We thank both reviewers for their thoughtful comments on this manuscript. Our responses to the reviewer's comments are given below in bold, with the changes we will make in the edited manuscript given in italics.

Response to Reviewer 1

In this study the authors investigate the decrease in the accumulated rainfall in southeast Australia that is not a result of change in the frequency or intensity of the cold fronts. They analyze the properties of fronts in two twenty year periods and show that the change is due to a shift in the location of the maximum westerlies which can be a result of wind anomalies and changes in zonal wave 3.

I find that the presented results are interesting and offer a new explanation to the phenomena. Yet parts of the analysis need to be further explained in order to better convince the reader on the validity of the results. The changes, first in the total rain and then in the location of the winds, are all very small and a better job needs to be done to explain the importance of these small changes. There are many places in the text where the authors refer to non-significant increase/decrease seen in the figures, this can give the wrong impression and understanding of the results you do have.

The paper is well in the scope of WCD, however, I feel that some rewriting of the results in the text is required as well as addressing the questions below.

Thank you for your detailed comments.

While we agree that many of the changes shown are small, they can nevertheless have substantial downstream impacts – for instance, a relatively small ~11% decline in total annual rainfall during the Millennium Drought has previously been shown to result in a 46% decline in streamflow with significant socioeconomical impacts (e.g. https://doi.org/10.1002/wrcr.20123). Reduced streamflow has been associated with a change in the rainfall-runoff relationship, which unpublished work suggests may be partly a result in changes in the proportion of rainfall from different weather systems, especially fronts as they are particularly important for light and moderate rainfall during the cool half of the year.

We will add more discussion of this to the paper, to better explain why the small changes we discuss are nevertheless important.

The figures need to be improved, especially the median red line in most of the figures is not seen at all. In figure 2 (line 219), for example, there are markers for the statistically significant latitudes but the line itself shows no difference.

Thank you for this observation – we had some difficulties in PDF conversion and should have more thoroughly checked the figures. We have made the shading lighter and the lines thicker, so it is easier to see the median line. An example is below, but the full vector figures will be provided to the publication team with the revised manuscript.

