Authors' response to reviewers' comments

Manuscript Number: egusphere-2023-1996

Deepening mechanisms of cut-off lows in the Southern Hemisphere and the role of jet streams: insights from eddy kinetic energy analysis

Thank you once again for the valuable feedback from the anonymous reviewer. We have incorporated these suggestions into the revised manuscript to enhance the clarity and robustness of our study. In this document, the responses to reviewer's comments are highlighted in red font.

Reviewer 1

General comments:

This study considers the depth of COLs in the southern hemisphere and, by using an energetics perspective, aims to understand the processes at play. The authors have made some progress since the first iteration of the manuscript. The authors tend to simply display the resulting calculations and, in my view, there is still a lack of explanation and detail as to how the processes unfold and why which would increase the impact of their work. As the aim of this work is to understand these processes, I think the authors should try to expand their analysis to highlight the processes at play.

We have tried to address this general comment by including more discussion and interpretation of the results.

Major comments:

1. There seems to be a lack of dynamical explanations given to explain the observations highlighted by the calculations done. For example, there is an increase in deep COLs with a strengthening in the polar front jet. Can you explain this using the energetics framework used in this work? There is a hypothesis that eddy feedbacks between the surface and the upper-levels. What does this do and how is related to the development of a deep COL versus a shallow COL from an energetics perspective? More detail needs to be added into the discussion and interpretation of the results, particularly associated to how COLs deepen (or not) in the energetics framework chosen, since this is the focus of this work.

Thank you for your valuable comment.

Although our findings show a clear relationship between the strengthening polar front jet and the increase in deep COLs, it is difficult to explain this link within the framework of eddy kinetic energy analysis. However, our analysis on energetics shows that deep COLs are positioned near the equatorward exit of a jet, which seems to facilitate the transfer of eddy kinetic energy from the upstream poleward jet into the COL. This feature is evident in the spatial distribution maps (Fig. 3) as well as in our deep COL composites (Fig. 6). We propose that the intensification of the polar front jet amplifies the convergence of ageostrophic fluxes and enhances baroclinic conversion. This, in turn, leads to heightened vertical motions and consequently the COL deepen into the lower troposphere. This characteristic is particularly pronounced in deep COLs, setting them apart distinctly from their shallow counterparts. We have explored these points, incorporating additional remarks in the results (Section 3.5) and conclusions.

In addressing the aspect concerning the eddy feedback mechanism between surface and upper levels, we recognize that our current energetic framework may not offer a comprehensive understanding of this interaction. However, we propose exploring avenues to examine deeper into the dynamics of these feedbacks in the future. One could involve investigating the role of vertical ageostrophic fluxes, which likely play a role in the deepening processes within COLs. We also highlighted the importance of diabatic processes for the interaction between mechanisms operating at different levels within deep COL systems and the need for their accurate representation in reanalysis data.

2. There seems to be a link between depth and intensity of COLs (ie. Deep COLs are generally strong). Yet, the authors state that jets affect depth and intensity of COLs differently (eg. L245). Are the four categories defined in this work interdependent? If so, should they be looked at separately and how why do the different jets impact deepening and intensity differently?

Yes, it is possible to examine the four categories individually, and we indeed have conducted distinct analysis for each category. However, we made a choice not to present separate analyses for each category, particularly due to limitations in space and the study's objective on elucidating the deepening mechanisms of COLs. This aim is clearly stated in the main objectives of the study and reinforced in the last paragraph of Section 3.2.

In an additional analysis, we performed a comparison involving the four categories by matching the tracks referred to each category. For example, by matching the strong COLs (50th percentile of strongest systems) against the deep COLs (those that extend to 800 hPa or lower), we found 81% of matched tracks, suggesting a significant correlation between the two categories. However, 19% of deep COLs fall into the category of weak COLs, indicating a level of variance within this classification. Similarly, we found 71% of matches between weak and shallow COLs. Therefore, despite strong and deep COLs (as well as weak and shallow COLs) present similar characteristics, these two categories do not exhibit identical systems due to differences in their classifications and the complex dynamics associated with COLs and their deepening mechanisms. A discussion on these statistics have been included in Section 3.2 and Conclusions.

