A climatology of cutoff lows in the Southern Hemisphere

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[1] The occurrence of cutoff lows (COLs) in the Southern Hemisphere at 500 hPa is studied for a 31-year period using atmospheric NCEP-NCAR reanalysis. The methodology combines objective detection and tracking for cyclonic systems with visual inspection in order to select those systems that segregate equatorward from the main westerlies. Hemispheric charts and frequency distributions are presented for COL distribution, initial and final locations, duration, intensity, and motion. COLs tend to cluster around the three main continental areas and to have a low frequency of occurrence over the oceans. Because particular features are shown by the COLs associated with each continent, three longitudinal sectors centered in Africa, Australia, and South America are defined. From the total of 1253 COLs detected, 10% were found in the African sector, 48% were found in the Australian sector, and 42% were found in the South American sector. Marked seasonal cycles with summer minima are found around South America and Africa but not over Australia. Over South America, net dissipation of COLs prevails while over Australia, generation is the dominant process. Active storm tracks and moist conditions seem to be responsible for fewer COLs, while low winds in the upper troposphere and dry conditions in the lower troposphere are associated with a higher frequency of occurrence. A trend in the number of COLs is significant only near South America with higher COLs after 1990. No relation was found between COL frequencies and the ENSO phenomena.

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1. Introduction

[2] The main purpose of this article is the climatological characterization of segregated depressions or cutoff lows (hereinafter COLs) over the Southern Hemisphere. COLs are upper-level low-pressure areas formed on the equatorward side of the maximum westerly winds in the polar or the subtropical jet stream. According to *Hoskins et al.* [1985] subtropical COLs are in essence similar to polar jet COLs, differing only by the importance of the Coriolis parameter. On an isentropic surface intersecting the tropopause, COLs are revealed as isolated centers of high cyclonic potential vorticity, with values typical of air from the lower stratosphere that has been advected by the upper winds away from the polar regions. COLs may extend to the surface itself before being destroyed by processes such as diabatic heating or friction or moving back into high latitudes [*Hoskins et al.*, 1985].

[3] Interest in COLs is primarily motivated by their association with stratosphere-troposphere exchange (STE) and their contribution to explosive surface cyclogenesis. Intense downward and upward motions near the center of a COL lead to a tropopause folding, thus increasing the STE of trace gases [e.g., *Holton et al.*, 1995]. For instance, *Rondanelli et al.* [2002] found that almost 70% of the cases of sudden ozone increase at Cerro Tololo (subtropical Andes) are associated with COLs crossing that region. When upper-level COLs move over regions of potentially unstable low-level air, they provide the dynamical forcing that may trigger rapid and severe surface cyclogenesis and subsequent strong winds and intense rainfall. Such events are not infrequent in eastern Australia [*McInnes and Hess*, 1992; *Katzfey and McInnes*, 1996] and eastern subtropical South America [*Seluchi and Saulo*, 1998; *Miky-Funatsu et al.*, 2004]. Even in those cases in which a COL does not produce surface lows (usually termed upper-level cold pools), midtropospheric ascent can lead to convective cloudiness and rainfall, as observed in tropical South America [*Kousky and Gan*, 1981], western South America [*Pizarro and Montecinos*, 2000], and eastern Australia [*McInnes and Hess*, 1992], and to strong winds and snowfall as observed in the Andes [*Vuille and Ammann*, 1997].

[4] To our knowledge there are two climatological studies of COLs in the Northern Hemisphere, those of *Kentarchos and Davies* [1998] and *Smith et al.* [2002]. In both cases geopotential height at a single level was used in the identification process. *Kentarchos and Davies* [1998] studied the occurrence of COLs lasting more than a day at the 200 hPa level for the period 1990–1994. According to them, the seasonal distribution of COLs in the Northern Hemisphere is related to the zonal strength of the jet streams, showing a larger frequency in the summer season when the zonal flow is weak and continental areas are warmer, increasing the

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potential for low zonal index configurations. They also found COLs to have a variable geographical distribution, a most frequent duration between 2 and 3 days, sizes ranging from 200 to 1200 km and irregular trajectories. *Smith et al.* [2002] identified and counted COLs at 500 hPa over a 46-year period in the Northern Hemisphere with special reference to eastern North America. They remark that distribution of COLs appears to be orographically and synoptically dependent with larger frequency and shifting equatorward during winter and spring.

[5] In two climatological studies dealing with cyclones and anticyclones in general at 500 hPa in the Northern Hemisphere [*Parker et al.*, 1989; *Bell and Bosart*, 1989], some of the lows that they analyzed would have been cut off. *Bell and Bosart* [1989] in their 15-year climatology consider specifically cyclone centers south (i.e., equatorward) of the main belt of westerlies and found high frequencies of events on the subtropical west coast of North America, on the east coast of Asia and from the East Atlantic Ocean through the Mediterranean Sea to Western Asia. The analysis of *Parker et al.* [1989] of cyclones and anticyclones over a 36-year period includes only the western half of the Northern Hemisphere. They found relative maxima of lows on the subtropical western coast of North America from September to January, over the central subtropical Pacific Ocean during summer and over south western Europe during most of the year, speculating that in all of these cases they were COLs.

[6] In the Southern Hemisphere, *Kousky and Gan* [1981] examined cyclonic vortices during a 5-year period over South America and the adjacent oceans, *Qi et al.* [1999] studied COLs in Southern Australia, and *Mishra et al.* [2001] performed a detailed analysis of a COL in Northeastern Brazil. No climatological study has been published for the whole Southern Hemisphere. Hemispheric studies of cyclones in general have been made for sea level [*Sinclair*, 1994] and the 500 hPa level [*Keable et al.*, 2002] but with no specific reference to COLs.

[7] This initial study of COLs in the entire Southern Hemisphere is a first step in furthering the understanding of the dynamics and impacts of this phenomenon. The search for COLs was done on the basis of 31 years, four-daily reanalysis fields using an objective detection software of depressions combined with a visual inspection. Details on the data, case detection and selection criteria are presented in section 2. The results are presented in section 3, including the geographical distribution of COLs, genesis and decay areas, annual cycles and trends, and their statistical characterization in terms of intensity, propagation and duration. Section 4 contains some discussion of our main findings.