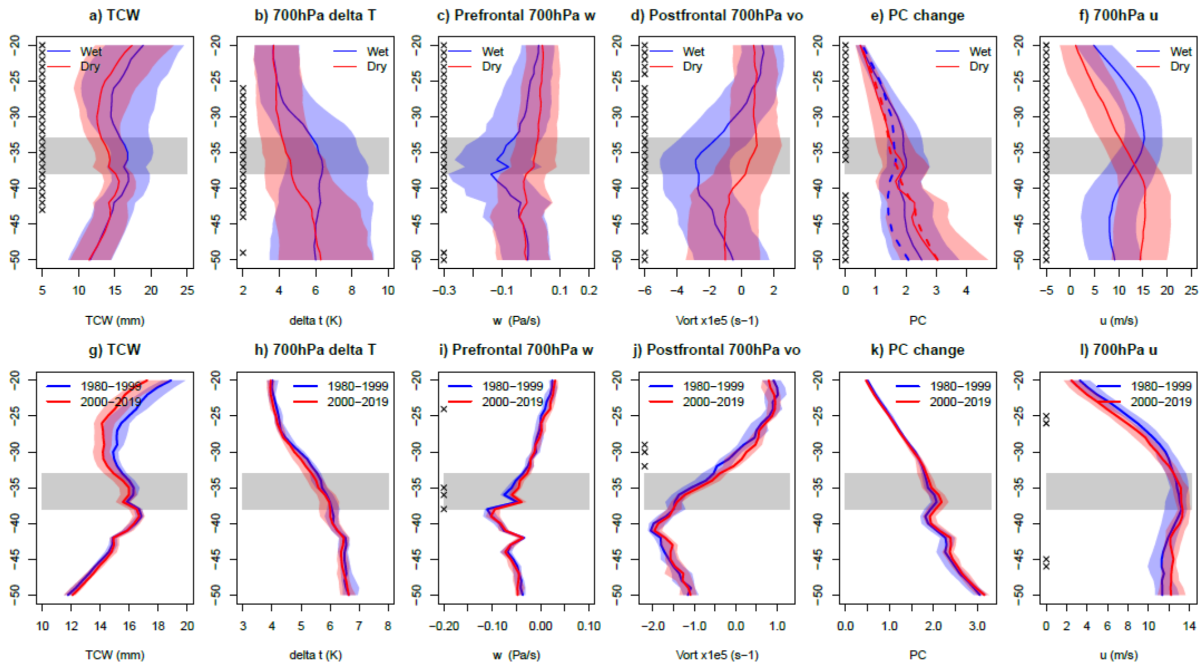

Figure R1. A clearer version of Figure 2

Line 100: First, the sentence is not very clear. Is it comparable to panel 1d and its caption? Second, what is the reason to extend the front all the way to 20S? in the example in fig. 1 you extend the points to latitudes that there were no fronts detected in the first place. If you extend all the fronts in this way, does this extension that you are adding not affecting the results that you find regarding the shift in the latitude of maximum westerlies? How do you determine how far north to extend the front?

You are correct – we want to create composites relative to the front for the region 20-50S as a way of understanding the circulation both north and south of our domain of interest. The extension was only made to have a reference longitude for building composites for further analysis. In many cases, there is no front identified by the tracking scheme at these latitudes, but circulation at these latitudes may still be connected with the front and influence its rainfall – for instance, in many cases a trough or a "northwest cloudband" may extend from the northern edge into the tropics, increasing the moisture and rainfall in the front region. We will explain this in more detail, including referencing work on the interactions between fronts, troughs, cloudbands and atmospheric rivers for generating rain in this region (e.g. https://doi.org/10.1175/JCLI-D-21-0606.1, https://doi.org/10.1175/JCLI-D-16-0686.1)

We will also rephrase the point to better match the caption:

"Outside of the latitudes with an identified front, we infer an extended "front" longitude based on the last recorded front point, so that composites can be calculated over the full 20-50S region"

Line 159-160: Fig.2 shows the total front rain, where the difference is not significant (according to the markings) and in the text you discuss the rain rate. I find this change in the accumulated rain very small, how does it compare to the differences in accumulated rain found in the other studies mentioned in the introduction?

The total front rain averaged across the region is mentioned in the next sentence ("a 32mm (9.4%) decline in total frontal rainfall in these latitudes between the two periods"); this change is not statistically significant (p=0.14), although it is comparable to other studies on declines in southeast

Australian frontal rainfall (e.g., a 35mm decline in https://doi.org/10.1002/joc.3597) and changes in total rainfall during the millennium drought (e.g., https://rmets.onlinelibrary.wiley.com/doi/abs/10.1002/joc.1627)

We will add to this section more discussion of the three time periods, as there is a statistically significant decline in total frontal rainfall between 1979-1996 and 1997-2009 (-14%, p=0.03), but a partial recovery in 2010-2019 (9% below the 1979-1996 average). We will also add an additional supplementary figure showing the three periods.

