https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

Weather and Climate Dynamics Discussions
Open Access
EGU

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

Philipp Breul[1], Paulo Ceppi[1,2], and Theodore G. Shepherd[3]

[1]Department of Physics, Imperial College London, London, United Kingdom
[2]Grantham Institute, Imperial College London, London, United Kingdom
[3]Department of Meteorology, University of Reading, Reading, United Kingdom

Correspondence: Philipp Breul (pyb18@ic.ac.uk)

Abstract. Most climate models show a poleward shift of the southern hemispheric 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 a poorly defined quantity that does not represent the latitude of a zonally coherent structure 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 the zonal-mean zonal wind response does not change with climatological jet latitude but stays fixed.

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 (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. Fluctuation-Dissipation Theory offers a theoretical foundation (Kubo, 1966; Leith, 1975); applied 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 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 recently, Curtis et al. (2020) and Simpson et al. (2021) identified 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 climatological jet latitude, as one would expect if the response were e.g. always a shift of the jet, but is the same independent of latitude. They speculated that this effect gives rise to the emergent constraint, since the response projects differently onto the jet, 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 is important for having confidence in its ability to constrain future responses (Hall et al., 2019). Here we show that both the EC and the anchored zonal wind response can be explained by a geometric argument, based on the zonal mean jet latitude being a poorly defined quantity in wintertime because of a zonal asymmetry due to 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 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. We use the periods 1950–2014 for the historical experiments and 2076–2100 for the SSP5-8.5 experiments, and the response is defined as the climatological difference between the two.The results presented are quantitatively the same when other time periods are chose. 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 wind grid point and its two neighbours, as was done by Barnes and Polvani (2013). 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 wind data that are spaced at least 5 grid points apart (approximately 14°) and have a strength of at least 4 m/s. This is the only part of the analysis where we use daily data rather than seasonal averages.

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

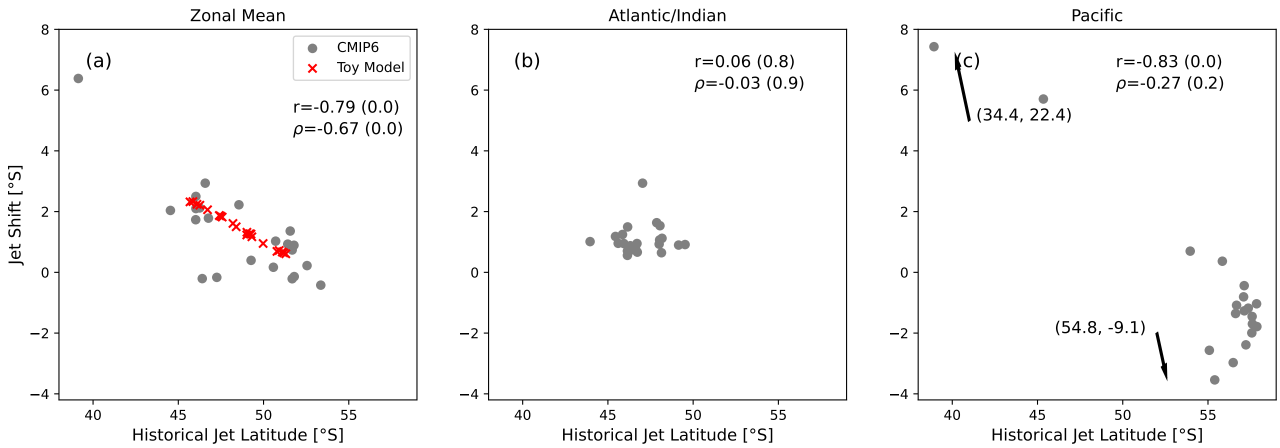

Figure 1. JJA climatological jet latitude against future jet shift for the CMIP6 models (grey) and the toy model (red, see Section 3.3 for details). The Pearson correlation coefficient r and the Spearman rank correlation coefficient ρ are given for the CMIP6 values together with their respective p-values.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

3 Results & Discussion

3.1 Emergent Constraint

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

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 region ($300°–120°$) and the Pacific region ($120°–300°$) respectively. We note that the exact hemispheric division is not too important, the values presented here were chosen since they cover the full longitudinal extent of the double jet structure in the climatological and model mean and at the same time divide the hemisphere into two equal parts. The Atlantic/Indian region clearly does not show an emergent constraint, 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 Spearman rank correlation is weak with a high p-value (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 comes from and why it only appears in the whole hemispheric zonal mean.