Another aspect concerning the influence of jets on the depth and intensity of COLs can be seen in the updated Figure 4 which now includes scatter plots showing the relationship between COL intensity and jet intensity. A positive correlation is observed between the intensity of both shallow and deep COLs and the subtropical jet, indicating that the subtropical jet likely contributes to the system intensity. While it is unclear why intensified COLs are associated with strengthened subtropical jet, we propose some potential mechanisms which one involves the induction of cyclonic vorticity on the poleward side of the jet, given in the supplementary Figure S2. This hypothesis is supported by the presence of a small-scale jet stream observed equatorward of COLs, as noted by Ndarana et al. (2021), which plays a role in both the formation and intensification of COLs. Additionally, factors such as temperature gradients and wind shear along the edge of the subtropical jet may contribute to the intensity of COLs. Nevertheless, further investigations are needed to fully understand these relationships.

Ndarana, T., Rammopo, T. S., Chikoore, H., Barnes, M. A., & Bopape, M. J. (2020). A quasi-geostrophic diagnosis of the zonal flow associated with cut-off lows over South Africa and surrounding oceans. Climate Dynamics, 55, 2631-2644.

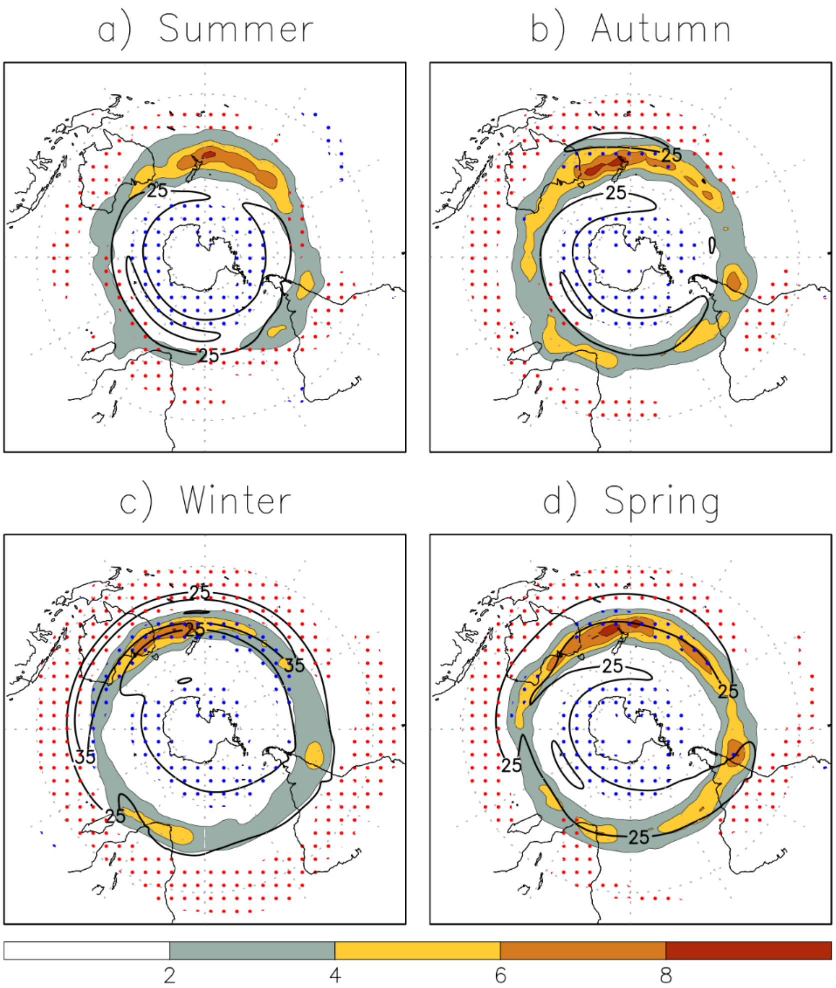

Figure S2: Zonal mean wind (black contour), relative vorticity (dots), and track density for deep COLs in the Southern Hemisphere for a) Summer (DJF), b) Autumn (MAM), c) Winter (JJA) and d) Spring (SON). Unit is as in Fig. 1 for track density. Zonal winds above 25 $m.s^{-1}$ are plotted for 10 $m.s^{-1}$ contour intervals. Blue (red) dots indicate values negative (positive) below (above) 1.0×10^{-5} s^{-1}, respectively. All fields are represented at the 300-hPa level.