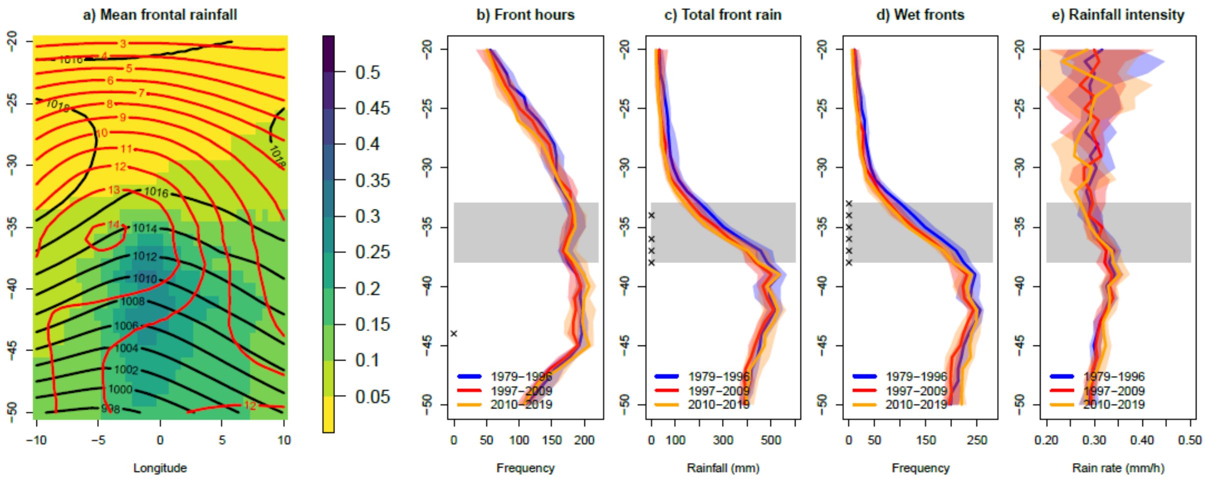

Figure R2. As in Figure 2, but for three periods (1979-1996, 1997-2009 and 2010-2019), with crosses showing statistically significant changes between the first two periods.

Line 220: The markings in figure 3 look between 28-33S, which one is correct?

Thank you for checking this. Figure 3j does show that changes are stronger over the latitudes 28-33S; however, the text refers to changes in the latitudes 33-38S as those latitudes are more closely linked to frontal rainfall (see Figure 3d). To clarify this, we will change the text to say:

" There is also a statistically significant weakening of post-frontal relative vorticity over 33-38°S (-11%), with larger changes in vorticity over 28-32°S"

Line 222: "While these changes are generally weak, and not necessarily aligned with the latitudes most relevant to our region of interest, together they are suggestive of an overall weakening of frontal baroclinicity" – this conclusion needs to be better explained.

Thanks for this comment. We will replace "overall weakening of frontal baroclinicity" with "weakening of uplift in the frontal area" demonstrated by weaking of pre-frontal vertical velocity, weak decrease in baroclinicity (to the south of our region of interest) and less subsidence behind the front, all of which is discussed in lines 216-222.

Technical comments –

Line 46-47: this sentence is unclear and was hard to follow.

We will rephrase this sentence to improve clarity:

"The Millennium drought ended in 2009, and was followed by heavy rain during the subsequent La Niña years 2010-2011. However, while average annual rainfall over the 2010-2018 period was close to the long-term average (Fu et al. 2021), this recovery is predominantly associated with increased rainfall during the warm season, when a lower proportion of rainfall is converted into

streamflow. In contrast, rainfall during the hydrologically important cool months of the year remained below the long-term average during the post-drought period 2010-2019 (Bureau of Meteorology and CSIRO, 2020; DELWP, 2020). "

Line 69: “two points” would be 2 degrees? If the grid is 1 degree as stated in the next line

We track fronts on a 1 degree grid and require that fronts are at least 2 grid points long. We will make this simpler in the text by saying "we track fronts using 1 degree data and require that fronts are at least 2-grid point long and have at least 1 point in southeast Australia (30-40°S, 135-150°E)

Line 179: who has a more negative vertical velocity?

Good catch; this sentence should say "Wet fronts have …"

Line 179: There is only one level presented, is this a result you found? If not please add reference.

We performed our analysis over a range of levels, but only showed a single level in the figure as other levels are broadly similar. We will add more information on the levels assessed to the methods at line ~77

Line 191: should be figure 3f

Thanks, we'll fix this

Line 219: maybe latitudes? And there is no (i) in fig. 2, please specify that it is in fig.3

Thanks, we'll fix this

Line 331: STRI, STRP are not defined. So are some of the other indexes that appear in the following lines. IOD is defined only on line 356 but used before.

We will add acronym definitions to L123-129 where we discuss the indices

Table 1 title: Pearson’s correlations

Thanks, we'll fix this

Line 367: missing reference?

We will make it clearer that this is analysis we performed: "Similarly, while there was a -0.4°/decade linear trend in the average northernmost latitude with U700>=10m/s (p=0.01), removing variability associated with STRI decreased this trend to -0.2°/decade (p=0.06)."