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

Weather and Climate Dynamics Discussions
Open Access
EGU

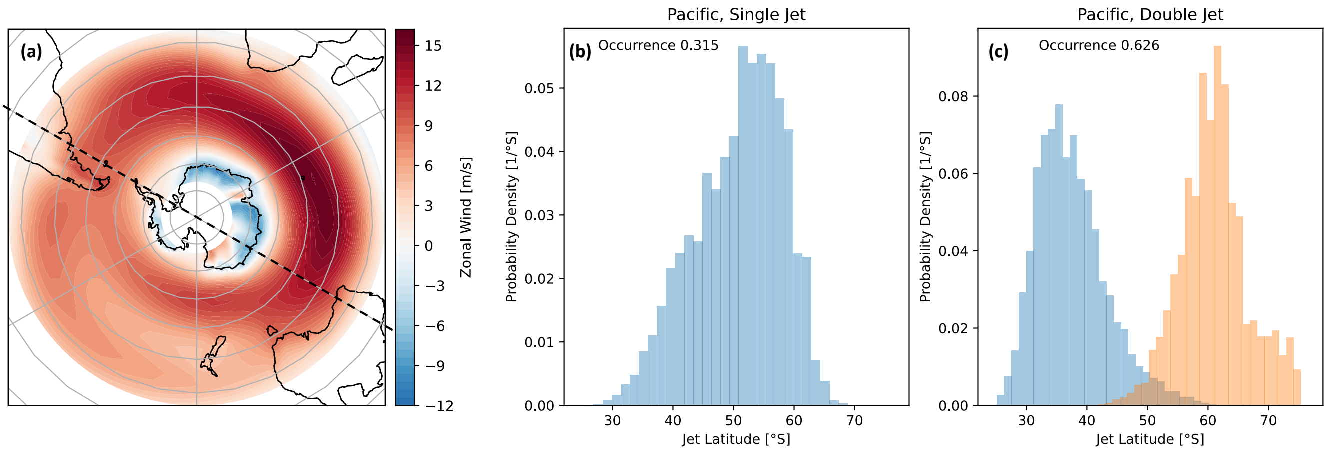

Figure 2. (a) 850 hPa Climatological zonal wind averaged over all CMIP6 models. The dashed black line divides the hemisphere into the Atlantic/Indian and the Pacific sectors. **(b)** Jet latitude probability density for days with a single jet structure in the Pacific; **(c)** Same as (b) for days with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

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. 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% of the time and a double jet 62.6% of the time, the residual 5.9% showed three peaks or more. We show the latitude probability density for the single jet and the two jets of the double jet structure 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 sector which shows a single jet 75.7% of the time and a double jet only 24.2% of the time.

The observed zonal asymmetry makes the zonal mean jet latitude a poorly defined metric. We sketch the resulting problem in Fig. 3, where we represent the observed jets using Gaussians. For demonstration purposes the jet spacing in the double jet structure is exaggerated slightly, but otherwise the values shown are realistic and fit in the range of model behaviour; see Figs. 4 and A1. Figure 3 shows that differences in the strength of the individual jets in the Pacific double jet structure lead to different zonal mean jet latitudes, even though none of the jet structures have moved. The results so far therefore suggest that the 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 shown in Fig. 1a (especially since it is not present in the separate halves of the hemisphere).

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

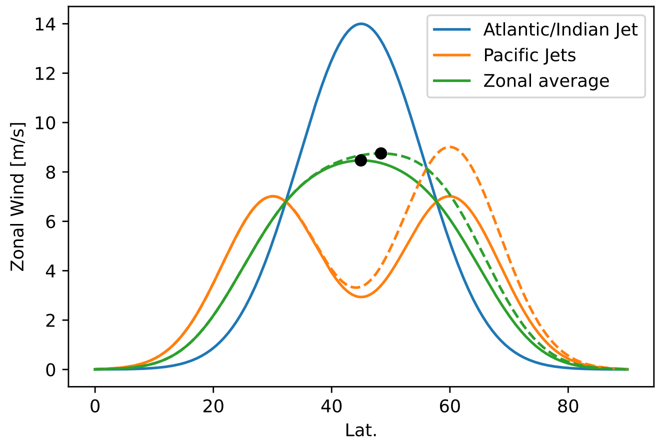

Figure 3. Sketch of the zonal mean zonal wind in the Atlantic/Indian and Pacific sectors and their zonal average. The dashed lines denote a different climatology, while the black dots mark the jet peaks in the two climatologies.

