Revisiting the wintertime emergent constraint of the Southern Hemispheric midlatitude jet response to global warming

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Abstract. Most climate models show a poleward shift of the southern hemispheric zonal-mean jet in response to climate change, but the inter-model spread is large. In an attempt to constrain future jet responses, past studies have identified an emergent constraint between the climatological jet latitude and the future jet shift in austral winter. However, we show that the emergent constraint only arises in the zonal mean, and not in separate halves of the hemisphere~~. This can be explained by the presence of a double jet structure in the Pacific region, making the zonal mean jet latitude~~, which questions the physicality of the emergent constraint. We further find the zonal-mean jet latitude to be a poorly defined quantity that does not represent the latitude of a zonally coherent structure, due to the presence of a double jet structure in the Pacific region during this season. The ~~usefulness of the emergent constraint is therefore questionable. This finding can further explain the prior finding among CMIP5 and CMIP6 ensembles that the meridional structure of~~ zonal asymmetry causes the previously noted large spread in the zonal-mean climatology but not in the response, which underlies the emergent constraint. We therefore argue that the emergent constraint on the zonal-mean ~~zonal wind response does not change with climatological jet latitude but stays fixed.~~ jet is a statistical artefact, and propose that emergent constraints on the jet response in austral winter should be based on regional rather than zonal-mean circulation features.

1 Introduction

The southern hemispheric midlatitude jet is predicted to shift poleward in response to greenhouse gas forcing. However, the magnitude of this shift differs among ~~Global Climate Models~~ global climate models (GCMs) (Barnes and Polvani, 2013; Curtis et al., 2020). This in turn increases the uncertainty of projected climate change impacts on the mid-latitude region (Shepherd, 2014). It is therefore necessary to constrain the range of future jet responses.

One way of narrowing down the range of model responses is by identifying emergent constraints (EC), which are across-model relationships between a climatological variable X and the response in the variable of interest Y (Hall et al., 2019). If such a constraint is found, it can be used by calculating X from real world data to predict the response in Y. ~~However, identifying the existence of an emergent constraint is a non-trivial task.~~ A commonly cited example involves the correlation between climatological jet latitude and future jet shift across CMIP models in southern hemispheric winter, first identified by

Kidston and Gerber (2010). As a physical explanation, the authors proposed Fluctuation-Dissipation Theory~~offers a theoretical foundation (Kubo, 1966; Leith, 1975); applied~~ , which in a simplified form ~~to the eddy-driven jet, it~~ links future jet shift to an annular mode timescale ~~(e.g. Ring and Plumb, 2008; Kidston and Gerber, 2010; Simpson and Polvani, 2016; Breul et al., 2022). Unfortunately, results from past studies could not identify an emergent constraint between the two variables in CMIP ensembles (Simpson and Polvani, 2016; Breul et al., 2022). Empirically, Kidston and Gerber (2010) found an EC between climatological~~ (e.g. Ring and Plumb, 2008; Breul et al., 2022). However, Simpson and Polvani (2016) cast doubt on these findings, since they found the inter-model spread in annular model timescale to have opposite seasonality to the correlation strength between jet latitude and shift. They further found the relationship between jet latitude and future jet shift ~~in the Coupled Model Intercomparison Project Phase 3 (CMIP3). However, using CMIP5 data Simpson and Polvani (2016) showed that this EC only holds in the wintertime; more~~ to hold in winter only but not summer.

More recently, Curtis et al. (2020) and Simpson et al. (2021) ~~identified the~~ confirmed the existence of the same wintertime constraint in CMIP6. Simpson and Polvani (2016) proposed a possible explanation for the EC by observing that the zonal wind response does not ~~vary with~~ track the climatological jet latitude, as one would expect if the response were e.g. always a shift of the jet, but is approximately the same independent of initial jet latitude. They speculated that this effect gives rise to the ~~emergent constraint~~EC, since the response projects ~~differently onto the jet~~ more or less strongly onto a jet shift, depending on its climatology. However, the reason for this “anchoring” of the response remains unclear.

An understanding of the physical basis of an ~~emergent constraint~~ EC is important for having confidence in its ability to constrain future responses (Hall et al., 2019). Here we ~~show~~ propose that both the EC and the anchored zonal wind response can be explained by a geometric argument, based on the ~~zonal mean~~ zonal-mean jet latitude being a poorly defined quantity in wintertime because of ~~a zonal asymmetry due to~~ zonal asymmetries associated with a double jet structure in the Pacific region. This questions the physical basis (and therefore the usefulness) of the zonal-mean jet latitude as a circulation metric in wintertime, and consequently of the EC.

2 Data and Methods

We use the austral wintertime (June–July–August, JJA) zonal wind at 850 hPa, regridded to a common T42 grid, from ~~the following 22~~ 39 models participating in the historical and SSP5–8.5 experiments of the Coupled Model Intercomparison Project Phase 6 (CMIP6)~~: AWI-CM-1-1-MR, BCC-CSM2-MR~~, ~~CAMS-CSM1-0, CanESM5, CAS-ESM2-0, CMCC-CM2-SR5, CMCC-ESM2, EC-Earth3-CC, EC-Earth3, EC-Earth3-Veg-LR, EC-Earth3-Veg, FIO-ESM-2-0, IITM-ESM, INM-CM4-8, INM-CM5-0, KIOST-ESM, MPI-ESM1-2-HR, MPI-ESM1-2-LR, NESM3, NorESM2-LM, NorESM2-MM and TaiESM1.~~ detailed in Table A1.

