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Exploring the vertical extent and deepening mechanisms of cut-off lows in the Southern Hemisphere: insights from eddy kinetic energy analysis

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Abstract. Downstream baroclinic development is a process involving the generation and redistribution of eddy kinetic energy (EKE) from upstream to downstream regions of baroclinic waves. While it is recognized that downstream baroclinic development plays a fundamental role in the development of cut-off lows (COLs), the mechanisms that govern their deepening are not yet fully understood. This study employs a track matching based-approach applied to the ERA-Interim reanalysis to examine the vertical extent of COLs in the Southern Hemisphere and elucidate the potential mechanisms contributing to their deepening. By analyzing the relative contributions within the EKE budget, we reveal that the deepening of COLs is primarily governed by the interplay between baroclinic processes and oriented ageostrophic fluxes. These fluxes act as conduits for importing kinetic energy from the upstream mid-latitude jet into the COL system. While this phenomenon is common across all COLs, our investigation reveals that the dynamical processes are notably more vigorous in deep structure COLs compared to their shallow counterparts. In addition, the COL vertical extent is influenced by diabatic processes and regional factors such as topography that modifies the characteristics of Rossby waves and their breaking. Understanding the key features of the vertical extent and deepening mechanisms of COLs is crucial for accurate forecasting, as it provides valuable information on the dynamics and evolution of these systems.

Keywords: Cut-off Lows, Vertical Depth, Extensions, Deepening, Energetics, Eddy Kinetic Energy.

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1 Introduction

Cut-off low (COL) pressure systems are characterized by closed low-pressure centers that detach or are "cut-off" from the main westerly flow (Palmén 1949). Typically forming equatorward from the mid-latitude jet, they can be identified as isolated high potential vorticity anomalies. COLs are known for their slow movement, varying in duration from short-lived to persisting for several days. Prolonged periods of precipitation associated with COLs often result in significant accumulations and may lead to floods in various locations (Singleton and Reason 2006, Llasat et al. 2007, McIness and Hubbert 2011)

The vertical extent and deepening mechanisms in cut-off low (COL) pressure systems represent important research topics in weather and climate research. Understanding the key aspects of the vertical extent and mechanisms that deepen COLs is of great importance because it offers valuable insights into the dynamics and evolution of these systems. Moreover, such understanding is crucial for enhancing the accuracy of COL prediction.

A seminal work to address the vertical structure of COLs is that of Palmén (1949) which revealed key features of these systems such as the quasi-barotropic structure, tropopause folding and thermal dipole patterns associated with cold and warm cores. Later, Frank (1970) observed that a relationship exists between the vertical extent of COLs and the associated cloud and precipitation patterns, which was corroborated by a more recent observational study (Porcù et al. 2007).

The vertical depth of COLs plays a critical role in determining weather conditions, directly influencing the intensity, duration and spatial extent of precipitation. In particular, deep COLs often lead to more intense precipitation and higher accumulations compared to their shallow counterparts (Porcù et al. 2007; Pinheiro et al. 2021). Nevertheless, the current literature lacks comprehensive studies addressing the potential mechanisms involved in the deepening of COLs. Analyzing the development of atmospheric systems from an energy perspective offers valuable insights into the diverse processes and interactions, including the various forms of generation, conversion and redistribution of kinetic energy.

Recently, there have been significant advances in the understanding of mechanisms underlying the development of COLs. Notably, studies have shed light on the crucial role played by the mid-latitude jet stream in supplying energy to COLs (Pinto and Rocha 2011; Gan and Piva 2013; Ndarana et al. 2021), particularly in regions of high-topography such as the Andes Cordillera in South America (Gan and Dal Piva 2016; Pinheiro et al. 2021) and the southern African plateau (Ndarana et al. 2021). Split jet streams and Rossby wave breaking facilitate the transfer of eddy kinetic energy (EKE) from the mid-latitude jet into the circulation of the COL, thereby intensifying the system (Ndarana et al. 2021).

The impact of ageostrophic fluxes on COLs is twofold: convergence enhances the development, while divergence promotes decay. Baroclinic processes, especially within intense COLs, have been identified as the primary source of kinetic energy (Pinheiro et al. 2021). Furthermore, the energy budget is influenced by diabatic processes, such as radiative cooling and latent heating, as demonstrated by various studies (Sakamoto and Takahashi 2005; Garreaud and Fuenzalida 2007, Cavallo and Hakim 2010, Portmann et al. 2018). Additionally, the interaction between upper-level potential vorticity and low-level potential temperature anomalies has emerged as a crucial mechanism influencing the extent of COLs (Barnes et al. 2021).

This study aims to provide an explanation for the deepening of COLs by employing energetic diagnostics. A novel approach is introduced to determine the vertical depth of COLs, followed by the application of the local EKE budget. These techniques present an opportunity to address the following scientific questions:

1. How sensitive are methods used to determine the vertical depth of COLs?
2. How is the spatial distribution of COLs in the Southern Hemisphere related to their vertical depth?
3. What mechanisms drive the vertical extension of COLs?

By addressing these questions, we hope to gain valuable insights into the deepening process and spatial characteristics of COLs along with a comprehensive understanding of the underlying mechanisms that govern their vertical extent. The remainder of the paper is organized as follows. Section 2 outlines the data and methods employed for tracking, estimating vertical depth, and calculating the EKE budget. Section 3 presents the results, and finally, Section 4 provides a summary of the main findings and conclusions.

2 Data and Methodology

2.1 Reanalysis dataset and tracking methodology

This study uses the ERA-Interim reanalysis data (hereafter ERAI; Dee et al. 2011) obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) for the period from 1979 to 2014. The ERAI reanalysis employs a spectral model with a N128 reduced Gaussian grid (~80km) and 60 vertical hybrid levels, produced with a four-dimensional variational data assimilation (4D-Var) system.

Before the tracking, the data are spectrally truncated at 42 wavenumbers (T42), and coefficients corresponding to total wavenumbers less than five are set to zero. This is done to reduce noise and eliminate large-scale background influences, similarly as done before (Pinheiro et al. 2017; 2021; 2022). The established TRACK algorithm (Hodges 1995, 1996, 1999) is employed to track T42 vorticity minima at various pressure levels (1000, 900, 800, 700, 600, 500, 400 and 300 hPa), using a consistent threshold (-1.0×10^{-5} s^{-1}) intentionally set relatively low to capture diverse cyclonic systems. The tracking is performed by minimizing a cost-function for track smoothness subject to adaptive constraints on track smoothness and displacement distance. The tracking is the same method as used for extratropical and tropical cyclones (e.g., Hodges et al. 2011, 2017), but with some adjustments to the slower moment of COLs, as discussed in Pinheiro et al. (2019).