Figure A2: it is like figure 5, not 4

Thanks, we'll fix that

Overview:

This study investigates the possible causes behind the decline in frontal rainfall in southeast Australia (SEA). It builds on previous regional studies that have highlighted that there is little evidence to suggest that frequency of fronts have not changed, yet there has still been a decline in rainfall. Using a wind-based front detection method, the authors investigate what frontal characteristics could be behind the decline in rainfall within SEA. The key result being that decline in rainfall in SEA is linked to a weakening and southward shift in the northern edge of the front. Although there are numerous complex factors that impact the northern extent of the fronts, the intensity and position of the subtropical ridge appears to play a key role.

Overall, the study contains interesting scientific results, has appeal to a wide audience and is well presented. Thus, it should be considered for publication after some revision.

Thank you for your helpful comments

Major Comments:

Perhaps one of the key findings here is that there is evidence that the northernmost latitude at which fronts extend into the region has shifted polewards (i.e. weaker zonal winds). However, it is not clear as to how this results in less rainfall. It is suggested that it could be measure of frontal intensity, but perhaps just some more discussion as to the why or how is needed. Could it be less moisture transported into the region or perhaps less moisture already in the region before the front passes through?

We will add additional discussion of possible mechanisms to the discussion, although it will be difficult to test without doing modelling experiments. One perspective is that the northern edge of frontal westerlies could be considered as the "true" northern edge of the front, in which case it is simply that the fronts and their associated rainfall are moving south, but this southward shift is not detectable yet in fronts objectively identified based on the surface wind change.

Since the major inputs to IVT calculation are winds and moisture, IVT doesn't have any better skill at explaining the rainfall declines when used in a linear regression than using our metrics of subtropical zonal winds. But we will add additional discussion of the potential role of the weakened subtropical winds in decreasing moisture transport into the frontal region in the discussion.

We initially tested the role of moisture transport (IVT) by looking at it in the local region 33-38S, where it is strongly correlated with rain, but local IVT had little change over the period (average of 203.9 in 1980-1999 vs 201.8 in 2000-2019).

In contrast, there has been a decrease in IVT to the north, which can in large part be explained by the weakening of winds to the north. While backtracking trajectories (e.g., Holgate 2022) generally suggest moisture for fronts in this region is sourced from the ocean to the southeast, some moisture is still advected from the ocean to the north-east, so weakening winds to the north of the region could reflect an overall decrease in moisture flux into the region.

There is a correlation of 0.63 between frontal rain and IVT in the region 28-33S, with IVT in this region decreasing from 161.5 in 1980-1999 to 152.2 in 2000-2019 ($p<0.001$). This is mostly due to a decrease in the zonal component of IVT, although there is also a slight decrease in the southward transport of moisture (Figure R3).