We use the periods 1950–2014 for the historical ~~experiments~~ experiment and 2076–2100 for the SSP5-8.5 ~~experiments~~experiment, and the response is defined as the climatological difference between the two. The results presented are quantitatively the same when other time periods are chosechosen. Unless otherwise specified, we always consider the wintertime seasonal average. The data is restricted to the latitude range 22°S – 78°S. The jet latitude is defined as the maximum of a parabola fitted to the maximum zonal mean zonal zonal-mean zonal wind grid point and its two neighbours, as was done by Barnes and Polvani (2013) Kidston and Gerber (2010). The jet shift is then the difference in climatological jet latitude between the historical and SSP5-8.5 experiments.

When determining whether multiple jets occur at the same time, we identify local maxima in the daily zonal mean zonal zonal-mean zonal wind data that are spaced at least 5 grid points apart (approximately 14°) and have a strength of at least 4 m/s. To filter out eddy contributions, we use a Butterworth low-pass filter with a cutoff frequency of $(8\,\text{days})^{-1}$ on the zonally resolved data. This is the only part of the analysis where we use daily data rather than seasonal averages. Owing to limited data availability, this analysis was restricted to 29 models, detailed in Table A1.

3 Results & Discussion

3.1 Emergent Constraint

First, we reproduce the wintertime emergent constraint EC that was found by Simpson and Polvani (2016) in CMIP5, and Simpson et al. (2021) in CMIP6, between the climatological jet latitude and the future jet shift in Fig. 1a. While we find a Pearson correlation coefficient of $r = -0.79$$r = -0.76$, the data includes one large outlieroutliers. Nevertheless, measuring the correlation strength with the Spearman rank correlation, which is less sensitive to outliers, still gives a high value of $\rho = -0.67$$\rho = -0.66$.

However, this relationship was obtained in the zonal mean. Fig. 2a shows the CMIP6 model average of longitudinally resolved zonal wind, which shows a clear asymmetry in the hemisphere, with a double jet structure in the Pacific region. Therefore we repeat the analysis in Fig. 1b and c for the Atlantic/Indian Indo-Atlantic region (300°– 120°) and the Pacific region (120°–300°) respectivelyseparately. We note that the exact hemispheric division is not too important, overly important; the values presented here were chosen since they cover the full longitudinal extent of the double jet structure in the climatological and model meanand , while at the same time divide dividing the hemisphere into two equal parts. The Atlantic/Indian Indo-Atlantic region clearly does not show an emergent constraintexhibit an EC, and features relatively little variation in both mean jet latitude and jet shift. While the Pearson correlation coefficient is high in the Pacific region, this effect seems to depend on a few large outliers , and indeed the (note the larger y-axis range in Fig. 1c). The Spearman rank correlation is weak with a indeed significantly weaker, and when excluding the outliers (historical jet latitude smaller than 50°S or jet shift more equatorward than -5°S) we only find small correlation coefficients with high p-value (-values. Note that we do not find a significant correlation when repeating the analysis for each jet of the double jet structure separately). This raises the question of where the emergent constraint EC comes from and why it only appears in the whole hemispheric zonal mean.

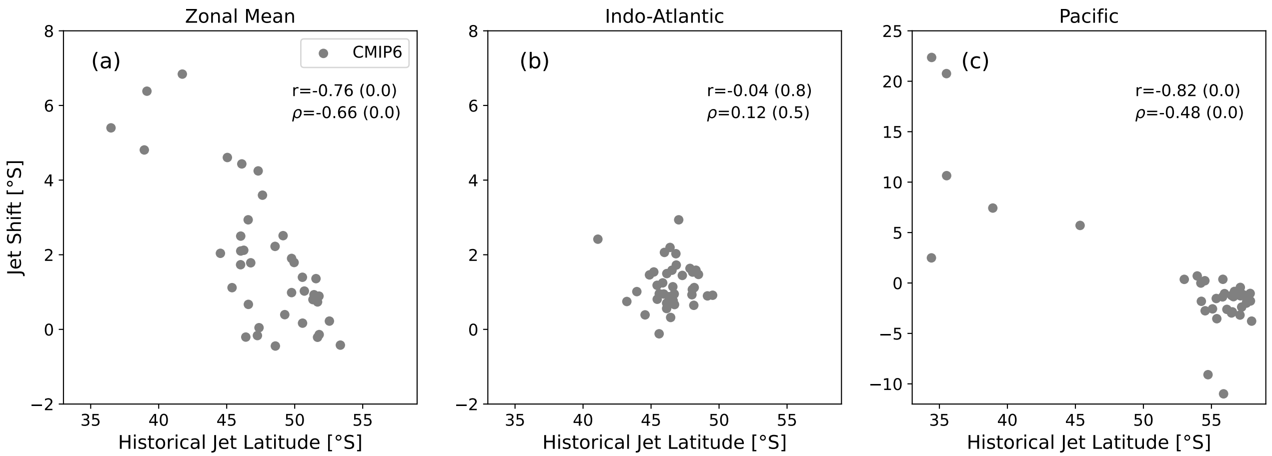

Figure 1. JJA climatological jet latitude against future jet shift for the CMIP6 models~~(grey) and the toy model (red, see Section 3.3 for details)~~. The Pearson correlation coefficient r and the Spearman rank correlation coefficient ρ are given for the CMIP6 values together with their respective p-values. The zonal mean was taken over **(a)** all longitudes, **(b)** 300°– 120°~~,~~ and **(c)** 120°– 300°. ~~In~~ Note the larger y-axis range in (c)~~, two out-of-range values are indicated by arrows together with their coordinates~~.