2. Data Source, Case Detection, and Selection Criteria

[8] Our climatological study of COLs in the Southern Hemisphere is based on the NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996] from which the presence of cyclones and their tracks were obtained for a 31-year period (1969 to 1999). The reanalysis fields have a 6-hour resolution on a 2.5° latitude × 2.5° longitude grid and include all mandatory levels from 1000 to 100 hPa. Since the size of a typical COL is in the range of 600–1200 km, they should be detectable in this data set. The original data were previously transformed to a polar stereographic grid on which the search for depressions was performed.

[9] The software used in the detection and tracking of depressions is that of Murray and Simmonds [*Murray and Simmonds*, 1991a, 1991b; *Simmonds and Murray*, 1999] applied to the 500-hPa level. This level was chosen because of its proximity to the Andean summit, which influence on COLs behavior is of special interest, and because it allows for the identification of low-pressure systems extending into the lower troposphere. (For the year 1999, we performed an independent detection of COLs applying the method to the 300 (200) hPa level obtaining similar results to the standard detection at 500 hPa; 85% (72%) of the COLs detected at 500 hPa were also found at 300 (200) hPa. The duration of the cases identified at the three levels agrees closely). A brief description of this software follows. Although the package is composed of three stages, only detection and tracking were used. Additional details of detection and tracking are given by *Murray and Simmonds* [1991a] and *Simmonds and Murray* [1999].

[10] Identification is not done directly on the grid point values but on a continuous field of geopotential obtained through a two dimensional (2-D) polynomial representation fitted with cubic splines. This representation allows finding the position of depressions by an iterative procedure using first and second derivatives after an initial search of maximum values of the Laplacian of the geopotential field. This procedure is not restricted to finding a closed contour at some specified interval so that open depressions are included. Depression strength is expressed in terms of the central Laplacian of the geopotential field. The search was restricted to depressions lasting at least 36 hours and reaching a strong and closed condition at some point during their lifetime. A closed condition is attained when a 2-D minimum in the geopotential field is present while the strong status refers to cases where the central Laplacian exceeds 5.0 gpm/(dol)^2 (dol = degree of latitude). The search covered the whole Southern Hemisphere in the latitudinal band 10°–60°S.

[11] To follow a COL from a given time t to the next ($t + \delta t$), both position and geopotential are extrapolated by taking a weighted average of the previous displacement from present t and previous values (t − δt) through the time interval (δt = 6 hours) and the climatological average cyclone velocity for the latitude. In the ‘‘future’’ field (t + δt) several detected COLs might be the continuation of each COL identified in the present time (t). Then probabilities are assigned to each pair formed by a detected COL at (t + δt) and the extrapolated ones for the same time. Such probability decreases exponentially with the separation between an observed from an extrapolated COL. The selected couples are those maximizing the sum of probabilities of a group. Ambiguities in the tracking procedure were reduced by the brief time interval between successive analyses together with the slow motion and small number of COLs. A complete track of a depression starts when the central Laplacian exceeds 2.5 gpm/(dol)^2 even though the depression might not be closed nor segregated, and terminates when it falls under this value.

[12] After the identification and tracking were completed in the 10° to 60°S latitudinal belt, the selection of COLs was