3.3 Toy Model

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

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

with θ the latitude, μ the jet latitude, σ the width and a the maximal jet strength. We set the values such that they fit the CMIP6 average for both the Pacific sector (see Fig. 4) and the Atlantic/Indian sector (see Fig. A1) for the historical and SSP5-8.5 scenario; the values can be found in Table 1. To simulate differences in historical jet latitude created by differences in double jet strength (as sketched in Fig. 3), we add a random variable equally distributed between $(-1.5, 1.5)\,\mathrm{m\,s^{-1}}$ to a_1 and a second random variable equally distributed between $(-3, 3)\,\mathrm{m\,s^{-1}}$ to a_2, creating 22 different realisations that emulate the range of CMIP6 model behaviour seen in Figs. 4a and b and the therefore also the response in Fig. 4c. These realisations correspond to the shaded red lines in Fig. 4. While this model will surely not capture 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.

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

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

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

Table 1. Toy model parameters from Eq. (1) used to fit the Atlantic/Indian jet (see Fig. A1) 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 parameter values that change between the historical and SSP5-8.5 scenario.

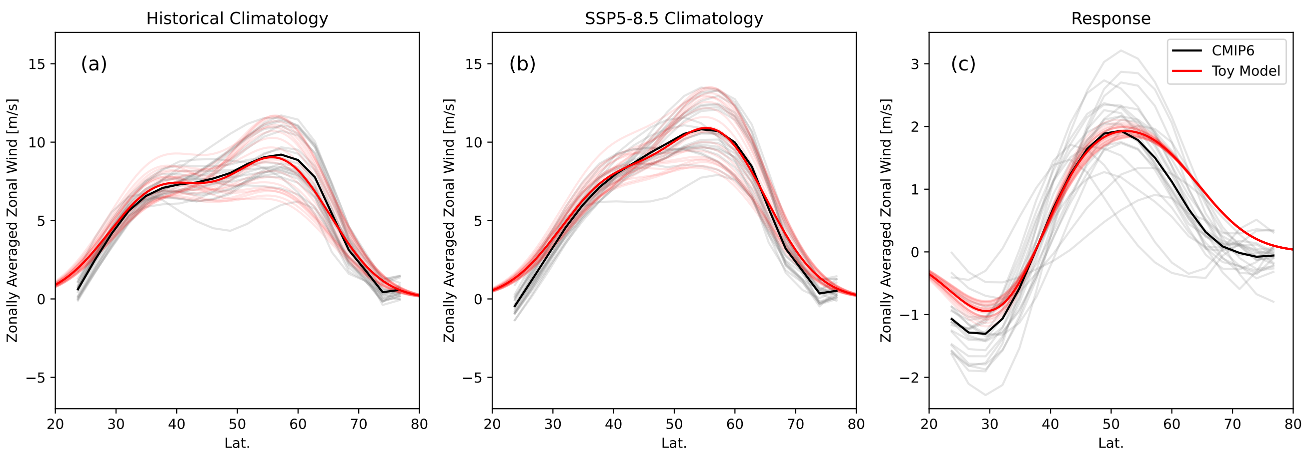

Figure 4. Zonal mean zonal wind in the Pacific sector (120°- 300°); individual CMIP6 models in grey and their average in black. In light red are the individual realisations of the toy model (see Section 3.3) and in bright red their average. **(a)** Historical period, **(b)** the SSP5-8.5 scenario, and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

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 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. We observe that the toy model can reproduce 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).