3.2 Climatological Jet Latitude

The origin and behaviour of the asymmetry introduced in the previous section has been investigated in several previous studies (e.g. Inatsu and Hoskins, 2004; Codron, 2007). To verify that the Pacific double jet structure exists physically and is not just an artefact of time and model averaging (e.g. in case of bimodality in the latitudinal distribution of a single jet), we ~~will~~ analyse daily data of the Pacific and ~~Atlantic/Indian sector~~Indo-Atlantic sectors. We identify the number and location of jets (as described in Section 2) in each sector for all historical days and models. For the Pacific sector we find a single jet ~~31.5~~38.7% of the time and a double jet ~~62.6~~57.3% of the time, ~~the residual 5.9~~while the residual 4% showed three peaks or more. We show the latitude probability density for ~~the single jet and the two jets of the double jet structure~~ single- and double-jet situations in the Pacific in Fig. 2b and c respectively. This shows that a double jet structure physically exists most of the time in the Pacific region, different from the ~~Atlantic/Indian~~ Indo-Atlantic sector which shows a single jet ~~75.7~~79.2% of the time and a double jet only ~~24.2~~20.6% of the time.

The observed zonal asymmetry makes the ~~zonal mean~~ zonal-mean jet latitude a poorly defined metric. We sketch the resulting problem in Fig. 3a, where we represent the observed jets using Gaussians. For demonstration purposes the ~~jet spacing in~~ two jets of the double jet structure ~~is exaggerated slightly~~ are positioned slightly further apart than what is typically found in CMIP models, but otherwise the ~~values~~ structures shown are realistic and fit in the range of model behaviour; see Figs. 4 and B1. Figure 3~~shows that~~ a demonstrates how differences in the strength of the individual jets in the Pacific double jet structure lead to different ~~zonal mean~~ zonal-mean jet latitudes, even though none of the jet structures have moved. To test whether this effect

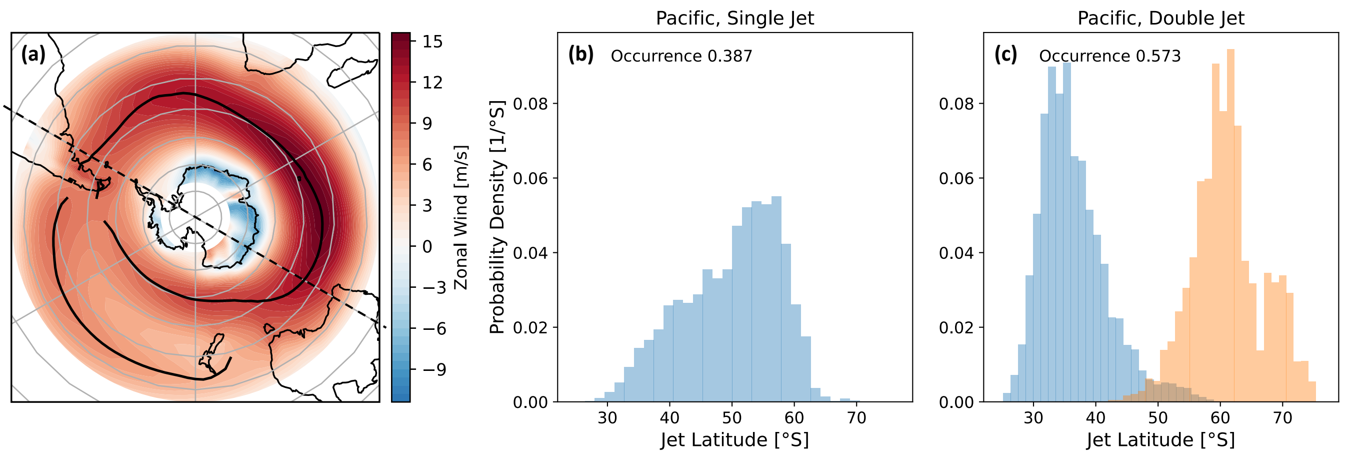

Figure 2. (a) 850 hPa ~~Climatological~~ climatological zonal wind averaged over all CMIP6 models; the solid black lines trace the jet positions. The dashed black line divides the hemisphere into the ~~Atlantic/Indian~~ Indo-Atlantic and the Pacific sectors. **(b)** Jet latitude probability density for days with a single jet structure in the Pacific; **(c)** ~~Same~~ same as (b) for days with a double jet structure.

is present in the CMIP6 ensemble, we plot the historical zonal-mean jet latitude against the difference in strength between the two Pacific jets for the CMIP6 models in Fig. 3b, where we find a strong correlation. Meanwhile, we find only weak Spearman correlation coefficients with high p-values between the zonal-mean jet latitude and either of the Pacific jet latitudes. This supports the hypothesis that differences in the Pacific double jet strength are able to account for the differences in the zonal-mean jet latitude, which could explain the larger spread in jet latitude in the zonal mean compared to the Indo-Atlantic sector. The analysis was limited to the 16 models that show two distinct peaks in the zonal-mean climatology over 120° – 300° for simplicity; using daily data a similar analysis could likely be performed for all models.

As an aside, we note that the spread in jet latitude over the Indo-Atlantic half of the hemisphere also contributes to the inter-model spread in zonal-mean jet latitude, as can be seen in Fig. 3c where we regressed the inter-model differences in zonal wind onto the inter-model differences in jet latitude. We further find an increase in the Indo-Atlantic mean jet latitude to be correlated with a strengthening of the mean poleward Pacific jet. However, this connection does not invalidate our point that the zonal-mean jet latitude does not reflect the latitude of any individual jet structure in the Pacific sector. Hence, in the following discussion we will focus on the Pacific contribution for reasons of simplicity.