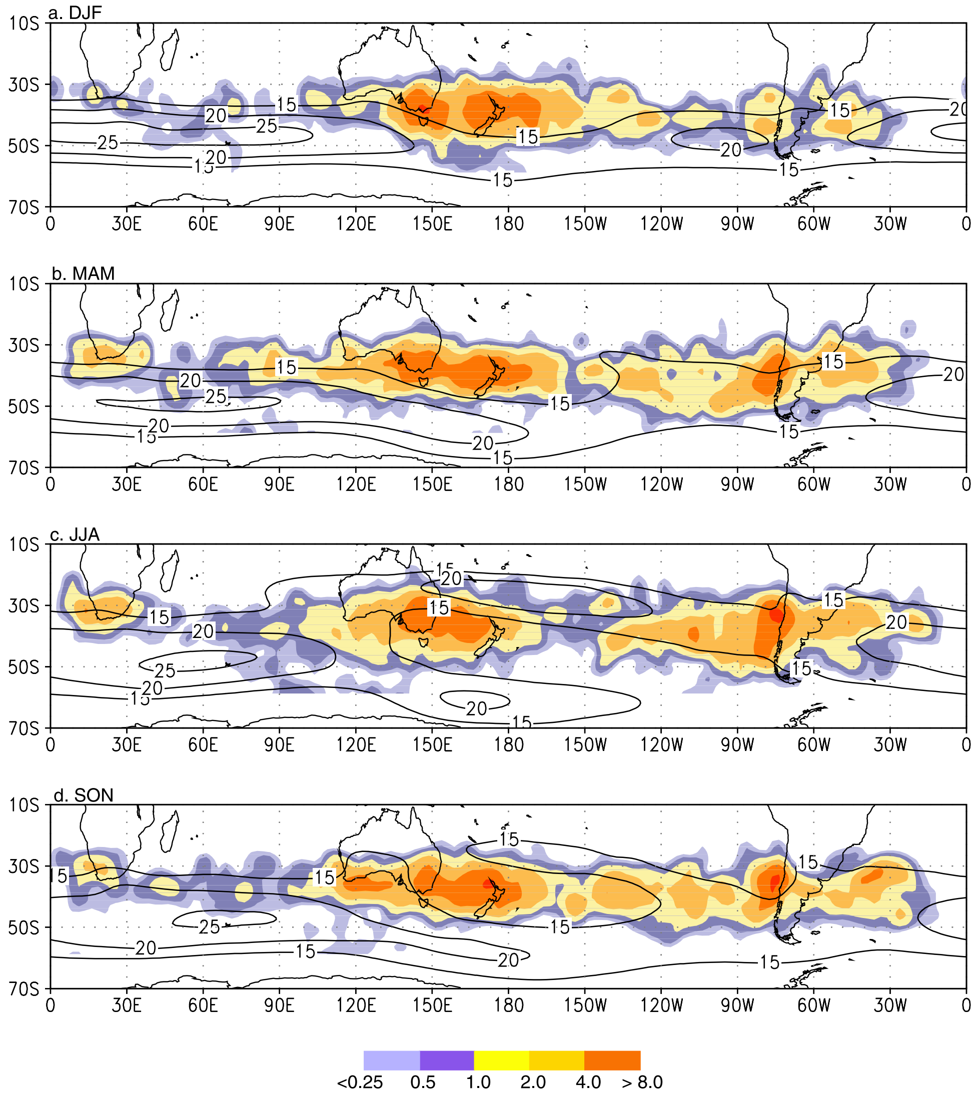

Figure 1. Seasonal average of the number of COL centers in 2.5° latitude × 2.5° longitude boxes normalized by area (31-year period). Isopleth values are indicated by the shaded scale at the bottom in number/season smoothed with a 3 × 3 point moving average. (a) Austral summer (December–January–February: DJF), (b) fall (MAM), (c) winter (JJA), and (d) spring (SON). Climatological mean 500 hPa isotachs for zonal wind component in m/s are shown for each season (solid lines).

performed in a two-step procedure. First, only depressions that move into latitudes north of the 50°S belt at some time were selected in order to include only cases where the cold air mass is significantly detached from its source region and in order to reject the numerous extratropical depressions. In the final step, characteristic features of COLs were introduced through a visual inspection of geopotential and temperature fields at 500 hPa drawn at 20 gpm and 2K intervals, respectively, with 200 hPa isotachs superposed. Selected cases were forced to comply with being segregated equatorward of the main westerlies with a split of the jet stream at the upwind side and a core colder than the immediate surrounding air. Addition of a cold core makes a significant difference with all previous works reducing the number of cases of COLs to those complying with the definition given by *Hoskins et al.* [1985].

[13] For track sections spanning between the first and last detection with a strong and closed status and that lasted longer than 1.5 days, COLs duration, intensity and velocity were summarized through frequency distributions according to season and longitude sector.

3. Results

3.1. Spatial and Temporal Distribution of COL Centers

[14] COLs, as defined above, are rather unusual events in the Southern Hemisphere: during the 31 years analyzed the selection process only retained a total of 1253 cases that at some point in their track reached a strong and closed status (average of 40 cases per year). In the latitudinal band between 10°S to 60°S the occurrence of COL centers were summed for each season in geographic squares of 2.5° latitude × 2.5° longitude and normalized by their areas (Figure 1). Therefore results correspond to the geographical density of centers.

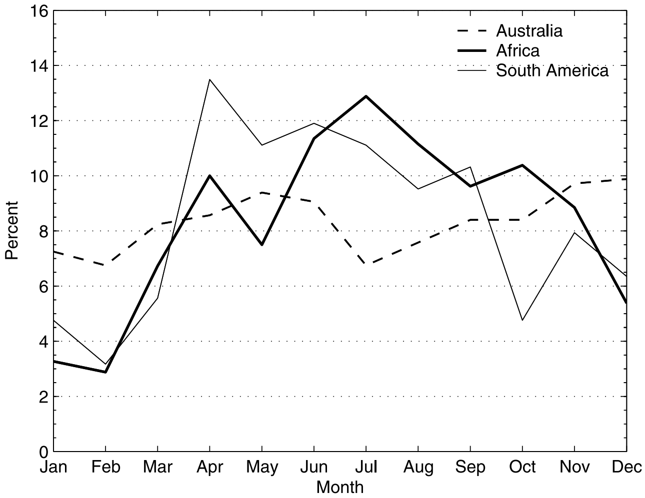

Figure 2. Mean annual cycle of COL numbers, expressed as a percentage of total annual number of cases, for the African (0° to 80°E), Australian (80°E to 140°W), and South American (140°W to 0°) longitudinal sectors.

[15] In all seasons, COLs are mostly found in a nearly zonal belt between 20°S to 50°S around the globe, and have a maximum density at about 38°S. From winter to summer the zonal axis of maxima drifts south about 4° of latitude. The COLs distribution, however, is far from uniform in longitude, with a large number of cases (up to 16 cases per season before smoothing) around the continents and well defined gaps over most of the oceanic regions (less than 0.25 cases per season over the south Atlantic east of 30°W).

[16] Orographic effects are apparent over the Andes which summits are associated with relative minima in COLs density, likely a consequence of cyclolysis by the forced ascent followed by rapid development on the lee side. At least two of this explosive cyclogenesis linked to a COL have been studied in subtropical South America [*Seluchi and Saulo*, 1998; *Miky-Funatsu et al.*, 2004]. *Smith et al.* [2002] report the same distribution across the Rocky Mountains in North America. Similar minima but weaker variations can be seen in the proximities of the southern part of the Australian Great Divide, across the African plateau and in summer across the New Zealand Alps.

[17] The spatial distribution of COLs is in sharp contrast with the migrating cyclones distribution, which spread rather evenly across various longitudes in the high latitudes of the Southern Hemisphere [*Keable et al.*, 2002], associated with a circumpolar storm track extending along 50°S [e.g., *Trenberth*, 1991].

[18] Because most of the COLs events occur in continental neighborhoods, three sectors associated with each of the continents were defined as follows: 0° to 80°E for Africa, 80°E to 140°W for Australia and 140°W to 0° for South America. The total number of COL's starting at some point in each sector were 126, 607 and 520, respectively (out of a total of 1253 cases). While the Australian sector exhibits a fairly invariable frequency of cases throughout the year, the South American and African sectors show a clear seasonality.

[19] Further details on the annual cycle for these three regions are shown in Figure 2 where they are expressed as a percentage of the total number of cases. For the African sector a well-defined cycle is apparent, with minima during summer months and four times more frequency of COLs in winter. In contrast, the Australian sector exhibits a comparatively fairly constant number of cases throughout the year. The cycle over the South American sector is less symmetric, decreasing from a maximum in April to a minimum in February followed by a sharp rise until April.