The resulting tracks are filtered based on horizontal wind components (u, v) in four offset points 5◦ geodesic from the vorticity center: 0^o (u>0), 90^o (v<0), 180^o (u<0) and 270^o (v>0) relative to north. This retains only closed cyclonic centers, as

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discussed in Pinheiro et al. (2019). The retained tracks are those that either move equatorward and reach latitudes north of 40°S or originate north of 40°S and persist for at least 24 hours.

Spatial statistics of the COLs are computed using spherical kernel estimators for track density and mean intensity (Hodges 1996). Track density represents COLs per season per unit area (5° spherical cap ≅ 106 km2), while mean intensity derives from T42 relative vorticity, scaled by -1 for the Southern Hemisphere. Additionally, feature density is calculated using all track points, implying a concentrated density contribution in a small region for slow-moving systems due to the higher point density.

2.2 Approach to determine the COL vertical depth

To analyze and quantify COLs, numerous algorithms have emerged, though only a few of them address multi-level cyclone detection and their connections. Existing algorithms establish cyclone position correspondence between levels based on feature point distances, utilizing mean sea level pressure or vorticity centers. These methods span from basic search tasks (Lim and Simmonds 2007, Porcù et al. 2007) to more advanced techniques based on optimal solution (Lakkis et al. 2019).

In this study, the track matching algorithm introduced by Hodges et al. (2003) and used to match tracks in different datasets (Bengtsson et al. 2009, Hodges et at. 2011, 2017, Pinheiro et al. 2020) is employed to match tracks between different pressure levels. The algorithm is used to compare tracks across different pressure levels by defining a mean separation distance (d_m), chosen here to be 5 degrees geodesic, and considering overlaps in time (χ) between corresponding points in the tracks. Temporal overlaps between tracks will be determined following a sensitivity analysis, as discussed in Section 3.1. The percentage of points overlapping in time is calculated using the approach described in Hodges et al. (2003), defined as follows:

$$\chi = 100[2n_m/(n_1 + n_2)]$$

where n_m is the number of points that match in time, and n_1 and n_2 are the number of points in the track corresponding to different pressure levels.

Assuming the COL development from upper to lower levels (Nieto et al. 2005), our method works top-down, starting at 300 hPa. Vorticity tracks (ξ_{300}) are matched against ξ_{400} if mean separation distance is $\leq 5^{\circ}$ and temporal overlap exists. Successful matches indicate extending COLs; unmatched ξ_{300} tracks imply the COL is confined to 300 hPa. An iterative process continues to lower levels (e.g., 500 hPa, 600 hPa), stopping at the last match or at 1000 hPa. The deepest successful match determines the COL vertical extent.

While our algorithm is simpler than the optimal solution-based one in Lakkis et al. (2019), it establishes consistent vertical associations, allowing a track stacking approach. Similar to their method, we start with two levels at a time and progressively extend the matches to adjacent pressure levels, enabling a sequential stacking process. It is important to note that COL

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deepening can exhibit varied characteristics and evolution across pressure levels, then a top-bottom approach might not capture all coupling types. Consequently, diverse matching procedures can lead to varying COL evolution outcomes.

2.3 Energetic diagnosis

Analyzing the EKE budget is a valuable approach for studying the development of COLs (Gan and Piva 2013, 2016, Pinheiro et al. 2022). In the present study, we employ the EKE budget to investigate the energy dynamics associated with the deepening of COLs. This is done by utilizing the methodology developed by Orlanski and Katzfey (1991), which incorporates essential mechanisms including baroclinic and barotropic conversions as well as ageostrophic flux convergence, commonly known as downstream development. The components of the EKE budget are computed as follows:

$$\frac{\partial\langle K'\rangle}{\partial t} = -\langle \nabla . \vec{V_a'}\phi' \rangle - \langle \omega'\alpha' \rangle - \left\langle \vec{V'} . (\vec{V_3'} . \nabla_3)\overline{\vec{V}} + \vec{V'} . \overline{(\vec{V_3'} . \nabla_3)\vec{V'}} \right\rangle + ADD + RES \qquad (1)$$

Here, K is the kinetic energy, $\vec{V}$ the horizontal wind, ϕ the geopotential, ω the vertical velocity, and α the specific volume. Overbars represent the time mean calculated for each month and year, primes the eddy part, subscripts a the ageostrophic component, and superscripts 3 the three-dimensional vector. The symbol $\langle \quad \rangle$ denotes volume integrals computed from the bottom (taken as the surface pressure) to the top (referred to the 100 hPa level).

In Equation 1, the 1st term on the right-hand side is the ageostrophic flux convergence, the 2nd term is the baroclinic conversion, the 3rd and 4th terms are the barotropic conversion, the 5th term (ADD) are additional terms which have small contribution for the EKE budget, such as the vertical advection of energy through the upper and lower boundaries. The budget residual (6th term, RES) represents processes or factors not fully accounted for in the EKE budget equation. These include friction, diabatic effects and discretization errors such as interpolation and finite differences. It could also arise from analysis increments due to data assimilation, affecting the energetics. Diabatic heating estimates from reanalysis products, reliant on microphysical processes, are significantly influenced by assimilation moist process parameterization (Pinheiro et al. 2022). The residual is computed by taking the difference between the observed/diagnosed EKE change (left-hand side, LHS) and the sum of known contributing EKE budget terms (right-hand side, RHS).

The energetics are computed by referencing the terms of Equation 1 to the tracks in a radial grid of 15° geodesic centered on the COL center, following the approach previously used in Pinheiro et al. (2022). The computation is performed in two ways: separately at each pressure level and integrated from 1000 hPa (or surface) to 100 hPa. Our analysis in this paper focuses on the two primary mechanisms of the EKE budget in COLs which are baroclinic conversion and ageostrophic flux convergence. Analyses are performed for each season, but only the mean fields are presented in the main text for simplicity and convenience.

3 Results and discussion

3.1 Sensitivity of track matching algorithm for the estimation of COL depth

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To assess the sensitivity of the track matching algorithm regarding the computation of COL depth, we investigate the influence of the mean separation distance (d_m) and temporal overlap (χ) between tracks at different pressure levels. Specifically, we vary the value of χ from 1% to 100% while keeping the threshold d_m fixed. This choice is based on observations that the estimation of depth is more sensitive to changes in χ than to d_m. It is worth noting that making d_m too large leads to a significant rise in the number of matches; however, this will introduce false matches involving unrelated cyclonic systems, particularly when using vorticity, which emphasizes small-spatial scale features. Therefore, we set the parameter d_m to 5 degrees geodesic, a value suitable for this study, considering that the vertical tilt of COLs is typically much smaller than this threshold (refer to Fig. 9 in Pinheiro et al. 2021).

A sensitivity analysis is designed by varying the parameter χ across a range of values. Setting χ to 1% requires that the mean separation distance between tracks at different pressure levels is satisfied with an overlap in time of at least 1% for the corresponding track points. Based on the results presented in Table A.1 of the Appendix, it was found that 20.3% of the ξ_{300} COLs extend all the way to the surface during at least one time step, indicating the presence of interconnected cyclonic features across all levels from 300 hPa to 1000 hPa.