The results so far therefore suggest that the ~~zonal mean~~ zonal-mean climatological jet latitude does not reflect the position of a zonally coherent structure. This implies that any analysis involving this measure of jet latitude should be interpreted with caution, including the ~~emergent constraint~~ EC shown in Fig. 1a (especially since it is not present in the separate halves of the hemisphere).

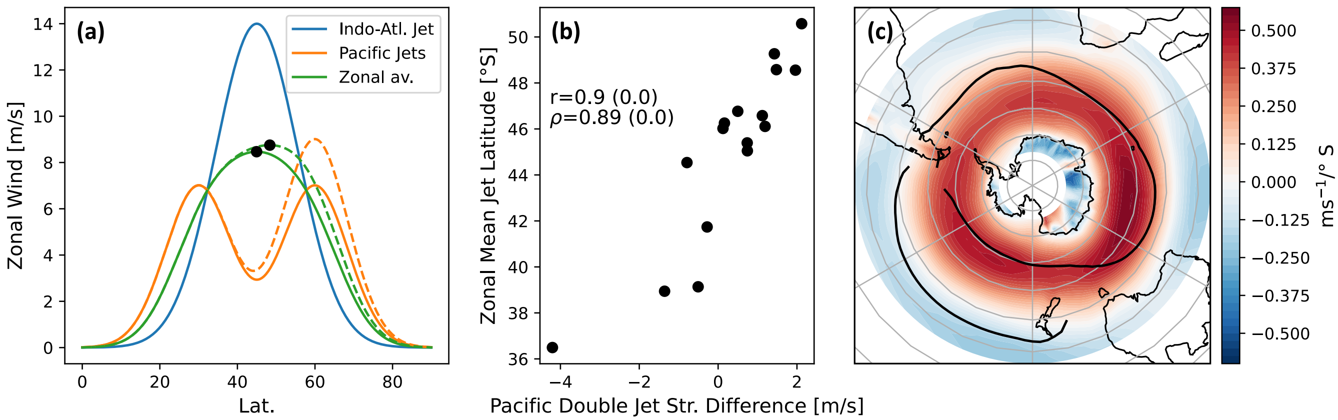

Figure 3. Sketch **(a)** Idealised sketch of the zonal-mean zonal mean zonal wind structures in the Atlantic/Indian Indo-Atlantic and Pacific sectors and their zonal average. The dashed lines denote a different climatology, while the black dots mark the jet peaks in the two climatologies. **(b)** The difference in strength between the Pacific double jets plotted against the zonal-mean jet latitude for the 16 CMIP6 models that show two distinct peaks in the Pacific zonal-mean climatology. **(c)** Inter-model differences in zonal wind climatology regressed onto the inter-model differences in zonal-mean jet latitude. The solid black lines trace the jet positions as in Fig. 2a.

3.3 Toy Model

To explore to what extent the zonal asymmetry in the jet can explain the observed response, In this section we introduce a simple toy model toy model to propose a mechanism that could cause the zonal-mean EC. The basis for the model are the same structures shown in Fig. 3a, i.e. a single jet structure for the Atlantic/Indian Indo-Atlantic half and a double jet structure for the Pacific half, which are then averaged together. The jets are represented by Gaussians of the form

$$g(\theta) = a \cdot e^{-\frac{(\theta-\mu)^2}{\sigma^2}}, \qquad (1)$$

with θ the latitude, μ the jet latitude, σ the width and a the maximal jet strength. The Pacific double jet is represented as the sum of two Gaussians. We set the values such that they fit the CMIP6 average for both the Pacific sector (see Fig. 4) and the Atlantic/Indian Indo-Atlantic sector (see Fig. B1) for the historical and SSP5-8.5 scenario; the scenarios. The values can be found in Table 1. For the Pacific double jet structure, we use the subscripts 1 and 2 to refer to the equatorward and poleward jet, respectively.

To simulate differences in historical climatological jet latitude created by differences in double jet strength (as sketched in Fig. 3shown in Fig. 3b), we add a random variable r_1 equally distributed between $(-1.5, 1.5)\,\mathrm{m\,s^{-1}}$ to the equatorward Pacific jet strength a_1, and a second random variable r_2 equally distributed between $(-3, 3)\,\mathrm{m\,s^{-1}}$ to the poleward Pacific jet strength a_2, creating 22 . The variations in the Indo-Atlantic mean state were found not to be qualitatively important and were therefore not included in the toy model for simplicity. In this manner we create 39 different realisations that emulate the range of CMIP6 model behaviour seen in Figs. 4Fig. 4a and b and the therefore also the response in Fig. 4c. These realisations correspond

	~~Atlantic/Indian~~ Indo-Atlantic	Pacific
Historical	$a = 13.5\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu = 47^\circ$, $\sigma = 15.5^\circ$	$a_1 = 7\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu_1 = 37^\circ$, $\sigma_1 = 12^\circ$ $a_2 = 8.5\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu_2 = 57^\circ$, $\sigma_2 = 12^\circ$
SSP5-8.5	$a = \mathbf{14.5}\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu = \mathbf{48}^\circ$, $\sigma = 15.5^\circ$	$a_1 = 7\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu_1 = \mathbf{39}^\circ$, $\sigma_1 = 12^\circ$ $a_2 = \mathbf{10}\,\frac{\mathrm{m}}{\mathrm{s}}$, $\mu_2 = 57^\circ$, $\sigma_2 = 12^\circ$

Table 1. Toy model parameters from Eq. (1) used to fit the ~~Atlantic/Indian~~ Indo-Atlantic jet (see Fig. B1) and the double jet structure in the Pacific (see Fig. 4) for both the historical and SSP5-8.5 scenarios. The strengths of the Pacific double jet structure a_1 and a_2 are ~~only~~ the base values, to which a random perturbation is added in each model realisation. ~~In bold are shown~~ The subscripts 1 and 2 refer to the more equatorward and more poleward Pacific jet, respectively. The parameter values that change ~~between~~ to approximate the ~~historical and~~ SSP5-8.5 ~~scenario~~response are highlighted in bold.