[20] The average annual numbers of COLs are 20, 17 and 4 cases in the Australian, American and African regions, respectively, with standard deviations of 5.3, 6.2 and 2.0. Thus interannual variability measured by the coefficient of

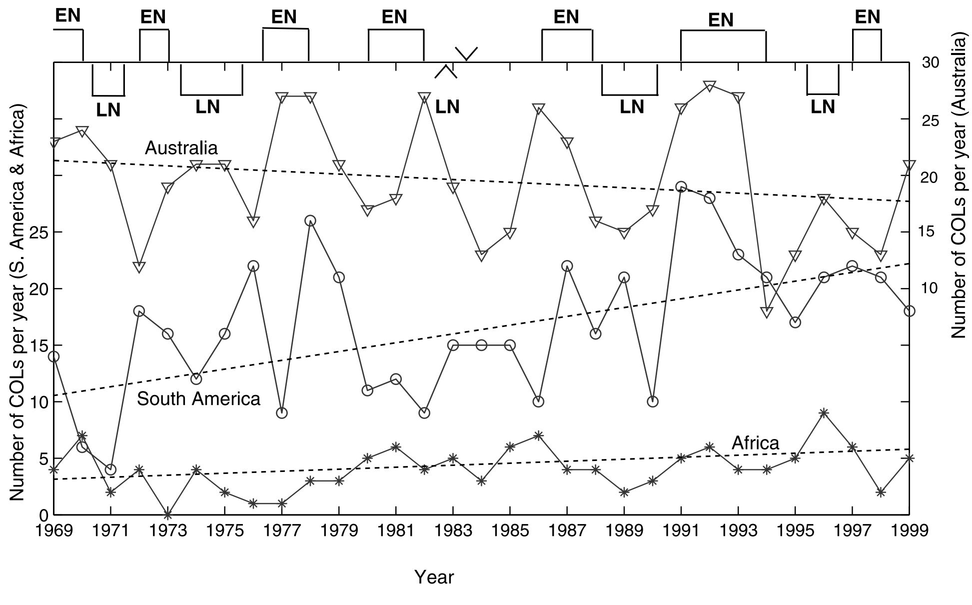

Figure 3. Time series for the annual number of COLs for each geographical sector from 1969 to 1999. El Niño and La Niña years (according to *Trenberth* [1997]) are indicated by symbols EN and LN. Dashed lines indicate linear trend.

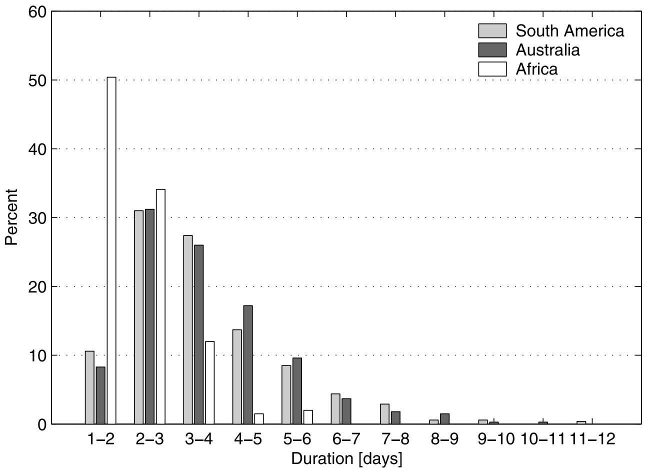

Figure 4. Frequency distribution of the average duration of COLs, expressed in days, for the African (0° to 80°E), Australian (80°E to 140°W), and South American (140°W to 0°) longitudinal sectors.

variation (s.d./average) is 37% in the American sector and 27% in the Australian sector. Over Africa it is even larger (50%) but here COLs are very infrequent. No association between the number of COLs and ENSO indices was found for any of the three regions. Interannual variations for each sector are shown in Figure 3. Linear trends fitted to the 31 annual values for each of the three regions were significant at the 95% level only for the American sector, where there was an increase of 3.4 ±2.3 cases/decade. On a cumulative graph the change in slope indicates that this is due to an increase in the annual number of cases that occurred around year 1990 in this sector. In the Australian sector no change could be detected. It is worth noting that *Keable et al.* [2002] found that midlatitude cyclones at 500 hPa exhibit a significant downward trend over the period 1958–1997 with an opposite trend in cyclone vigor.

3.2. Duration, Intensity, and Velocity of COLs

[21] Frequency distributions for duration (all seasons) are presented in Figure 4. For the Australian and South American sectors, the duration has a modal value between 2 and 3 days (nearly a third of the cases in that class) with frequency decreasing for longer durations down to less than 10% for the 5–6 days class. In the African sector duration of COLs are briefer, decreasing rapidly from the first class (less than 2 days) to almost none for durations beyond 4 days.

[22] Frequency distributions for intensities, measured by the maximum value of the central geopotential Laplacian on any one track, are shown in Figure 5 in units of gpm/(dol)^2. The maximum value of the Laplacian is about 25% larger than the average value over the track and exhibits a fairly good linear relation with it. Highest frequencies are between 8 and 12 gpm/(dol)^2, being slightly larger over the Australian sector with no climatological seasonal differences. In Figure 6 we show the geographical distribution of the maximum intensity that reached any one COL, by placing a symbol where such event (i.e., the time of the maximum intensity) occurred. Of course, most symbols cluster in the regions of the maximum COLs density found in Figure 1. Within those regions, there is no clear separation in the locations of COLs according to their intensity, indicating no geographical preference for extreme intensity.

[23] Trajectories followed by COLs are in general extremely variable, although COLs move eastward in most cases. The mean velocity of propagation for each COL was estimated during its close strong phase as its net displacement divided by the time it takes to move from the initial to the final position. The frequency distribution for the annual mean is presented in Figure 7 for the three sectors. Modal intervals are very similar for all regions and seasons: 4 to 6 m/s for the zonal component and −2 to 2 m/s for the meridional component, so that the dominant motion is directed to the east, with about half the cases moving north and half south. Note that COLs move slower than the average midtropospheric westerly winds and typical migratory systems, both of which move at about 10 m/s. In a seasonal decomposition, American and African COLs moved substantially slower in summer than in other seasons, while over the Australian sector no major climatological seasonal differences were evident.