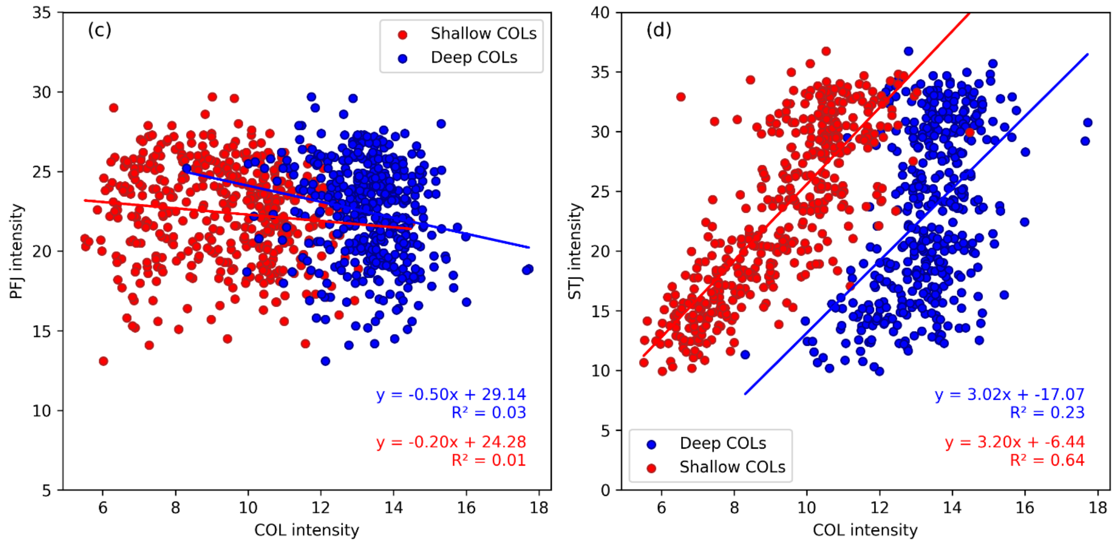

Figure 4 (main manuscript): Scatter plots indicating the relationships between monthly mean COL intensity and jet intensity for (c) polar front jet and (d) subtropical jet.

Specific comments:

• L98: “if mean separation” – missing “the”?

It has been changed

• L110: what are the reasons for the choice of extension level (400hPa for shallow; 800hPa for deep).

The chosen pressure levels (400 hPa for shallow and 800 hPa or lower for deep COLs) effectively capture the contrasting vertical extents of COLs. Shallow COLs are typically situated in the upper troposphere, making 400 hPa suitable for their characterization. Conversely, deeper structures of COLs are better represented by 800 hPa or lower. Notably, each of the three categories (deep, medium, and shallow) accounts for approximately 30% of the total COLs, ensuring a balanced representation across different types in our analysis. We have commented how the vertical depths were chosen in Section 2.3.

• L112-113: where is the track is intensity metric calculated? Is it the most intense value in the track? Or mean? Be specific.

This is calculated based on the maximum intensity observed along each track using the minimum 300-hPa relative vorticity in the Southern Hemisphere. We have added this information for better understanding.

• L127-128: Do you just mean monthly means? The sentence is hard to understand.

Yes, we are essentially referring to monthly means. We calculate the average values for each month separately, considering the varying number of days (28-31) in each month, based on the 6-hourly data, and this is done individually for each month and year. We hope this clears up any confusion.