The number of systems reaching the surface remains relatively consistent for χ values ranging from 1% to 25%, corresponding to percentages ranging from 20.3% to 19.5%. However, there is a significant decrease in the number of matches when χ exceeds 50%. This observation suggests that the coupling between upper and lower levels may occur more frequently during the mature to decay stages of the COL life cycle, influencing the number of matches. When χ is set to 75%, indicating a large overlap threshold, less than 10% of systems are identified as deep COLs. These findings indicate that using a high χ value restricts the number of matches, resulting in an underestimation of labeled deep systems.

Although determining the optimal threshold for establishing correspondence between upper and lower-level low pressure systems is challenging, employing a small χ value appears suitable for this task as it ensures capturing at least one time step during the life cycle of a well-defined stacked cyclonic system. To address this, the analysis of COL depth in this study adopts χ=1% and d_m=5. This implies that the mean separation distance between tracks at adjacent pressure levels is less than 5 degrees, and there is overlap in time for at least one track point. This criterion guarantees that COLs are vertically aligned or tilted at the designated pressure level, as demonstrated in Pinheiro et al. (2021).

Using geopotential data instead of relative vorticity to estimate the vertical depth of COLs offers an alternative approach. However, some care is required in selecting an appropriate threshold as geopotential magnitude generally increases with height in baroclinic systems. Previous studies (Porcù et al. 2007, Barnes et al. 2021) used varying geopotential thresholds for each pressure level to obtain vertical depth, which requires different subjective thresholds at each level. In contrast, vorticity-based identification does not require adjusting the threshold according to pressure level, as vorticity measures the atmospheric flow's rotation. Moreover, weaker vorticity COLs are less likely to be identified in the geopotential field (Pinheiro et al. 2019).

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3.2 Regional differences in COL depths

Studying the regional variations in the vertical extent of COLs is important for understanding the associated weather patterns, enhancing forecasting accuracy, and assessing the potential impacts on diverse regions. The recent study by Barnes et al. (2021) analyzed COL extent in South America, South Africa and the Australia-New Zealand region. Their findings revealed that deep COLs appear to be more prevalent in Australia and New Zealand, while relatively shallower COLs are observed in the southern African region.

Expanding on their study, we conduct an analysis of eight distinct genesis maxima regions in the Southern Hemisphere (Figure 1a). This approach allows for a more detailed examination of regional differences in the vertical extent of COLs. By using the tracks identified by Pinheiro et al. (2022) and applying the COL depth estimation method outlined in Section 2.2, we determine the lowest pressure level reached by the upper-level COL throughout its entire life cycle.

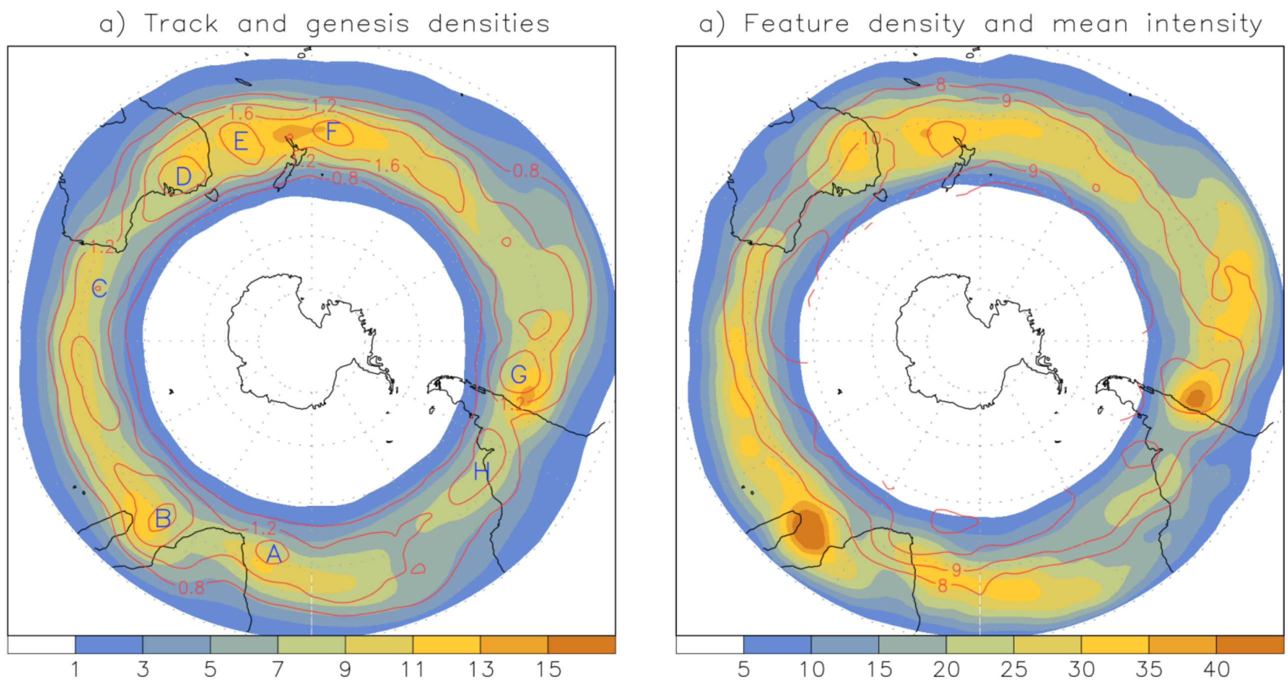

Figure 1: (a) Track density (shaded) with genesis density (contour) and (b) feature density (shaded) with mean intensity (contour) for all identified 300-hPa vorticity COLs. Regions of maximum genesis are denoted by A(32^{o}S 10^{o}E), B(29^{o}S 39^{o}E), C(33^{o}S 105^{o}E), D(34^{o}S 142^{o}E), E(33^{o}S 161^{o}E), F(34^{o}S 166^{o}E), G(34.5^{o}S 80^{o}W) and H(35^{o}S 57^{o}W). Unit is 10^{-1} s^{-1} for mean intensity and number per season per unit area for the other densities, where the unit area is equivalent to a 5^o spherical cap (≅10^6 km^2). Mean intensity is suppressed for track density below 1.0.

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Figure 2 illustrates the variations in COL depth across pressure levels and regions. We adopt the conceptual evolution of COLs that develop at upper levels and extend downwards to the surface (Nieto et. al. 2005). Our results indicate that the vertical extent of COLs is relatively consistent in the upper troposphere but exhibits more significant differences below 500 hPa. Deep COLs are more frequent in regions E, F (southeast Australia), and H (southwest Atlantic Ocean), with approximately 30% of total COLs extending all the way to the surface. Recent research by Pinheiro et al. (2022) has highlighted the significance of baroclinic conversion as the main EKE contributor for the COLs in regions E, F and H, suggesting a potential mechanism for their deepening.