[24] COLs in the South American sector are perturbed by the Andes Range standing across their paths; in the upwind sector (140°W to 70°W) the most frequent direction is northeastward while on the lee side sector (70°W to 0°) it becomes almost due east. Geographical distributions of the mean velocity vectors for summer and winter are shown in Figure 8a. They have been averaged from the COL onset to the time of maximum intensity and are located at each mid point. Similarly, Figure 8b shows the mean velocity vectors averaged from the time of maximum intensity to the COL demise. A comparison between both stages indicate that COLs tend to move faster and with a northward component in the growing phase, relative to the decaying phase.

3.3. Formation and Decay Areas

[25] The time when a COL is formed is defined as the first detection with a strong and closed condition in its trajectory. Similarly, the last detection complying with these

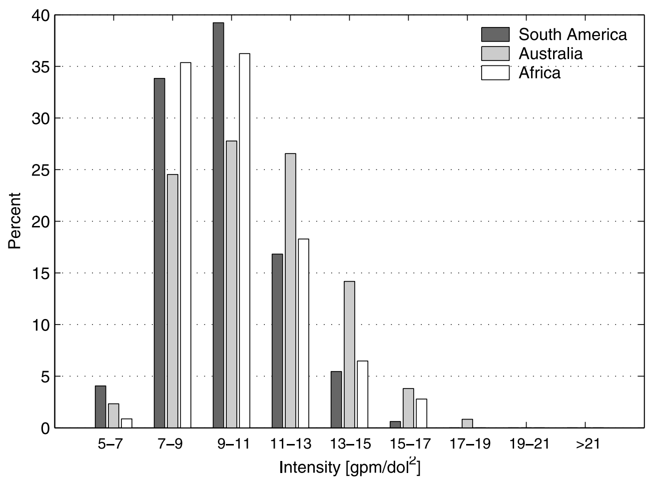

Figure 5. Frequency distribution of the maximum intensity of a COL on any one track expressed by the central Laplacian in gpm/(dol)^2 (dol = degree of latitude) for the African (0° to 80°E), Australian (80°E to 140°W), and South American (140°W to 0°) longitudinal sectors.

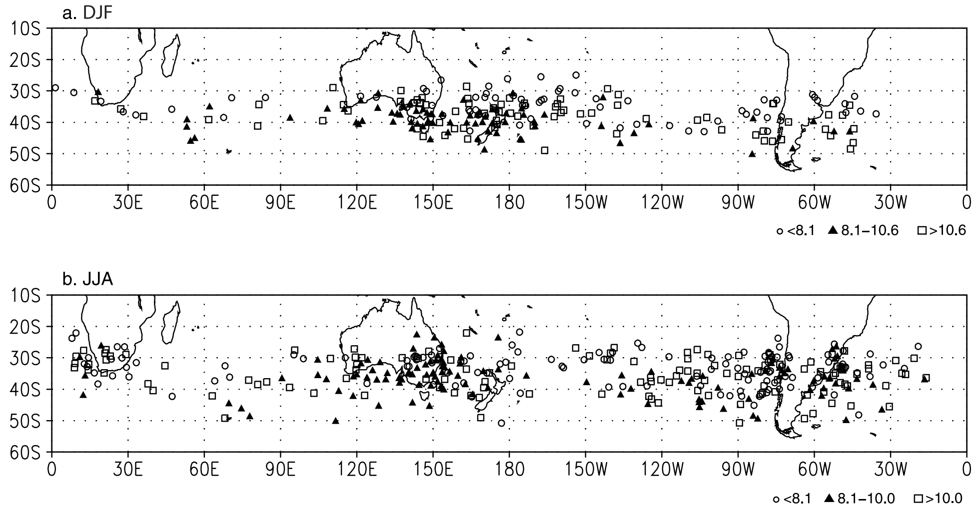

Figure 6. Intensity of COLs characterized by the maximum value of the geopotential Laplacian in gpm/(dol)^2 for (a) austral summer and (b) austral winter. Symbols correspond to seasonal terciles: first (circle), second (triangle), and third (square).

requirements was considered as the demise of the COL. The geographical distribution of areas where COLs are formed and vanish are shown in Figure 9 for summer and winter months.

[26] In winter, prominent formation areas (more than 2 cases per season) are associated with each of the three continents: one west of Africa, two over the Australian southern coast and one west of South America. During summer there are prominent formation centers only over southern Australia and New Zealand. As the result of the general easterly drift of the COLs, last detections tend to occur on the east coasts of the continents. In the American sector, lows also disappear along the Pacific coast and over the Andes.

[27] To further identify regions where building or decaying processes prevail, the number of COLs crossing various meridians at any latitude were evaluated at 10° longitude intervals across the hemisphere (Figure 10a) for summer and winter. Differences between successive longitudes (Figure 10b), reflect the net formation of COLs, that is, the number of new cases formed in the interval minus the number that fall below the detection threshold. A distinctive feature is the increase of crossings on the western side of the continents and a decrease on the eastern side. This change is very well defined for the Great Dividing Range in eastern Australia (90°E to 150°E), and the Andean Range of South America (140°W to 70°W). The longitudinal differences confirm that there is a net generation of COLs on the upwind side of the continent and a net destruction on the lee side. These zonal variations are consistent with the already mentioned tendency of COLs to cluster around the main continental areas.