• L132: “jet streams exhibit relatively small seasonal variations” – is this true of the subtropical jet in the southern hemisphere? The subtropical jet is barely visible in the mean in summer for example (ie. Fig 3).

Indeed, we are specifically referring to the fact that the subtropical jet in the Southern Hemisphere typically exhibits relatively small variations in its position rather than its intensity. We have now revised the sentence to make this point clearer.

• L145: Missing "."?

It has been corrected.

• L162: Do you mean Section 2.3?

Yes, it has been changed. Thank you.

• L166: Deep and strong COLs show similar frequencies and distributions – it may be useful to provide some statistics of the various combinations. Are most strong COLs also deep?

Indeed a good point and somewhat related to the second major comment from the reviewer. To address this, we have appended a paragraph outlining the match percentages between deep and strong COLs, as well as between shallow and weak COLs (please see Section 3.2).

• L184-185: RWB occurs in regions of weak climatological zonal flow and RWB is also associated with the development of COLs. The authors further state in L193-194) that COLs occur in regions of weakened westelies. However, in the authors results the find that deep COLs occur most frequently during polar jet stream increases during transitions seasons and mention that this is consistent with previous RWB work. Could you clarify this alignment and elaborate?

Thank you for your insightful comment. The apparent contraction can be clarified by recognizing the differential impacts of subtropical and polar front jets on COLs, a point that may not have been clearly expressed in the previous version of the manuscript but has been addressed in the revised edition following our modifications.

While RWB and COLs typically occur in regions of weakened zonal flow, our findings suggest that the mechanisms conducive to COL deepening are more likely when a strong polar front jet exists upstream of a COL. This observation is discussed in response to the first major comment and also throughout the paper. Specifically, the presence of a strong polar front jet intensifies ageostrophic fluxes, facilitating the transport of EKE northeastward from the poleward jet to the COL.

Our research suggests that the polar front jet plays a role in creating favorable conditions for COL deepening, while the subtropical jet emerges as a significant mechanism for their intensification. We have updated Figure 4 in the paper to incorporate and discuss the relationship between jet intensity and COL intensity, aiming to provide a clearer understanding of these interactions.

• L213 and L218: "anticyclonic vorticity" – do you mean anticyclonic barotropic shear?

Previous studies have demonstrated that the majority of COLs develop from anticyclonic barotropic shear type, however our emphasis here lies on emphasizing the influence of an intense subtropical jet which generate anticyclonic vorticity anomalies over its equatorward side and cyclonic vorticity anomalies poleward, as demonstrated in Fig. 2 of supplementary material.

• L285: "poleward jet shifs to the east" – I do not really see this occurring in your figures. Could you be more specific? Maybe plogng the jets on some of these timelags may help.

Figure S3 presents the same variables as those depicted in Figure 5 of the main manuscript, with the addition of the 300-hPa zonal wind mean (indicated by the green line). This shows that the decay of the COL coincides with the poleward jet shifting eastward, thereby discontinuing the supply of energy to the system. We have included this figure as supplementary material and appropriately referenced it in the main manuscript.