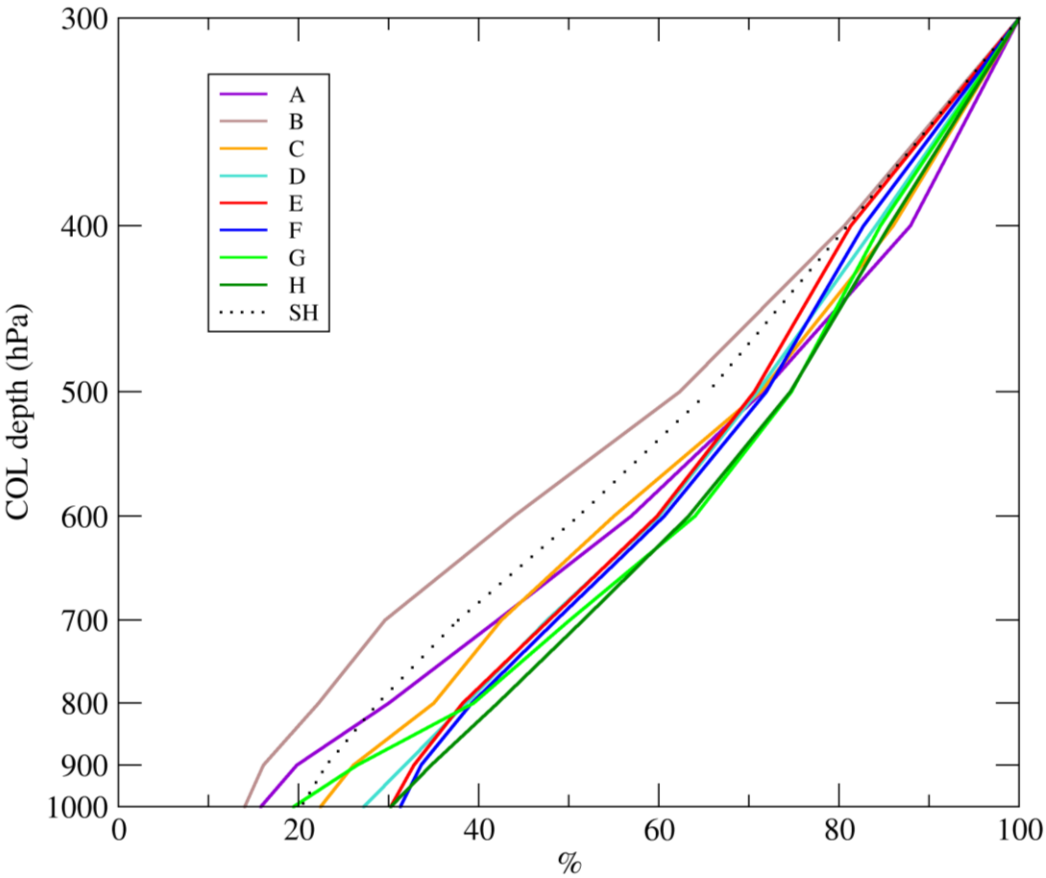

Figure 2: Percentage of low-pressure centers reached at various pressure levels for regions defined in Figure 1 (indicated by different colors) and for the entire Southern Hemisphere (dotted line). The 300-hPa track counts for each region are as follows: 741 (A), 950 (B), 746 (C), 1042 (D), 1048 (E), 1047 (F), 804 (G), and 611 (H).

Interestingly, there are regions where COLs extend to lower levels as much as the deepest observed systems do, but the extents reduce dramatically at levels below 800 hPa. This is particularly the case for the region G COLs (South East Pacific). A similar sharp decrease in the number that fully extend to the lowest level occurs for the regions A and C COLs (South East

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Atlantic and South East Indian Ocean). According to Pinheiro et al. (2022), these COLs share common attributes: COLs that originate in regions A, C and G are situated upstream of the major continents and are dominated by upper-level ageostrophic fluxes, possibly associated with stationary Rossby waves.

Considering the entire Southern Hemisphere, our analysis demonstrates a relatively homogeneous distribution of COL extents between 300 and 600 hPa. However, extents between 700 and 900 hPa are less common, aligning with the findings of Barnes et al. (2021). In contrast to their previously reported 51.7% fully extended COLs, our analysis suggests that only 20.3% of COLs extend all the way to the surface. These differences may arise from methodological variations, as previous studies (Porcù et al., 2007; Barnes et al., 2021) relied on the geopotential, which is less sensitive to identifying weaker systems at 300 hPa (Pinheiro et al. 2019). As vorticity is better at detecting weaker systems than geopotential, resulting in differences in the total identified systems, vorticity is expected to identify fewer deep COLs as a proportion of all systems. Moreover, earlier studies likely included numerous higher latitude vortices, which predominantly exhibit a deep vertical structure. Barnes et al. (2021) highlight that excluding more poleward latitude COLs minimizes these discrepancies.

3.3 Spatial variability of shallow, medium and deep COLs

Based on the algorithm outlined in Section 2.2, three categories of COLs based on their vertical extents are proposed: shallow, medium, and deep COLs. Shallow COLs (Figure 3a) are defined as low-pressure systems primarily confined to the upper troposphere, not extending lower than 400 hPa. Medium COLs (Figure 3b) are defined as originating at high levels and extending down to between 500 hPa, and 700 hPa. Deep COLs (Figure 3c) are defined as developing at 300 hPa and extending down to 800 hPa or lower. Although deep COLs can exhibit tilted or stacked structures, this analysis does not consider the vertical tilt. A discussion on the vertical tilt of COLs has been addressed by Pinheiro et al. (2021).