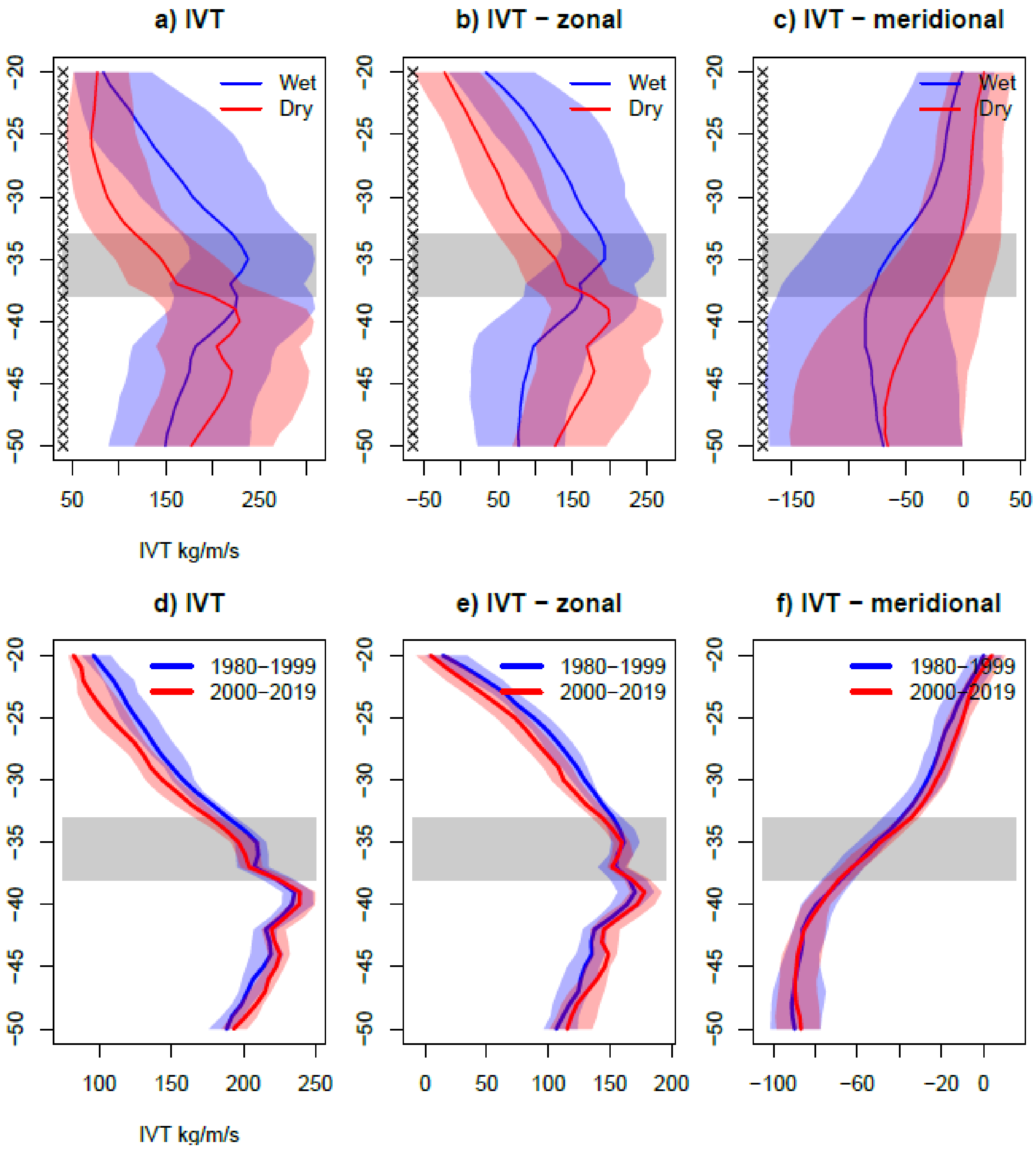

Figure R3 – As in Figure 3, but for IVT (left) and its zonal (b) and meridional (c) components on wet vs dry fronts (left) and 1980-1999 vs 2000-2019 (right)

Minor Comments:

A domain map early on in the manuscript would help the reader understand the domain of the study. This could be used to showcase the domains described in lines 70-71. A satellite image of day used to describe the front detection method could be an example of a domain map.

Thanks, this is a good suggestion! While satellite data is a good idea, we thought it would be more useful for the domain map to show an example of key fields from ERA5 on a given day – MSLP, rain, and the location of identified fronts. We will add the figure below to the manuscript.