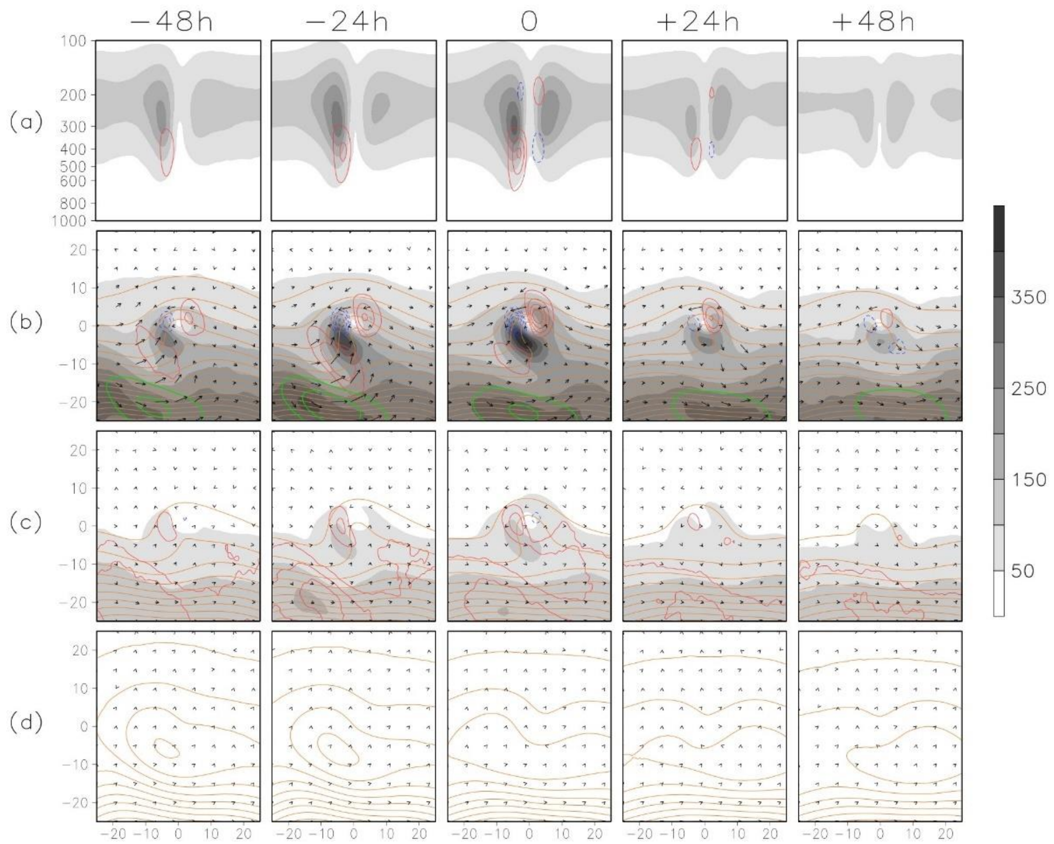

Figure S3: Temporal evolution of shallow COLs in the Southern Hemisphere relative to the time and space of maximum intensity in ξ_{300}. The panels depict: (a) vertical cross-sections of total EKE (shaded) with baroclinic conversion (contour); (b) vertically integrated ageostrophic flux convergence (blue and red contours) with EKE (shaded), geopotential height (orange line), zonal wind mean (green 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 hPa, while total EKE is indicated by 10^9 Joule.

• L290: How do we see momentum transfer from the jet into the COL from your results?

In atmospheric motions, the transfer of energy is closely linked to the redistribution of mass and momentum. In the revised version, we have removed the sentence we cited the term “momentum”.

• L293: “stationary nature of Rossby waves” – surely we are talking about transient Rossby waves here and not stationary waves?

We appreciate your consideration on this point. While it is true that transient Rossby waves play a significant role in atmospheric dynamics, particularly in driving weather systems, there is also substantial evidence supporting the importance of stationary Rossby waves for the development of COLs. It is important to acknowledge that while some COLs can travel large distances within a westerly wave, many exhibit shorter trajectories, eventually remaining stationary or moving westward. This behavior can be related to quasi-stationary waves which effectively act as blocking mechanisms, influencing the movement and persistence of these weather systems.

In response to the reviewer’s suggestion, we have opted to replace the previously cited sentence concerning the “linked to stationary nature of…” with a more detailed discussion of the differences between shallow and deep COLs in terms of energetics.

• Section 3.5: The residual is presumed here to be mostly connected with diabatic processes. This is of course a reasonable assumption. However, is it possible that some of the residual is generated by frictional processes associated with deep COLs? Do the residuals on different surfaces reveal anything here?

We agree with reviewer. Indeed, one factor that may contribute to the residual is the unknown contribution from the friction, which is difficult to assess because this is not computed directly. It is possible that stronger systems have a larger residual contribution from frictional effects. We have added a note to address this consideration.