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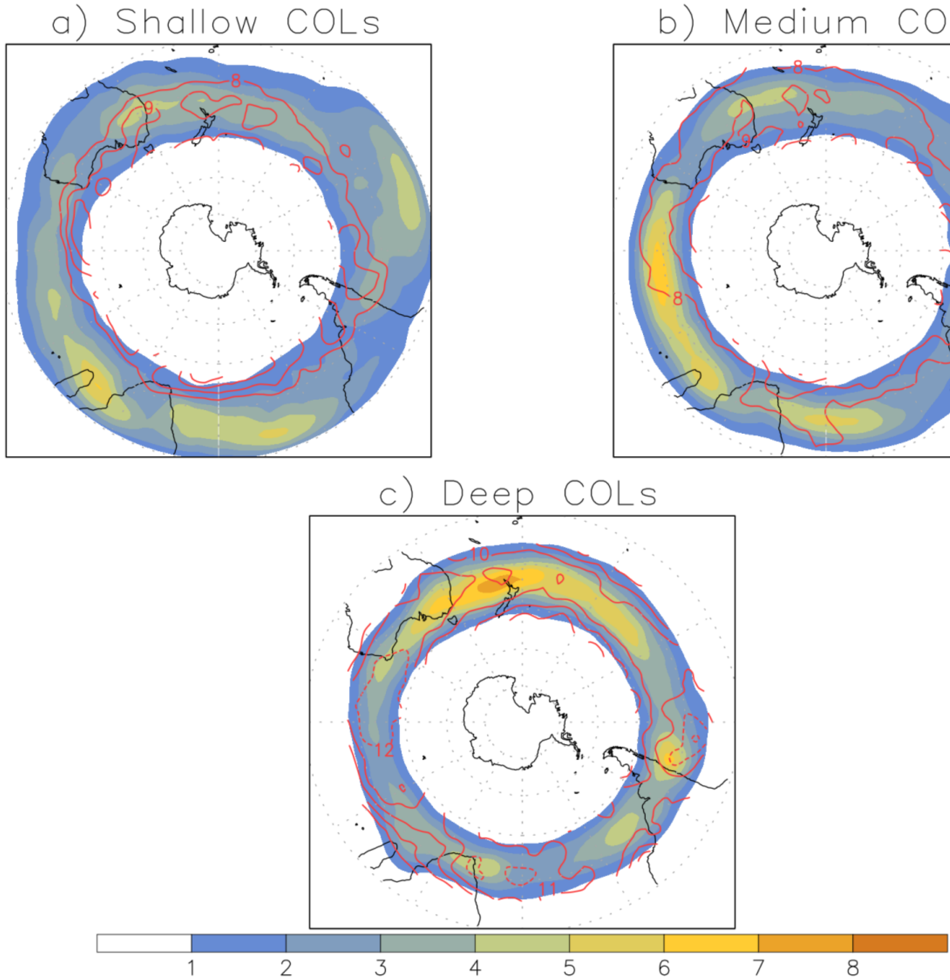

Figure 3: Track density (shaded) and mean intensity (contour) for (a) shallow, (b) medium and (c) deep COLs in the Southern Hemisphere. Unit is the same as in Figure 1.

Figure 3 demonstrates substantial regional variations in the distribution of COLs based on their vertical extents. There are regions that exhibit a high concentration of deep COLs, as in the eastern Australia, New Zealand, and western Pacific. The split-jet structure during austral winter may be one reason why COLs are deeper in the Australian region, as this causes vorticity advection and deepens the trough-ridge system (Ndarana et al. 2020). Additionally, the southwestern Atlantic Ocean, especially that neighboring South America, is another preferred location for deep COLs. In contrast, the COLs found in the southeast Africa and South Indian Ocean regions predominantly consist of shallow and medium-depth systems.

We found that the vertical extent of COLs varies with latitude, with shallow COLs occurring at all latitudes, while deep COLs are more prevalent at higher latitudes and less frequent north of 30°S. One interesting exception to this pattern is found in the southeastern Pacific, where deep, strong COLs can be observed at more northern latitudes than in other regions.

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This phenomenon aligns with the high mean intensity of COLs near the central coast of Chile, as shown in Figure 1c and previously discussed in Vuille and Ammann (1997).

3.4 Shallow COLs vs deep COLs: contrasting from the energetics point of view

When it comes to unraveling the intricate mechanisms behind the deepening of COLs, understanding the role of specific mechanisms in determining their vertical extent can be aided by examining their energetics. Early studies have investigated the dynamical mechanisms of COLs by examining their vertically integrated energy budgets (Gan and Piva 2013, 2016, Ndarana et al. 2020, Pinheiro et al. 2022). In this study, we adopt a similar approach but direct our attention towards the two primary contributing mechanisms of the EKE budget: baroclinic conversion and ageostrophic flux convergence. We compare deep and shallow COLs and investigate the possible implications of energetics for their deepening.

Figures 4 and 5 show the temporal evolution of composite shallow and deep COLs, respectively, for horizontal and vertical fields. The four stages described in the conceptual model of Nieto et al. (2005) and shown in Pinheiro et al. (2021) are seen to be reproduced for shallow and deep COLs, involving the following stages: upper-level trough (-48h), tear-off (-24h), cut-off (0), and decay or dissipation (+24 and +48h). Time is referenced to the time of maximum intensity in the 300 hPa vorticity.

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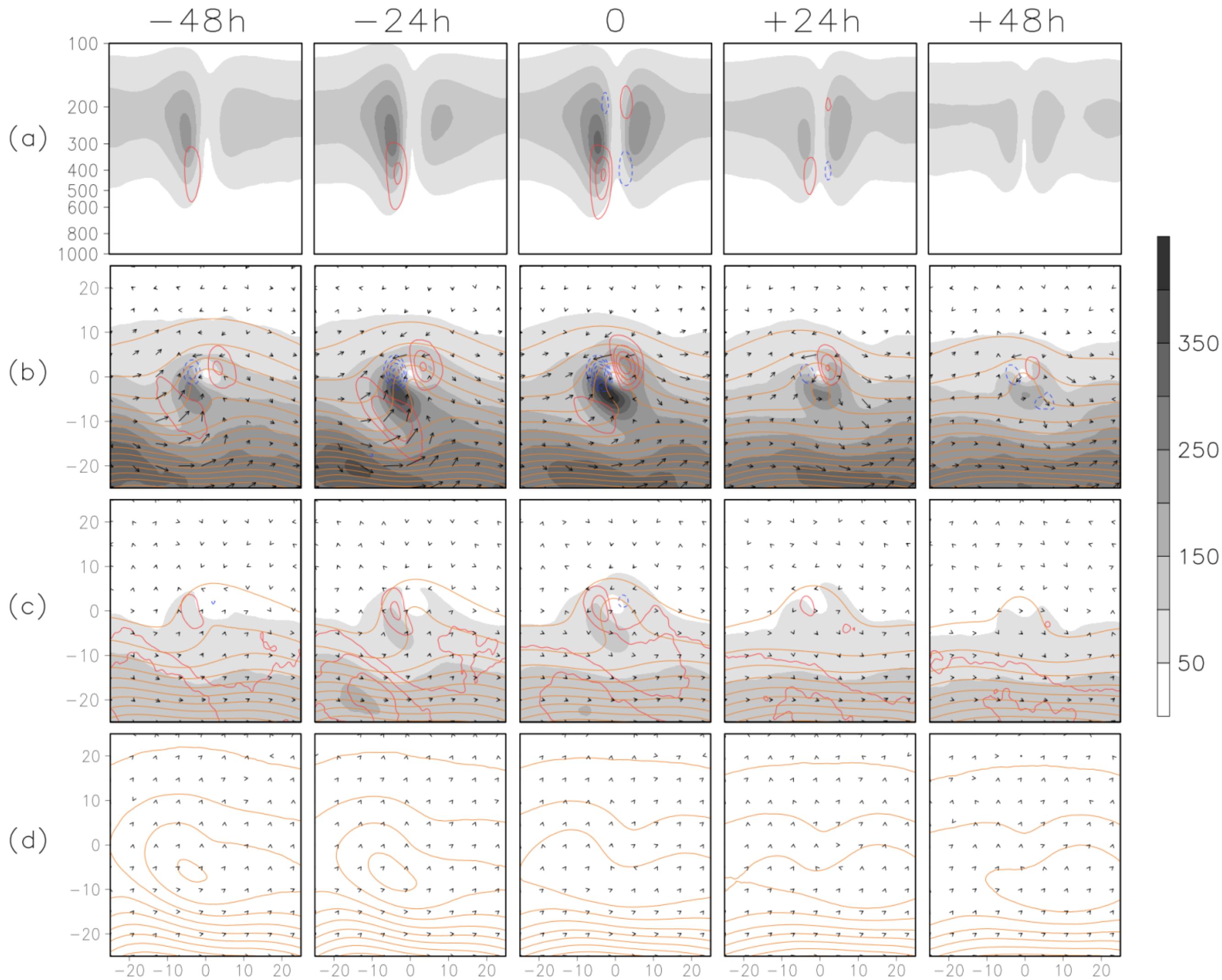