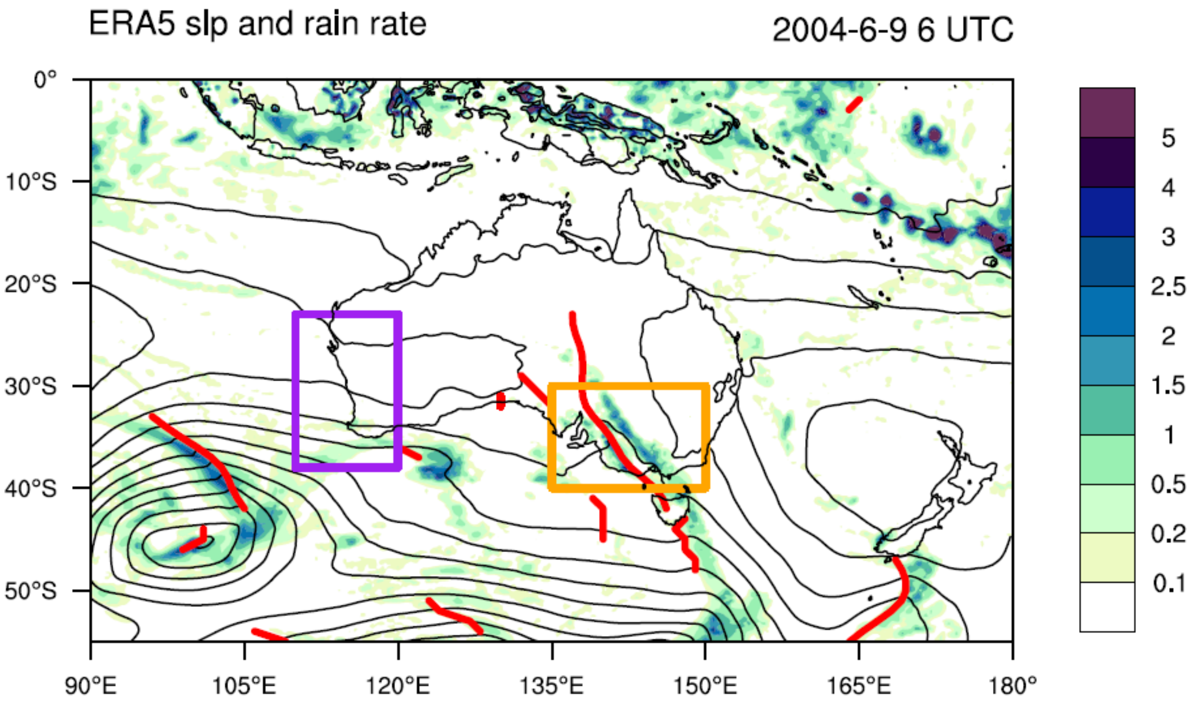

Figure R4. ERA5 rain rate (shading, mm/h), MSLP (contours) and all identified cold fronts (red lines) for 600UTC on 9 June 2004. The SEA (orange) and SWWA (purple) regions used for front identification are also marked.

Consistency between the use of 'Southern Hemisphere' (e.g. line 7 and line 24) and 'southern hemisphere' (e.g. line 18 and 21) throughout the manuscript.

Thanks, we'll change all mentions to lower case

Line 84 – Is there any evaluation on ERA5 precipitation data with that of stations in the region? Not necessary for this study, just out of general interest for the reader in terms of decline seen in ERA5 compared to that in the observations.

This is a good question, and we will add some additional discussion of this to the methods section.

Global evaluation of ERA5 suggests generally small errors over southern Australia (https://rmets.onlinelibrary.wiley.com/doi/full/10.1002/qj.4351), while some studies with the older ERA-Interim reanalysis over the southern ocean suggests that biases are generally low for frontal rainrate and moderate rainfall intensities, but with a tendency to overestimate pre-frontal rainfall and underestimate non-frontal rainfall (https://doi.org/10.1029/2018JD028700). The declines in frontal rainfall over the period in this paper from ERA5 are broadly consistent with declines found using both station (https://doi.org/10.1002/joc.3597) and gridded (https://doi.org/10.1007/s00382-020-05588-6) datasets, giving some confidence in results.

Line 92-100 – Consider linking each bullet point to the associated figure panel in Fig. 1.

Good idea, we'll do that.

Line 100 – Could you explain Point 4 in more detail. It is not clear as to why this has been done.

We want to create composites for the region 20-50S as a way of understanding the circulation both north and south of our domain of interest at the time when a front is found in our region of interest. In many cases, there is no front identified by the tracking scheme to the north or south of our region, but circulation at these latitudes may still influence frontal rainfall – for instance, in many cases a trough or a "northwest cloudband" may extend from the northern edge of the front into the tropics, increasing the moisture advection to and rainfall in the front region. We will explain this in more detail, including referencing work on the interactions between fronts, troughs, cloudbands and atmospheric rivers for generating rain in this region (e.g. https://doi.org/10.1175/JCLI-D-21-0606.1, https://doi.org/10.1175/JCLI-D-16-0686.1)

Line 149 – Colorbar needs a label and units

Units are in mm/h, which is listed in the caption

Line 160 – 32mm per season?