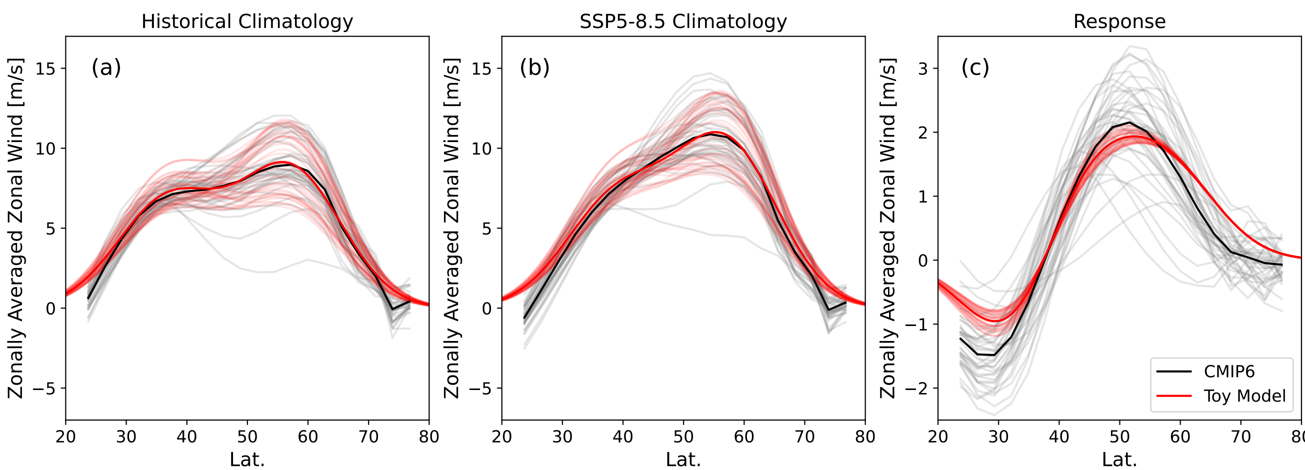

Figure 4. ~~Zonal mean~~ Zonal-mean zonal wind in the Pacific sector (120° ~~-~~ – 300°); individual CMIP6 models in grey and their average in black. In light red are the individual realisations of the toy model (see Section 3.3) and in ~~bright~~ dark red their average. **(a)** Historical period, **(b)** the SSP5-8.5 scenario, and **(c)** the climate-change response as the difference between (b) and (a).

~~to the shaded red linesin Fig. 4~~(light red lines). While this model ~~will surely not capture~~ cannot describe every aspect of the inter-model differences in jet climatology, we believe it captures the essential features for our problem, while at the same time being relatively simple. By design, the spread in toy model responses is minimal, since the same change in parameters is used for all realisations – see Fig. 4c for the Pacific sector and Fig. B2c for the zonal mean.

The parameters of the toy model are given in Table 1~~were chosen to approximate the historical and SSP5-8.5 climatological model mean~~. We note that the change in parameters between the historical and SSP5-8.5 scenarios signifies a poleward shift and strengthening of the ~~Atlantic/Indian~~ Indo-Atlantic jet structure, and in the Pacific basin a poleward shift of the equatorward