Figure 4 Temporal evolution of shallow COLs in the Southern Hemisphere relative to the time and space of maximum intensity in ξ_{300}. The panels depict: (a) vertical cross-sections of total EKE (shaded) with baroclinic conversion (contour); (b) vertically integrated ageostrophic flux convergence (contour) with EKE (shaded), geopotential height (orange line) and ageostrophic fluxes (vectors) at 300 hPa; (c) vertically integrated baroclinic conversion (red contour) with EKE (shaded), geopotential height (orange line) and ageostrophic fluxes (vectors) at 500 hPa; and (d) EKE, geopotential height (orange line) and ageostrophic fluxes (vectors) at 1000 hPa. Contours represent 0.003×10^{10} Joule.s^{-1} for integrated quantities, 50 gpm for geopotential height at 300 and 500 hPa, and 20 gpm for geopotential height at 1000, while total EKE is indicated by 10^9 Joule.

During the upper-level trough and tear-off stages of shallow COLs (Figure 4), the mid-latitude jet upstream acts as the primary source of energy for the COL. Concurrently, ageostrophic fluxes transport EKE northeastward from the jet stream to the rear side of the COL, forming a westward energy center, as observed by Gan and Piva (2013). As the system intensifies, this energy center expands due to positive baroclinic conversion occurring to the west of the COL, driven by descending cold air (refer to the supporting information of Pinheiro et al. 2021). These characteristics resemble those observed in a previous study of intense Southern Hemisphere COLs (Pinheiro et al. 2022). However, it is worth noting that in the case of the stronger COLs, the baroclinic processes and ageostrophic fluxes are much more intense. During the decay stage, baroclinic conversion and ageostrophic fluxes weaken, contributing to the gradual dissipation of the COL.

The development described above occurs similarly in deep COLs, as depicted in Figure 5. However, the energy growth in deep COLs occurs more vigorously due to the presence of stronger ageostrophic fluxes on the rear side of the COL. Moreover, there is enhanced baroclinic conversion upstream of the COL which is associated with a more intense mid-latitude jet than observed in shallow systems. This suggests that the jet stream plays a role in the deepening of COLs. The stronger baroclinic processes and ageostrophic fluxes observed in deep systems are likely responsible for the longer lifetimes observed in deep COLs (4.7 days) compared to shallow COLs (3.3 days). These factors contribute to a greater interaction between the mechanisms operating at different levels within deep COL systems.

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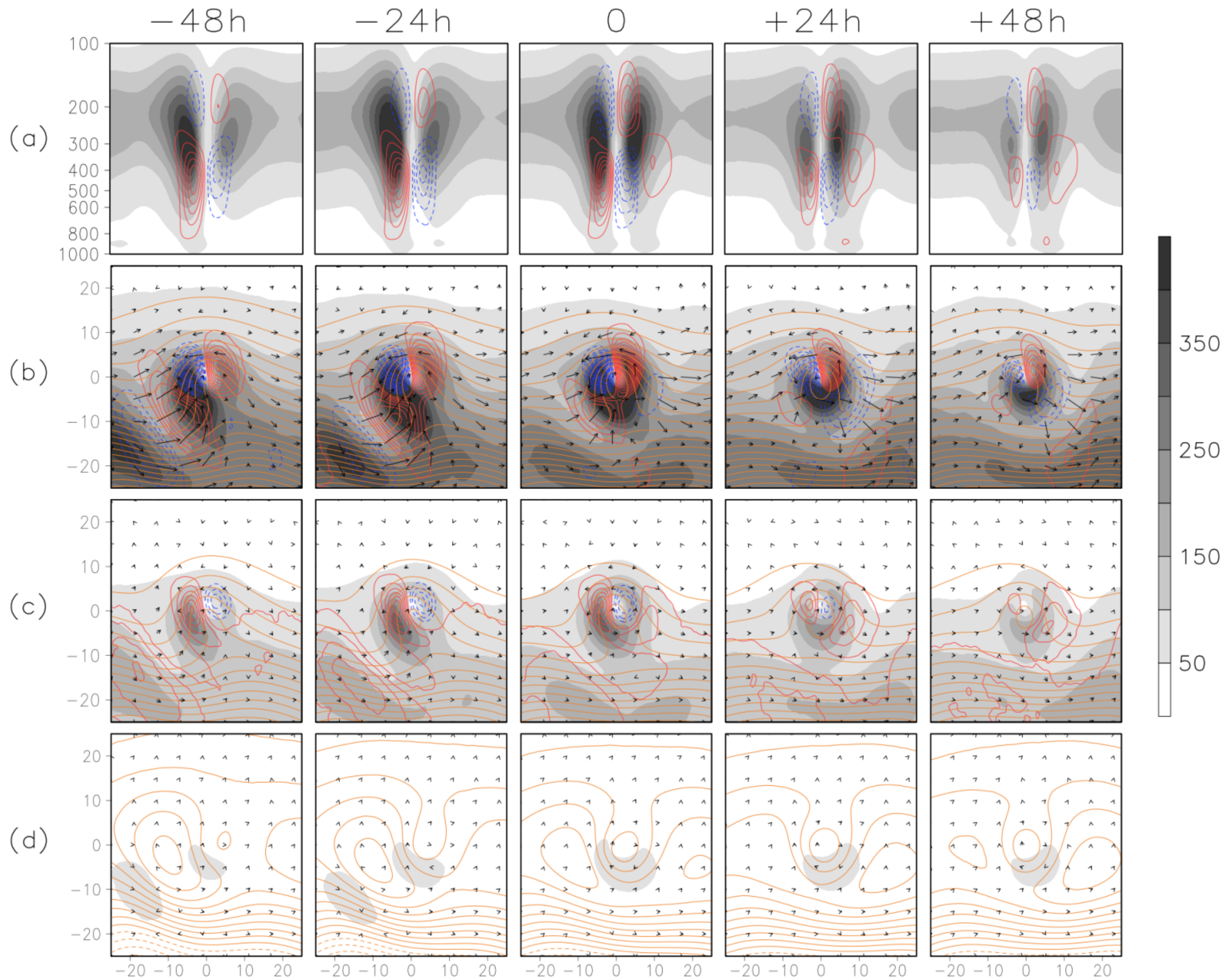

Figure 5: Same as Figure 4 but for deep COLs in the Southern Hemisphere.