4. Discussion

[28] The geographical distribution of COLs in the Southern Hemisphere spreads in a zonal strip between the subtropical and middle latitudes like those found in the Northern Hemisphere [*Kentarchos and Davies*, 1998; *Bell and Bosart*, 1989; *Parker et al.*, 1989], but their occurrence

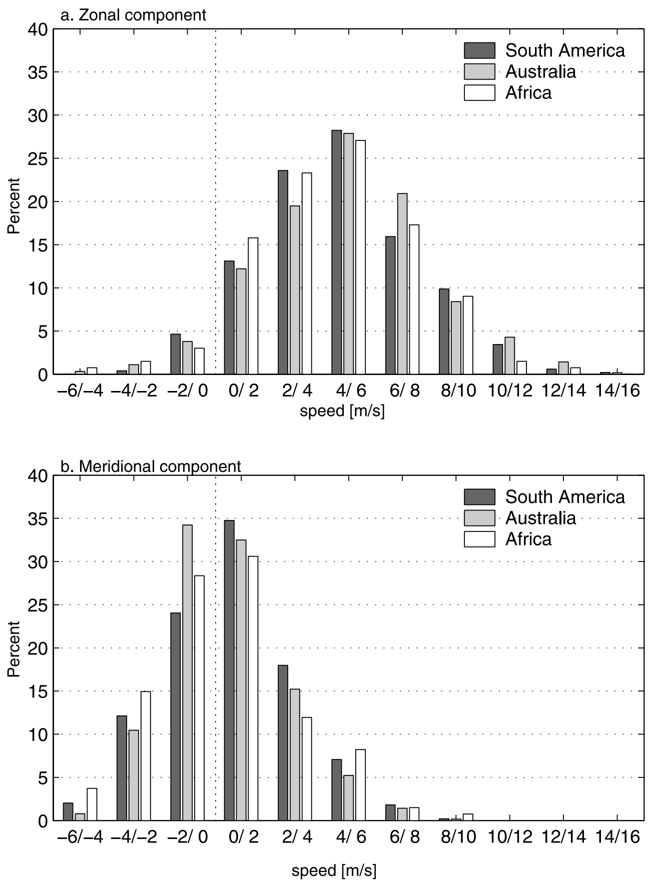

Figure 7. Frequency distribution of the velocity of COLs in m/s averaged over the strong closed phase interval for the African (0° to 80°E), Australian (80°E to 140°W), and South American (140°W to 0°) longitudinal sectors. (a) Zonal component and (b) meridional component.

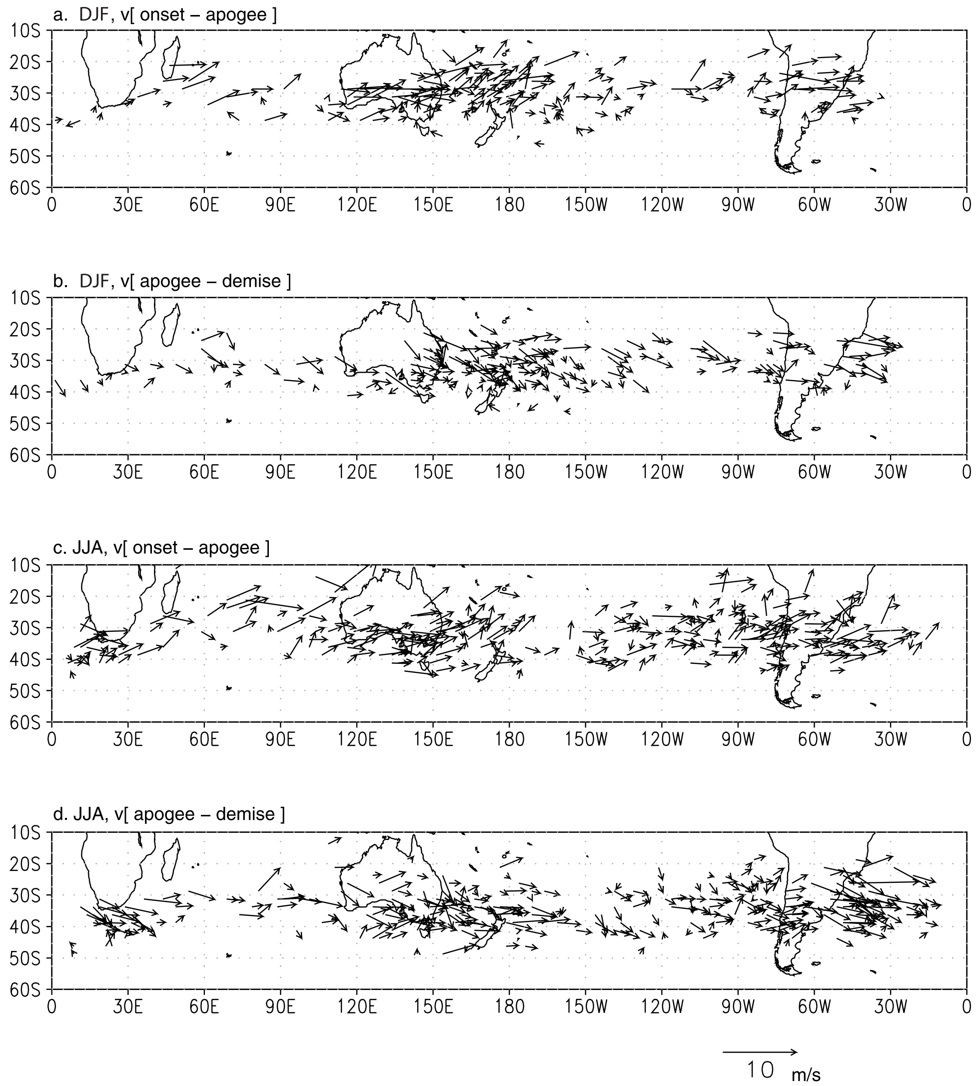

Figure 8. (a) Mean velocity of each COL in summer, obtained by averaging the 6-hour wind components from the onset to the time of maximum intensity. The vectors are located in the corresponding midpoint. (b) As Figure 8a but the mean velocity obtained by averaging the 6-hour wind components from the time of maximum intensity to the demise of the COL. (c) As Figure 8a but for winter. (d) As Figure 8b but for winter. Scale of magnitude is indicated by the arrow in the bottom right corner.

is more frequent around continents, especially in the proximities of Australia-New Zealand and South America, than in the intervening oceanic regions. This preference for continental sectors is in agreement with the findings in the 500 hPa level by *Bell and Bosart* [1989] for "closed cyclone centers south of the main westerlies" (their Figure 8) and *Parker et al.* [1989] study on the western Hemisphere (their Figures 1 and 3), but to a lesser extent in *Kentarchos and Davies* [1998, Figure 5] for the 200 hPa level.