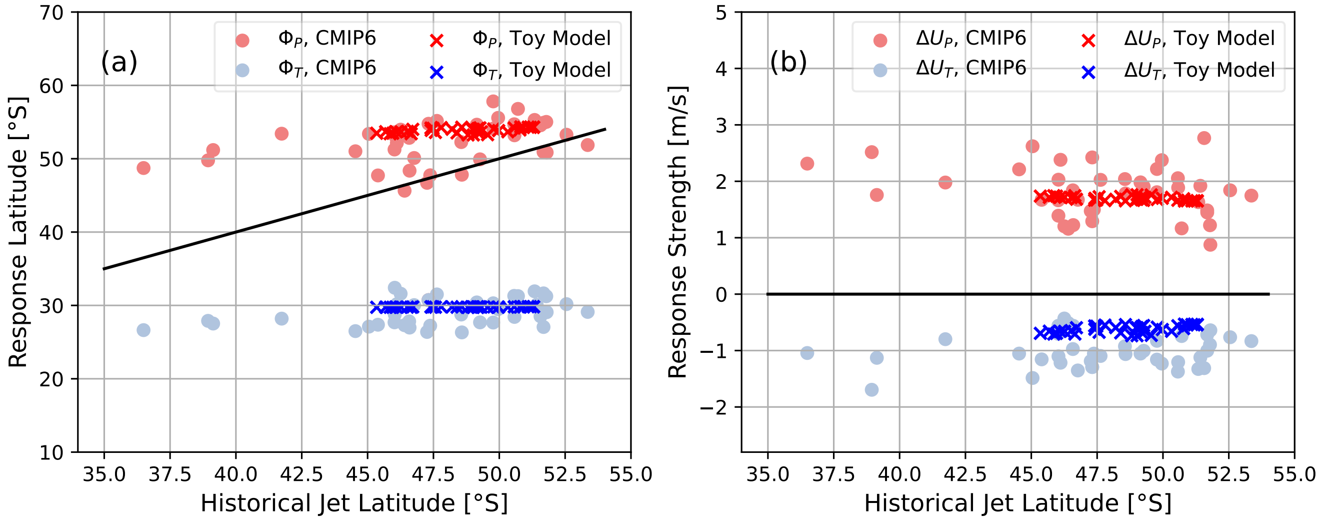

Figure 5. Comparison of the response structure of the CMIP6 ensemble with the toy model results. **(a)** Φ_P and Φ_T, respectively the latitude of the peak and trough of the zonal wind response, against the historical jet latitude. The black line shows the identity. **(b)** ΔU_P and ΔU_T, respectively the amplitude of the peak and trough of the zonal wind response, against the historical jet latitude. The black line marks zero response strength.

jet and a strengthening of the poleward jet. These conclusions are qualitatively in agreement with the changes observed in the jet strength and location histograms derived from daily data (not shown). Additionally, we note that the toy model results discussed below are not qualitatively dependent on including the response from the ~~Atlantic/Indian~~ Indo-Atlantic sector, although including it brings the results into closer quantitative agreement with the CMIP6 ensemble.

3.4 Response Structure

We now turn to testing whether the toy model can reproduce the observed inter-model relationships in the zonal-mean jet response. For this we reproduce prior analyses from Simpson and Polvani (2016) and Simpson et al. (2021) by plotting the response peak and trough locations (Φ_P and Φ_T), as well as their strength (ΔU_P and ΔU_T), against the historical jet latitude ~~– see Fig. 5~~(Fig. 5). We observe that the ~~toy model can reproduce~~ response peak and trough in Fig. 5a generally do not follow the identity line (although the response peak Φ_P does to an extent), but stay fixed or "anchored". The toy model shows both the anchoring of Φ_P and Φ_T (Fig. 5a) as well as the asymmetry in response strength between ΔU_P and ΔU_T (Fig. 5b).

The toy model ~~can provide insights into the origin of the observed response structures in Fig. 5. The first conclusion is that at least part of the differences~~ reproduces the response anchoring out of two reasons. First, it simulates parts of the large spread in zonal-mean ~~historical jet latitude come from differences in relative~~ jet latitude by perturbing the strength of the Pacific double jet structure, ~~since the toy model can represent a large portion of the mean jet latitude spread using only random variations of~~

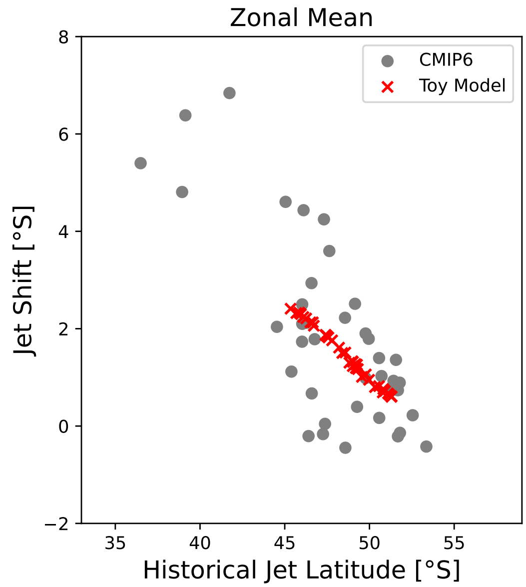

Figure 6. As in Fig. 1a with the results from the toy model added.

~~the Pacific double jet strengths (see sections 3.2 and 3.3). In~~ which is in line with the previous findings for CMIP6 (Section 3.2). Second, the toy model ~~we use~~ uses the same response for all realisations, derived from the model-mean climatological change in the two halves of the hemisphere. ~~This, coupled with the spread in jet latitude which does not reflect a change in position of any of the jets, leads to the anchored response shown~~ These two effects taken together lead to the toy model showing an anchored response in Fig. 5a. We note that unlike the toy model, the CMIP6 ensemble does show inter-model differences in the ~~zonal mean~~ zonal-mean response (Fig. B2c), which are the ~~cause~~ reason for the larger spread of Φ_P and Φ_T compared to the toy model, but crucially ~~the~~ these differences do not seem to be related to the historical jet latitude.

Furthermore, in the toy model ~~shows that~~ the asymmetry between ΔU_P and ΔU_T in Fig. 5b has its origin in both halves of the hemisphere (the plot would be qualitatively similar if only including the response of either half of the hemisphere). While CMIP6 models simulate a poleward shift of one of the jets in each basin (the equatorward one in the Pacific half and the single jet in the ~~Atlantic/Indian~~ Indo-Atlantic half), we also observe a jet strengthening (the poleward one in the Pacific half and the single jet in the ~~Atlantic/Indian~~ Indo-Atlantic half). This leads to the response peak (ΔU_P) being stronger than the response trough (ΔU_T).