While shallow COLs gradually weaken toward the surface, exhibiting an anticyclonic circulation pattern (see Figure 4d), deep COLs show a distinct multi-level interconnected vortex structure. This notable distinction becomes evident from the cut-off to decay stages, particularly when significant positive baroclinic conversion is observed to the east of the deep systems. This is consistent with the findings on strong COLs shown in Pinheiro et al. (2022) and can be attributed to the combined effect of warm ascent air (thermally direct circulation) and mid-tropospheric diabatic heating. Strong upward vertical motion contributes to the increase in EKE, facilitating the coupling between upper- and lower-level depressions. Additionally, diabatic heating generates eddy available potential energy which is converted to EKE through baroclinic conversion, as described in Orlanski and Katzfey (1991). This mechanism represents a fundamental forcing for the

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development of COLs (Cavallo and Hakim 2010). A more detailed discussion on this topic will be provided in the next section.

3.5 Impacts of diabatic processes on residual energy and its influence in the deepening of COLs

Numerous studies have demonstrated the influential role of diabatic processes, such as radiation, latent heating and planetary boundary layer processes, in the development of synoptic-scale systems (Davis and Emanuel 1991, Stoelinga, 1996). As pointed out above and discussed in some detail by Pinheiro et al. (2022), inaccuracies arising from the misrepresentation of diabatic heating in reanalyses can introduce uncertainties into the energetic framework. Therefore, investigating the influences of diabatic processes on residual energy can enhance our understanding of their impact on the deepening mechanisms of COLs.

Figure 6 shows the spatial and temporal distribution of residual energy in composites of shallow and deep COLs. The patterns of residual energy exhibit similarities in shallow and deep COLs, with significantly higher magnitudes observed in deep systems. Negative residual energy dominates throughout the lifecycle of both shallow and deep COLs, as indicated by the red values in Figure 6, representing the integrated volume within a 15-degree radial distance centered on the vortex center.

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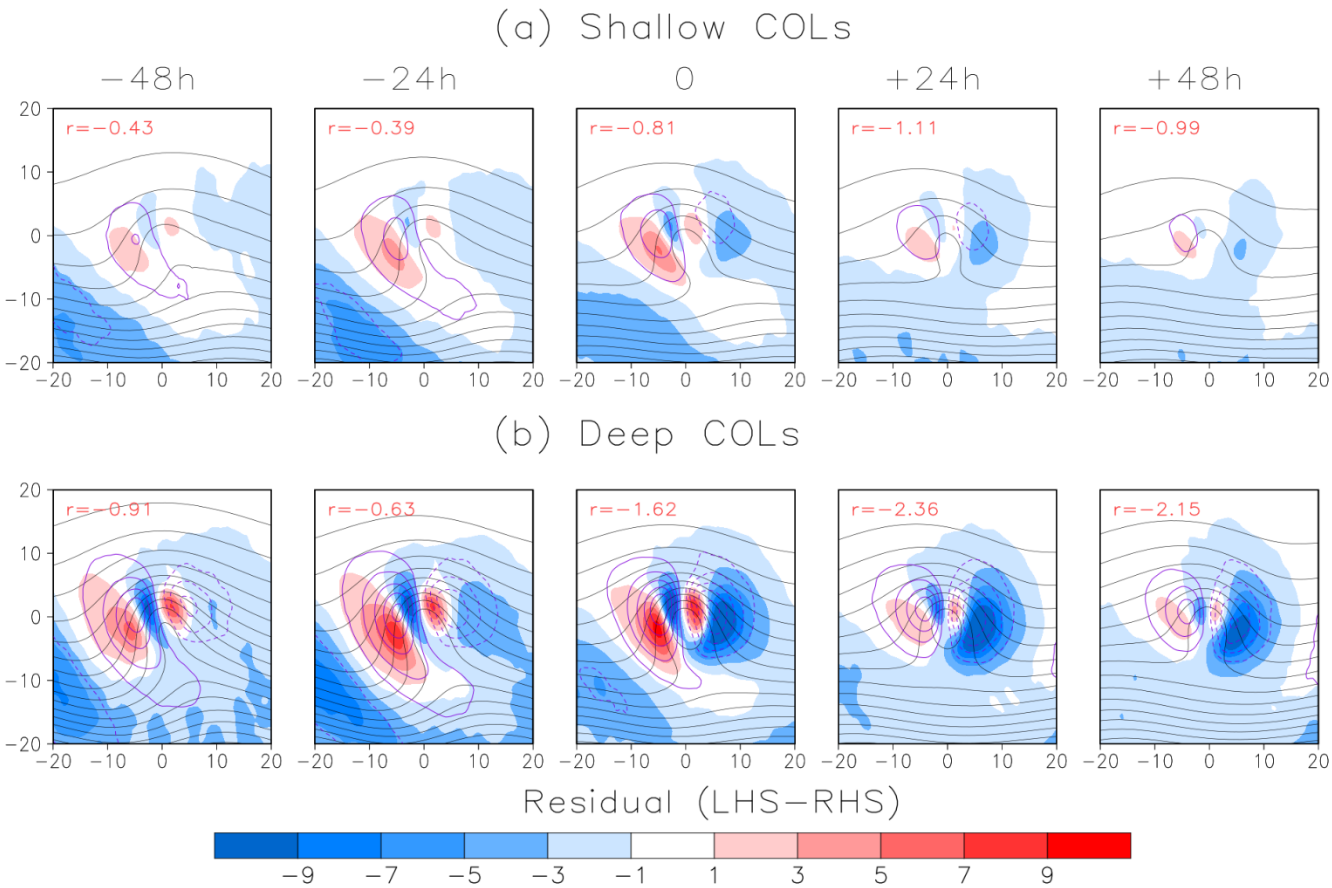

Figure 6: Temporal evolution of the residual energy in Joule (shaded) scale by 10^9, geopotential height (black contour) at 300 hPa for contour intervals 50 gpm, and vertical velocity (purple contour) for contour intervals 0.05 Pa.s^{-1}, where solid (dashed) contours indicate positive (negative) values. Red values represent the residual energy vertically averaged within a 15-degree spherical cap region centered on the COL location.

While negative residual energy prevails, it is worth noting that positive values emerge west of the COLs during the upper-level trough and tear-off stages. Conversely, negative residual energy is observed to the east of the COLs during the cut-off and decay stages. This contrasting pattern is particularly pronounced in deep COLs, consistent with previous findings on strong COLs (see Figure 4 of Pinheiro et al. 2022).