We will correct this to "32mm (9.4%) decline in the average frontal rainfall per season"

Line 171 – Typo - 'South African'

Thanks, we'll fix that

Line 186/187 – I can understand why this is done, but perhaps for consistency in the Phillips Criterion acronym (PC) can just be used as it has already been used earlier.

Ok, we'll change to PC

Line 190 – does this infer that wet fronts move more slowly through the region compared to dry fronts?

This is an interesting question, which is difficult to assess as individual fronts are not tracked between time steps.

One thing we tried is looking at the number of consecutive time steps with a front identified in the region, although this does not distinguish between cases of a single slow-moving front or multiple consecutive fast-moving fronts. We found that front "events" of less than 24 hours had lower average rain rates than longer events (0.09 mm/h vs 0.16 mm/h), but there was no change between 1980-1999 and 2000-2019 in the average duration of front conditions (20h vs 19.4h) or in the number of front "events" of 24 hours or more (35.45 vs 35.10)

Line 201 – Should the label for the blue in Fig 3. a-f not be "wet" instead of Rain>=0.1mm/hr? That would just keep it consistent with the text. You could also consider splitting Fig. 3 into two separate figures.

We prefer to keep Figure 3 as a single figure as it makes it easier to compare whether the latitudes relevant to frontal rain and the latitudes with significant changes align. But we have increased the font size slightly and changed the legend to say wet, see figure R1 in our response to Reviewer 1

Line 201 – Could the font not be made larger in Fig. 3? The mean lines are also difficult to read in the figure.

We have made the shading lighter and the lines larger in figure 3 for ease of comparison, see figure R1 in our response to Reviewer 1

Line 251 – Similar to an earlier comment. Can one infer that the speed at which a front passes through a domain has a direct effect on the volume of rainfall produced?

This is discussed briefly in response to your previous comment – while this seems intuitively reasonable it is difficult to assess using our datasets

Line 276 – are the results for this section any different if the winter is broken down into an early vs late winter?

This is a good question. Monthly data has larger variability, which means changes in individual months or shorter periods are generally not statistically significant, which is why we focused on the extended period in the paper.

When comparing 1979-1996 and 1997-2009 (Figure R5a), there are clear declines in frontal rainfall for all months April-October. However, in the period 2010-2019 frontal rainfall in the early season April-June has mostly recovered, but July-October has not.

Looking at days with strong frontal westerlies in the subtropics (Figure R5b), these are generally only seen for fronts during the cool months, and have declined in frequency for all months (except May)

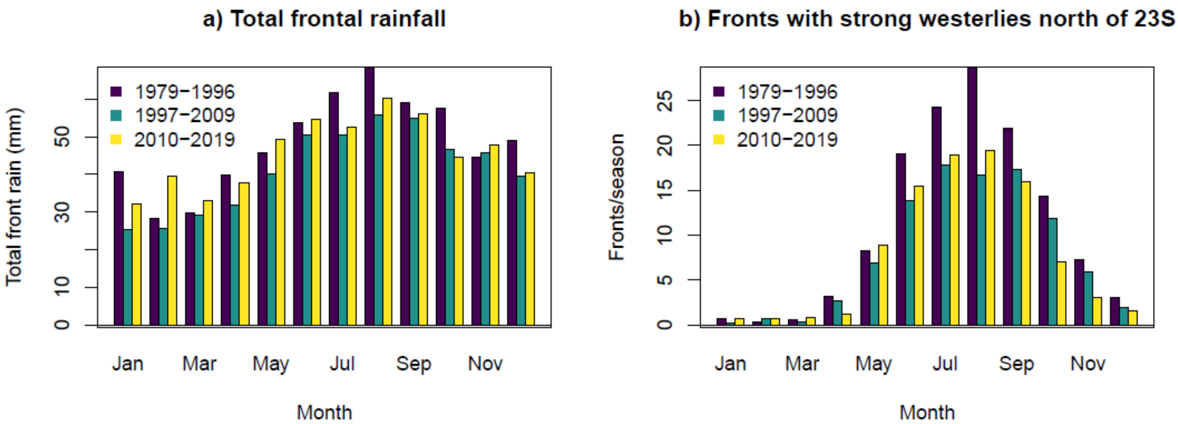

Figure R5. a) Total accumulated frontal rainfall by month for the three periods of interest. B) Number of front days per month where U700>=10 m/s is recorded at least as far north as 23°S.