~~As an aside, we note from Fig. 5a that, while the response trough latitude Φ_T is clearly anchored and does not move with the jet latitude, the peak latitude Φ_P is less clearly anchored even when discarding the low-latitude outlier~~ Coming back to the EC, we reproduce Fig. 1a in Fig. 6 and also add the results from the toy model. We ~~point out, however, that the anchoring~~

~~was clearly present for Φ_P in Simpson et al. (2021), who used a larger model ensemble, including more low latitude models. Coming back to the emergent constraint shown in Fig. 1a, we~~ note that the toy model ~~can reproduce the main features of the CMIP6 behaviour~~shows an EC. In the toy model, the EC arises from the ~~fact that~~ anchored response, because the response is the same in all realisations, but ~~how much it projects~~ it projects differently onto a shift ~~depends on the~~ depending on the zonal-mean climatological jet latitude. ~~This explanation~~ While this geometric argument was already proposed by Simpson and Polvani (2016)~~. However, we~~ , our toy model results suggest that the zonal asymmetry could ultimately be the origin of the anchored response, and thus of the EC.

We stress again that the full hemispheric zonal-mean jet latitude should not be interpreted as the latitude of a zonally coherent jet structure, but instead arises from averaging over different hemispheric regions that show different structures. This kind of measure and its associated ~~emergent constraint~~ EC should therefore be interpreted with caution. Ultimately, Fig. 1b demonstrates that in regions with only a single jet, there is no relationship between jet latitude and future jet shift~~and we also~~ , and furthermore we did not find a relation when considering the jets of the double jet structure individually (not shown).

We note that Bracegirdle et al. (2013) (hereafter B13) analysed the relation between climatological jet position and future jet shift in the Atlantic, Indian and Pacific sectors separately in a CMIP5 ensemble. The authors acknowledged that the jet latitude might be poorly defined in the Pacific region, but used it as a measure nevertheless. They did find a correlation of $r = 0.39$ in the Atlantic sector in the annual mean, which was significant at the 5 % level. However, this is not necessarily in contradiction to our findings, given the use of annual averages. As in our present work, B13 found high correlation coefficients in the Pacific region both for individual seasons (except for DJF) as well as for the annual mean. Unfortunately no scatter plot was provided, except for the annual mean, making it hard to judge to which extent the seasonal results might be dominated by outliers, as in our findings (Fig. 1c). We further stress that, as acknowledged by B13, the jet position is poorly defined in the Pacific. The presence of an EC in the annual mean is consistent with the findings here, since it is an average over a double jet structure in winter and a single jet structure in summer. The mechanism would therefore be the same as for the zonal-mean results presented here.

4 Summary and Conclusion

We ~~demonstrate~~ argue that the wintertime ~~zonal mean~~ zonal-mean jet latitude is a poorly defined quantity, since it averages over a single jet structure in the ~~Atlantic/Indian~~ Indo-Atlantic region and a double jet structure in the Pacific region. It should therefore not be interpreted as a location measure of a zonally coherent structure. We ~~further~~ demonstrate that a substantial amount of the historical jet latitude variation among the CMIP6 ensemble can be explained by relative differences in strength of the Pacific double jet structure. ~~Furthermore, we show~~ Using a simple toy model, we propose that the previously observed anchoring of the zonal-mean zonal wind response ~~(i.e. the fact that the response structure does not follow the climatological jet latitude; Simpson and Polvani (2016); Simpson et al. (2021))~~ (i.e. the fact that the response structure does not track the climatological jet latitude; S is an artefact of the zonally asymmetric jet structure in CMIP5 and CMIP6 leading to large variations in historical jet latitude but comparatively little spread in response.

~~Based on these findings, we show~~ Following Simpson and Polvani (2016), we suggest that the previously identified ~~emergent constraint between~~ EC between zonal-mean historical jet latitude and future jet shift can be explained in the context of the anchored zonal wind response projecting differently onto a jet shift, depending on the climatological jet latitude. ~~However,~~ The toy model demonstrates how the EC could arise from the zonal asymmetries without any direct causal link between zonal-mean jet latitude and future zonal wind changes. Regardless of the mechanism for the anchored wind response, however, the physical interpretation of ~~this emergent constraint~~ the EC is unclear, since the measure of ~~zonal mean~~ zonal-mean jet latitude is poorly defined. ~~This conclusion is~~ These conclusions are further supported by the fact that the EC only holds in the zonal mean and does not appear in the Pacific or ~~Atlantic/Indian~~ Indo-Atlantic halves of the hemisphere separately. ~~Thus, it appears~~

Our results thus suggest that the apparent EC identified in previous work is a statistical artefact, caused by failing to properly account for the confounding factor of longitudinal asymmetry. This is a special case of a statistical phenomenon known as the Yule-Simpson effect (e.g. Goltz and Smith, 2010). Hence the results presented here demonstrate that caution is needed when using zonally averaged metrics to interpret zonally asymmetric circulation features, such as the wintertime southern hemispheric jet. We therefore suggest moving away from the search for an EC on the zonal-mean circulation, and instead focusing on individual hemispheric sectors with physically coherent circulation features.

Appendix A: Models

Appendix B: Toy Model

Here we show the same comparison of ~~zonal mean zonal~~ zonal-mean zonal winds from the CMIP6 ensemble with the toy model as in Fig. 4, but for the ~~Atlantic/Indian~~ Indo-Atlantic sector (Fig. B1) and the full hemispheric ~~zonal mean~~ zonal-mean (Fig. B2).