The residual energy suggests the existence of development mechanisms that are either not considered in our approach or inadequately represented in the reanalysis data. A common issue lies in accurately representing diabatic processes, such as radiative cooling and latent heating, which pose challenges for reanalysis. A significant negative residual, particularly pronounced in deep COLs, is observed east of COLs where enhanced ascent and convection can introduce additional energy

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sources and unresolved phenomena contributing to the residual. In contrast, positive residual prevails along the western COL edge, possibly influenced by sinking air that promotes radiative cooling.

Uncertainties in measurement techniques, including inhomogeneous observations, analysis increment, and model parameterizations, are especially important in regions of intense convection. Although diabatic heating does not directly influence the EKE budget as it is not included in the energetic framework, errors in the reanalysis due to the misrepresentation of these processes (see https://confluence.ecmwf.int/display/FUG/Section+4.2+Analysis+Increments) can lead to inconsistencies in the energetic analysis, as discussed by Pinheiro et al. (2022).

4 Discussion and conclusions

In this study, we have investigated the underlying mechanisms driving the deepening of COLs in the Southern Hemisphere, focusing on the regional variations in COL depths. Our analysis has also shed light on the impacts of diabatic processes on residual energy and its influence on the deepening of COLs.

Firstly, the sensitivity analysis of the track matching algorithm revealed that the estimation of COL depth is more responsive to changes in temporal overlap (χ) than the mean separation distance (d_m) between tracks at different pressure levels. By adopting a small χ value, we ensured the capture of the critical time steps during the life cycle of well-defined stacked cyclonic systems. This approach identified 20% of COLs extending all the way to the surface, highlighting interconnected cyclonic features across various pressure levels.

It is worth noting that the proportion of deep depth systems obtained using this approach is significantly lower than what were observed in previous studies (Porcù et al. 2007, Barnes et al. 2021). This disparity can be attributed to differences in methodologies between these studies as using vorticity a larger number of systems are identified so the proportion is relative to a larger sample size. By adopting vorticity as the tracking variable, we avoid arbitrary decision in selecting thresholds for multiple levels, as can occur with geopotential. We believe that employing vorticity provides greater consistency in identifying cyclonic features, resulting in a more reliable assessment of their depths and behavior.

Regional differences in COL depths were then explored across eight genesis maxima regions in the Southern Hemisphere. Remarkably, deep COLs were found to be more frequent in regions E, F (southeast Australia), and H (southwest Atlantic Ocean), with approximately 30% of COLs extending all the way to the surface. These findings are consistent with earlier studies (Lim and Simmonds 2007, Barnes et al. 2021). Baroclinic conversion emerged as a significant mechanism contributing to the deepening of COLs in these regions, as also found in strong COLs (Pinheiro et al. 2022). In contrast, regions such as southeast Africa and the South Indian Ocean were characterized by predominantly shallow and medium-depth systems. One contributing factor could be the intensified jet stream and baroclinicity observed over the South Atlantic and Indian oceans (Nakamura and Shimpo 2004). Notably, region G (southeast Pacific Ocean) showed a sharp decrease in COL extensions below 800 hPa. In this particular region, the development of COLs was observed to be influenced by upper-level ageostrophic fluxes, likely associated with stationary Rossby waves induced by the Andes Cordillera.

We categorized COLs into three groups based on their vertical extent: shallow, medium, and deep. Our analysis demonstrated considerable regional variations in the distribution of COLs across these categories. We particularly noted a latitude-dependent distribution, with deep COLs being more common at higher latitudes and less frequent north of 30°S. An interesting exception was observed in the southeastern Pacific, where deep and strong COLs tend to occur more frequently at lower latitudes compared to other regions.

From an energetics perspective, the comparison between shallow and deep COLs offered valuable insights into their vertical extent and deepening mechanisms. Deep COLs exhibited more vigorous energy growth due to stronger ageostrophic fluxes and enhanced baroclinic conversion. The presence of a more intense mid-latitude jet played a significant role in deepening COLs. These stronger baroclinic processes and ageostrophic fluxes contributed to longer lifetimes and greater interaction between mechanisms operating at different levels within the deep COL systems.

Shallow COLs showed a gradual weakening toward the surface, characterized by an anticyclonic circulation pattern. Conversely, deep COLs exhibited a distinct multi-level interconnected vortex structure. The presence of warm ascent air and mid-tropospheric diabatic heating contributed to the increase in eddy available potential energy that can be converted into eddy kinetic energy, leading to the coupling between upper- and lower-level depressions in deep COLs.

We further examined the impacts of diabatic processes, including radiation and latent heating, on the residual energy and their potential influence in deepening COLs. Negative residual energy dominated throughout the lifecycle of both shallow and deep COLs, with deep COLs exhibiting significantly higher magnitudes. The presence of negative (positive) residual energy to the east (west) of the COLs pointed to the existence of dissipation (intensification) mechanisms not adequately represented in the reanalysis data, particularly related to latent heating (radiative cooling), as discussed in Cavallo and Hakim (2010). Addressing the accurate representation of diabatic processes in reanalyses is essential to maintain consistency in the energetic analysis and emphasizes the need to investigate their influence for the deepening of COLs.

In summary, this paper has significantly advanced our understanding of COL vertical extent in the Southern Hemisphere, providing valuable insights into their sensitivity, regional variations, and energetics. Future research can build on these findings to improve weather predictions and better prepare for the impacts of COLs on regional and global weather patterns.

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Appendix

See Table A.1.

Table A.1 Sensitivity of the number of ξ_{300} COLs to time overlap for each pressure level (hPa), expressed as a percentage of the total number. The overlap thresholds are 1%, 5%, 10%, 25%, 50%, 75%, and 100%.

	1%	5%	10%	25%	50%	75%	100%
300	100.0	100.0	100.0	100.0	100.0	100.0	100.0
400	80.9	80.9	80.9	80.8	79.2	66.0	11.2
500	65.5	65.5	65.5	65.1	61.9	42.9	2.2
600	51.1	51.0	50.9	50.3	45.7	25.8	0.5
700	37.7	37.7	37.5	36.9	31.6	14.9	0.2
800	28.8	28.8	28.6	28.0	23.0	9.7	0.1
900	23.1	23.0	22.9	22.3	18.1	6.9	0.0
1000	20.3	20.2	20.1	19.5	15.4	5.6	0.0

Code/data availability

The code used in this study is available upon request from the corresponding author for researchers interested in reproducing or extending the findings presented in the paper. The ERA-Interim reanalysis data was sourced from the ECMWF server. Please contact corresponding author's email for access to the code.

Author Contributions

Henri Pinheiro: Conceptualization, investigation, data curation, methodology, writing – original draft, visualization.

Kevin Hodges: Software development, writing - review and editing.

Manoel Gan: Writing - review and editing.

Competing interests

The authors declare no competing interests in relation to the research, authorship, or publication of this paper.