Line 285 – Consider re-ordering the panels in Figure 5.

Thanks, good idea. We will reorder the panels in the final manuscript to place the mean rainfall first (a), as it is the first panel discussed in the text.

Line 325 – Is there any intraseasonal variation with the relationship between the different drivers and frontal frequency / rainfall? For example, does the IOD have a stronger relationship with frontal rainfall during the late winter months compared to the early winter months?

This is another good question. While DMI and STR are significantly correlated with the frontal rainfall and the latitude of the frontal westerlies in both May-July and August-October, the DMI link strengthens considerably in the second part of the season as this is when the DMI gets stronger. We will add text to that effect in the text around line 350, e.g. *"Given that the IOD is most active in spring, the associated between IOD and Australian rainfall is strongest around the springtime (e.g., Cai et al. 2011). The correlation between the DMI and total frontal rainfall also strengthens from -0.39 during May-July to -0.65 during August-October. In both seasons negative IOD is associated with an increased frequency of wet fronts and a northward shift in latitudes with frontal westerlies, but no significant change in the total number of fronts"*

Table R1. As in Table 1, but for May-July and August-October separately. Bold indicates significance for $p<0.05$.

Variable	STRI	STRP	SOI	NINO3.4	DMI	SAM	NINO3.4 - DMI	DMI - NINO3.4
Front days MJJ	-0.13	**-0.42**	0.04	0.02	0.09	0.01	-0.02	0.10
Total front rainfall MJJ	**-0.64**	**-0.50**	**0.50**	-0.28	**-0.39**	-0.06	-0.15	-0.31
Number of wet fronts MJJ	**-0.54**	**-0.60**	0.29	-0.19	-0.23	-0.10	-0.12	-0.19
Average latitude of U>=10m/s MJJ	**-0.64**	**-0.50**	**0.49**	-0.18	**-0.43**	-0.05	-0.01	**-0.41**
Front days ASO	**-0.65**	**-0.73**	**0.35**	-0.25	-0.28	-0.34	-0.14	-0.16
Total front rainfall ASO	**-0.61**	**-0.48**	**0.44**	**-0.38**	**-0.65**	0.19	-0.04	**-0.60**
Number of wet fronts ASO	**-0.74**	**-0.62**	**0.48**	**-0.42**	**-0.65**	0.09	-0.10	**-0.58**
Average latitude of U>=10m/s ASO	**-0.84**	**-0.70**	**0.45**	-0.32	**-0.53**	0.10	-0.02	**-0.49**

Line 339 – Typo - 'Pearson's

Thanks, we will fix

Line 340 – Typo - 'm/s'

Thanks

Line 348 – Could this be linked to anomalous moisture transport from the tropical Indian Ocean? Or is the impact more of changes on the Hadley Circulation and a weaker / stronger STR?

Most of the moisture for rainfall events in southeast Australia is sourced from the southern ocean as well as from the ocean to the east (e.g. https://doi.org/10.1175/JCLI-D-19-0926.1 supplementary figure S11b, "southeast coast Victoria") and previous work by, e.g., Cai suggests that the IOD mostly influences Australia's climate via a wave train in the extratropics

(https://doi.org/10.1175/2011JCLI4129.1). We will add a mention of the potential role of moisture transport.

Line 368 – Just a general comment, what role does topography and wind direction play? Could this account for any minor differences between the two Australian domain?

Southwest Western Australia and southeast Australia have very similar mean climates, so are often clustered together (e.g., in https://doi.org/10.1071/ES20003). However, you are correct that there are differences in regional topography and wind interactions, as well as other factors such as ocean temperatures and coastal orientation, that can contribute to differences between the regions. For example, the regions typically source moisture for rainfall from different ocean basins and have different relationships with climate drivers such as ENSO and IOD. Given these differences, the similarities between the two regions regarding frontal rainfall in this paper were stronger than expected, although both regions have seen related declines in cool season rainfall (e.g., https://doi.org/10.1002/joc.1964).

Line 427 - 'South Africa'
Thanks, we'll fix this