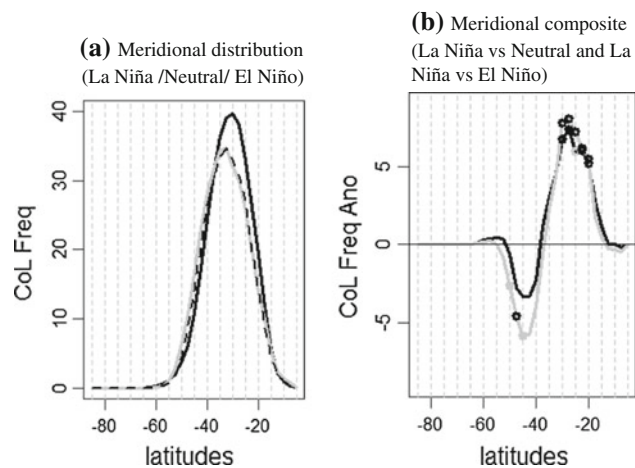


Fig. 11 The CoLs' frequency composites La Niña, El Niño and Neutral are built from the five strongest La Niña, the five strongest El Niño and the five neutral events during the period 1979–2008. The mature stage of La Niña/El Niño events is usually attempted during December and January, consequently, the year is centered on December–January (La Niña events, from July to June: 1988/1989; 1998/1999; 1999/2000; 2000/2001; 2007/2008. El Niño events, from July to June: 1982/1983; 1986/1987; 1991/1992; 1994/1995; 1997/1998. Neutral events, from July to June: 1979/1980; 1980/1981; 1983/1984; 1989/1990; 2005/2006). **a** Mean annual CoL frequency during La Niña (black line), El Niño (grey line) and Neutral (dashed line) events. **b** La Niña versus Neutral events (black line) and La Niña versus El Niño (grey line), Grey/Black points = sig. >90%/95% (two tailed Student's *t* test)

La Niña and poleward during El Niño events. On Figs. 12 and 13, we can see that this feature most evident in the Southern Pacific, which records a larger proportion of the total CoL frequency and where the latitudinal domain of occurrence is large. Focusing on the Southern Pacific, the apparent displacement could be caused by the generally lower Z500 level in the inter-tropical zone during La Niña while it is generally higher here during El Niño. Warmer conditions in the tropical zone increases the meridional gradient of pressure between low and mid-latitudes and potentially reinforces the sub-tropical jet. This configuration may be unfavorable for CoLs in sub-tropical latitudes. However, during El Niño events, in the Pacific South America (PSA, e.g. Mo 2000) region, Z500 is lower

between $\sim 30^{\circ}\text{S}$ – 45°S but higher (or neutral) around 60°S resulting in a reduction of the meridional gradient of pressure between $\sim 45^{\circ}\text{S}$ and $\sim 60^{\circ}\text{S}$, meaning a regional weakening of the polar jet. Thus during El Niño, CoLs are on average more numerous between 42.5°S and 50°S but this feature concerns only the PSA region.

In the African sector, CoLs tend to be slightly more numerous during La Niña on the Atlantic Ocean side while they tend to be more frequent during El Niño events on the Indian Ocean side (in the Mozambique Chanel and to the southeast of Madagascar). The regional sub-division chosen by F2005 (see above), does not show the link with ENSO because CoL occurrence was summarized over areas responding inversely to the ENSO signal. Some verifications have been realized to estimate if the long term trend of CoL frequency affects the statistical links with ENSO. De-trended regional indices of CoL frequency have been correlated with de-trended fields of air temperature at 2 m in the goal to verify if the linear correlations are significant in the equatorial Pacific (not shown). These maps confirm the regional statistical relationships with ENSO as presented on Fig. 13 (see supplementary material, part G).

6 Conclusion

This study documents Southern Hemisphere CoL characteristics. Using an automated scheme, CoL trajectories were established at the 500 hPa level and throughout the SH over the period 1979–2008. Their general features as well as their climatology have been studied and compared with previous work in the literature. It was found from this analysis that CoLs are more common in the sub-tropical latitudes, between 20°S and 45°S near continents as indicated in previous studies. They are more numerous from the late-summer until autumn. In winter they are fewer but deeper and occur more frequently at higher latitudes, while in summer they are weaker and occur more frequently in lower latitudes. The seasonality of CoLs' frequency varies regionally: in summer they tend to be more numerous on the western side of the oceans and more numerous in winter on the eastern side.