[29] The relatively infrequent occurrence of COLs over the oceans (Figure 1) appears associated with the prevalence of mid tropospheric jet streams across the oceans, which effectively steer extratropical systems. Cyclonic systems are steered up to their exit sectors, where they can become detached from the main westerlies and transform into unsteered COLs. This occurs in the winter season south of Australia where, at 500 hPa level, a jet stream at 45°S splits into a subtropical jet (at 30°S), that crosses the Pacific Ocean in a WSW direction reaching the South American coast at 45°S, and a polar jet (at 60°S), which vanishes in the central Southern Pacific. This minimum in the westerlies strength over eastern Australia and New Zealand has been associated with frequent blocking (southward excursions of warm air) [*Trenberth and Mo*, 1985] but at the same time can also generate cutoff cyclones (northward excursions of cold air). The South American case is similarly associated with a minimum in the westerlies during winter and spring, but this feature is not so well defined in summer, when COLs occurrence is infrequent and cannot affect the climatological mean zonal flow to a detectable extent. *Bell and Bosart* [1989] also found that cyclones south (equatorward) of the main westerlies are unusual in the baroclinically active regions over the east coasts of Asia and North America.

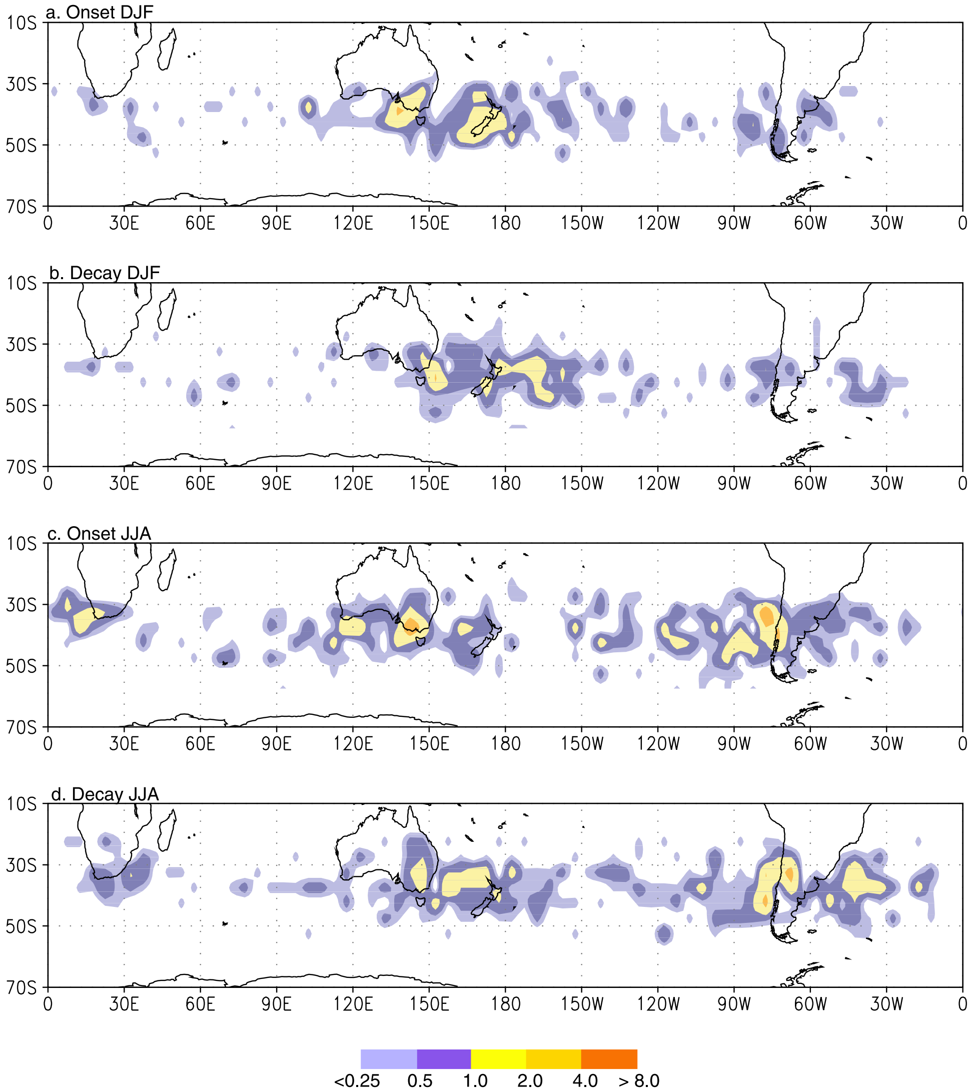

Figure 9. Seasonal average number of first (onset) and last (decay) points of the strong closed phase for COLs in 2.5° latitude × 2.5° longitude boxes. Isopleths values indicated according to shaded scale at the bottom in number/season smoothed with a nine-point 2-D moving average. (a) Summer onset, (b) summer decay, (c) winter onset, and (d) winter decay.

[30] Southern Hemisphere COLs are more frequent in winter, opposite to the summer maxima in the Northern Hemisphere. The latter has been associated with the general decrease of midlevel westerlies in the Northern Hemisphere during summer [*Kentarchos and Davies*, 1998]. In contrast, seasonality in the westerlies is very weak in the Southern Hemisphere (except over the Indian Ocean), so that other factors must be at play to explain the well defined summer minimum in the South American and African sectors.

[31] The importance of diabatic processes in the decay of COLs in the upper troposphere has been stressed by *Hoskins et al.* [1985] in consideration of their remoteness from the boundary layer where friction can be an efficient dissipative agent, and their relatively short lives are too brief for the typical time needed to be returned into polar latitudes. During the austral summer, deep, moist convection often reach subtropical latitudes over Africa and South America (Figure 11). Since the most effective process in the destruction of COLs is the release of latent heat, summer conditions near Africa and South America tend to shorten their lives, and fewer COLs satisfy the selection criteria of being strong and closed systems and lasting for at least 36 hours. Furthermore, latent heat release over subtropical Africa and South America sustain upper-level anticyclones that enhance the zonal winds on their southern border and steer low-pressure systems toward higher latitudes (Figure 11). In contrast, summertime deep convection doesn't develop over most parts of Australia so that COLs destruction by the release of latent heat would not be as effective.