Author contributions. PB designed the toy model, performed the model analysis, and wrote the paper. Both PC and TGS contributed to the interpretation of the results and the writing of the paper.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Weather and Climate Dynamics

Model	Monthly	Daily			
AWI-CM-1-1-MR	x		BCC-CSM2-MR	x	
CAMS-CSM1-0	x		CAS-ESM2-0	x	
CESM2	x		CESM2-WACCM	x	x
CIESM	x		CMCC-CM2-SR5	x	x
CMCC-ESM2	x	x	CNRM-CM6-1	x	x
CNRM-CM6-1-HR	x	x	CNRM-ESM2-1	x	x
CanESM5	x	x	EC-Earth3	x	x
EC-Earth3-CC	x	x	EC-Earth3-Veg	x	
EC-Earth3-Veg-LR	x	x	FGOALS-f3-L	x	x
FGOALS-g3	x	x	FIO-ESM-2-0	x	
GFDL-CM4	x	x	GFDL-ESM4	x	
HadGEM3-GC31-LL	x	x	HadGEM3-GC31-MM	x	x
IITM-ESM	x	x	INM-CM4-8	x	x
INM-CM5-0	x	x	IPSL-CM6A-LR	x	x
KACE-1-0-G	x	x	KIOST-ESM	x	
MIROC-ES2L	x	x	MIROC6	x	x
MPI-ESM1-2-HR	x	x	MPI-ESM1-2-LR	x	x
NESM3	x	x	NorESM2-LM	x	x
NorESM2-MM	x	x	TaiESM1	x	x
UKESM1-0-LL	x	x			

Table A1. The CMIP6 models that are used in this analysis; monthly data was available for all models but daily data for only a subset.

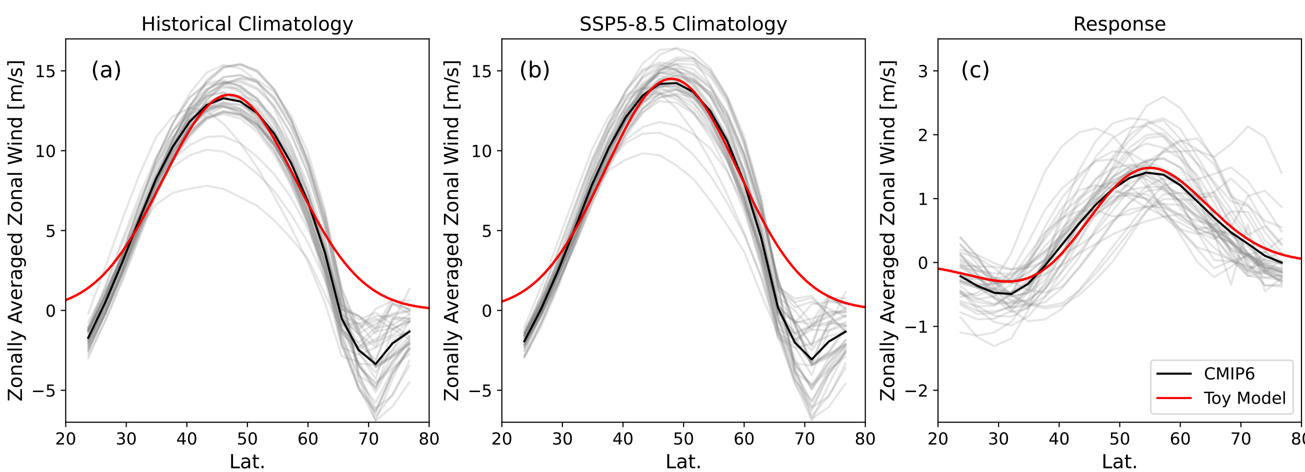

Figure B1. As in Fig. 4 but for the ~~Atlantic/Indian~~ Indo-Atlantic sector (300°- 120°).

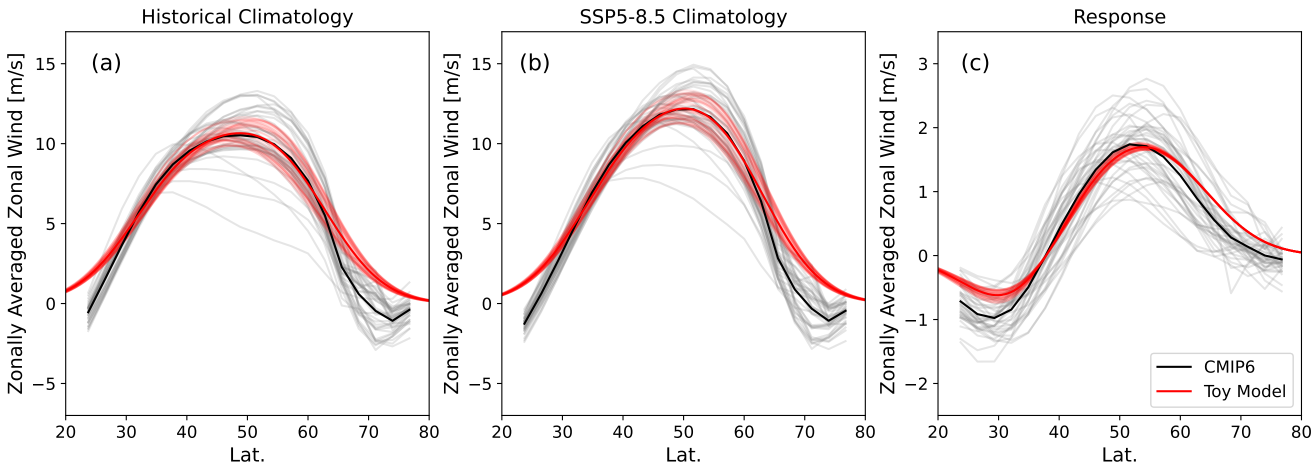

Figure B2. As in Fig. 4 but for the full-hemispheric ~~zonal mean~~zonal-mean.

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