CoLs occurrence is closely linked with cut-off highs and surface anticyclone formation. On average, high pressure systems associated with CoLs are centered in the mid-latitudes (around 50°S). The situation associated with cut-off development corresponds to a reduction of the pressure/temperature meridional gradient between tropical and mid-latitudes and a reinforcement of the gradient between mid and high latitudes. Thus, the statistically positive relationship between CoLs frequency and SAO, on seasonal time-scale and longer time-scale, may be manifest physically via cut-off highs.

Fig. 12 Zonal composite La Niña versus El Niño for two latitudinal bands (1-black line = 20°S–30°S, 2-grey line = 42.5°S–50°S), Grey/Black points = sig. >90%/95% (two tailed Student's *t* test)

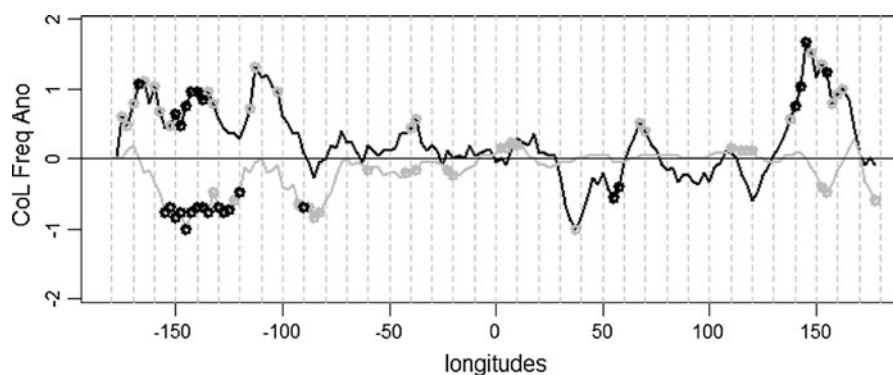
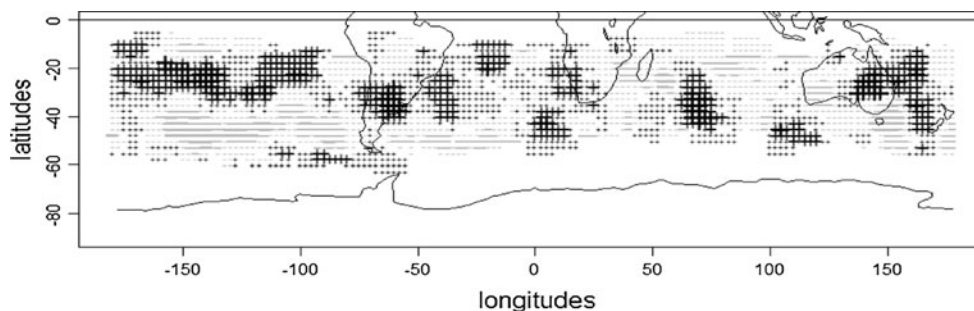


Fig. 13 Composite La Niña versus El Niño events. The black + and grey - signs signify more/less CoLs during La Niña than during El Niño events. Larger signs = sig. >90% and bold signs = sig. >95% (two tailed Student's *t* test)



On inter-annual time scales, CoL frequency is related to ENSO with more systems during La Niña events. This feature, more evident in lower latitudes (between 17.5°S and 30°S) of the Australia/South Pacific sector, is consistent with Caruso and Businger (2006) who found that Kona storms in the Hawaii region are more numerous during La Niña than during El Niño events.

The frequency of CoLs in the SH significantly increases by about 25% over the period 1979–2008. This trend is mainly the result of a strong positive shift of the number of CoL generations between 1998 and 1999. More CoLs may signify more cut-off highs located in mid-latitudes. This observation may be attributed to the rising of pressure/temperature in mid-latitudes. IPCC (2007) reports that the geopotential height 700 hPa rose in mid-latitudes of the SH along the period 1979–2001. This change in mid-latitudes' atmospheric pressure/temperature seems to be linked to the reduction (increase) of mid (high) latitude cyclone frequency over the past seventy years (e.g. Simmonds and Keay 2000; Keable et al. 2002; Lim and Simmonds 2009) and possibly also related with an increase frequency of CoLs. More CoLs may signify more cut-off highs located in mid-latitudes and consequently may induce a more frequent poleward displacement of the jet stream and the storm-track (the causality sense can also be reversed).

However, the IPCC (2007) note spurious trends in Reanalysis data (NCEP and ERA40) over southern oceans and these trends could affect the climatology and the observed trends in CoLs' frequency particularly over the oceans.

Changes in CoL features are of major interest for many sub-tropical regions and may affect rainfall in the future. A follow-on paper will examine the contribution of CoLs on precipitation over South Africa on both seasonal and inter-annual-time scales.

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