[32] Moisture availability to feed deep convection seems also to explain the contrasting effect of the landmasses of Australia and South America in the generation/dissipation of COLs during winter (Figure 10b); while over the Australian continent there is a net generation of systems to be dissipated in the western Pacific, over the South American continent dissipation of COLs generated over the eastern Pacific by orographic ascent dominates. Most

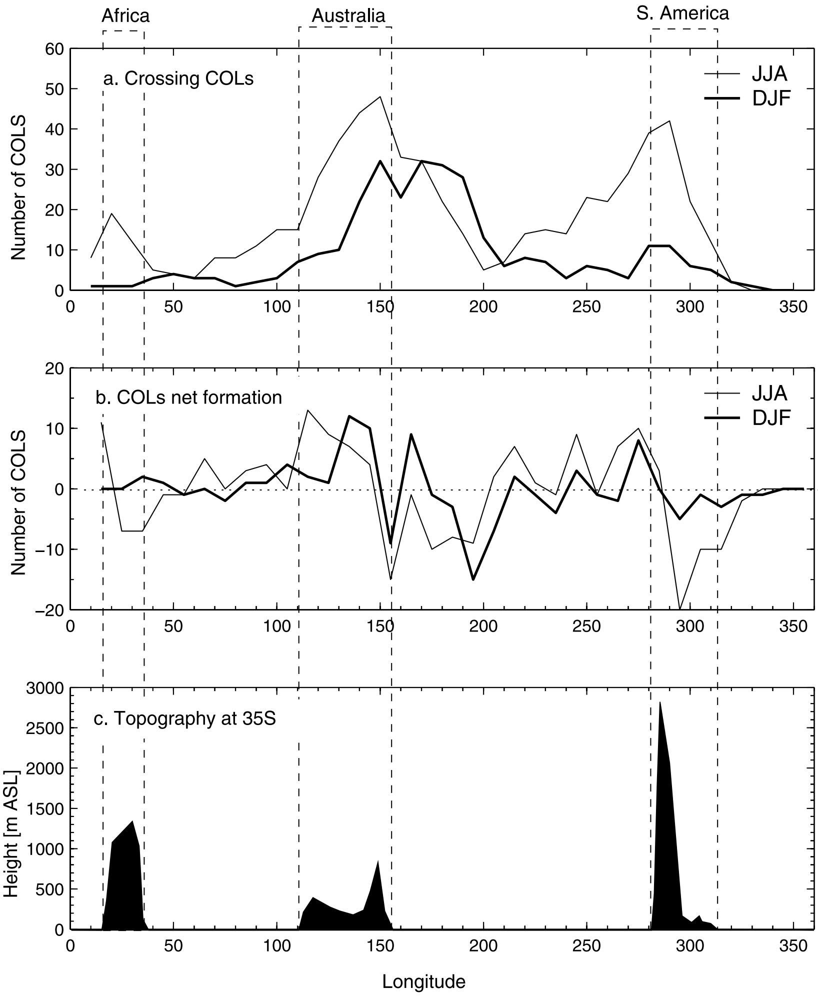

Figure 10. (a) Average number of COLs crossing meridians at 10° longitude interval for summer (DJF) and winter (JJA). (b) Net formation of COLs. (c) Topography meridional profile at latitude 30°S.

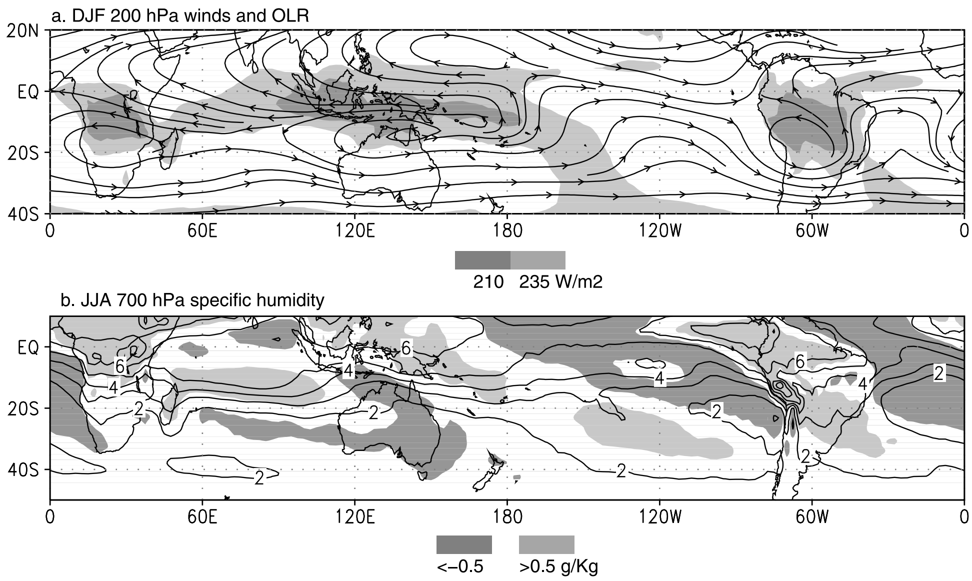

Figure 11. (a) Climatological mean 200 hPa winds (streamlines) and outgoing longwave radiation (shaded) for the austral summer (DJF). (b) Climatological mean 700 hPa specific humidity (contoured every 1 g/Kg) and specific humidity anomalies with respect to the zonal mean (shaded).

of Australia's inland is dry all year round (e.g., Figure 11b) an the dissipation of COLs by latent heat release is infrequent. A similar situation occurs over the eastern Pacific, where very dry conditions prevail. Immediately to the east of the Andes, however, moisture availability is abundant, leading to a rapid COLs dissipation in convective storms over eastern subtropical South America [*Seluchi and Saulo*, 1998].

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