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

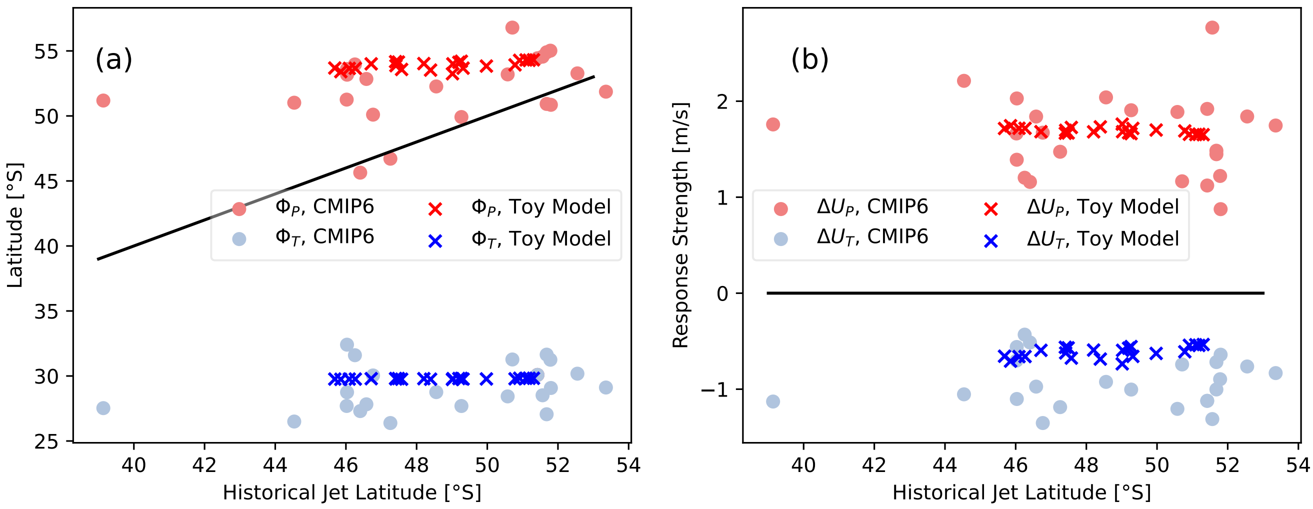

Figure 5. Comparison of the response structure of the CMIP6 ensemble with the toy model results. **(a)** Φ_P and Φ_T, respectively the latitude of the peak and trough of the zonal wind response, against the historical jet latitude. The black line shows the identity. **(b)** ΔU_P and ΔU_T, respectively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

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 in zonal-mean historical jet latitude come from differences in relative 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 the Pacific double jet strengths (see sections 3.2 and 3.3). In the toy model we use 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 in Fig. 5a. We note that unlike the toy model, the CMIP6 ensemble does show inter-model differences in the zonal mean response (Fig. A2c), which are the cause for the larger spread of Φ_P and Φ_T compared to the toy model, but crucially the differences do not seem to be related to the historical jet latitude.

Furthermore, 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 half), we also observe a jet strengthening (the poleward one in the Pacific half and the single jet in the Atlantic/Indian half). This leads to the response peak (ΔU_P) being stronger than the response trough (ΔU_T).

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

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 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. In the toy model, the EC arises from the fact that the response is the same in all realisations, but how much it projects onto a shift depends on the climatological jet latitude. This explanation was already proposed by Simpson and Polvani (2016). However, 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 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 did not find a relation when considering the jets of the double jet structure individually (not shown).

4 Summary and Conclusion

We demonstrate that the wintertime zonal mean jet latitude is a poorly defined quantity, since it averages over a single jet structure in the Atlantic/Indian 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 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)) is an artefact of the zonally asymmetric jet structure in CMIP5 and CMIP6 .

Based on these findings, we show that the previously identified emergent constraint between 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 physical interpretation of this emergent constraint is unclear, since the measure of zonal mean jet latitude is poorly defined. This conclusion is further supported by the fact that the EC only holds in the zonal mean and does not appear in the Pacific or Atlantic/Indian halves of the hemisphere separately. Thus, it appears 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.

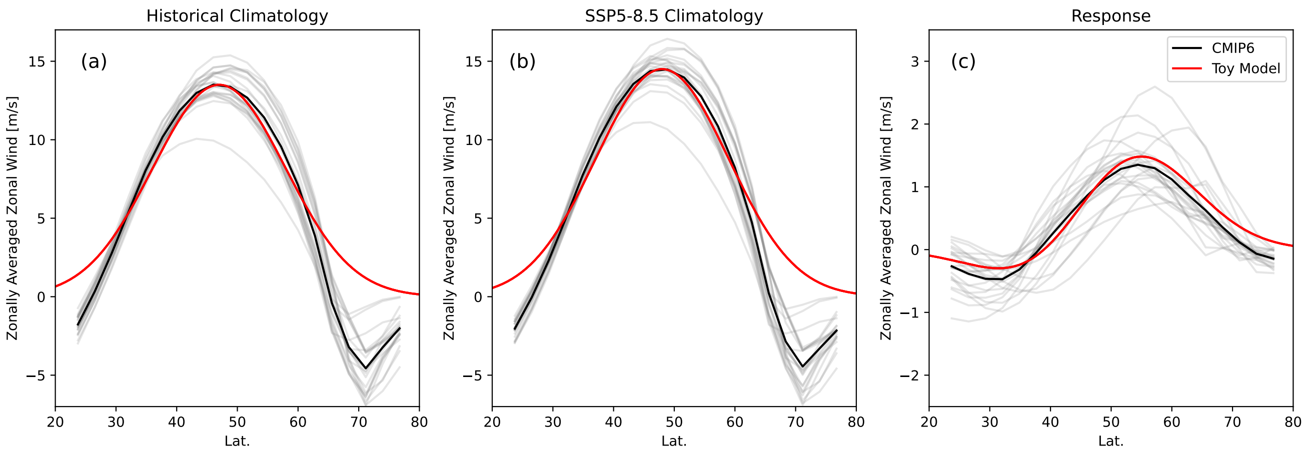

Figure A1. As in Fig. 4 but for the Atlantic/Indian sector (300°- 120°).

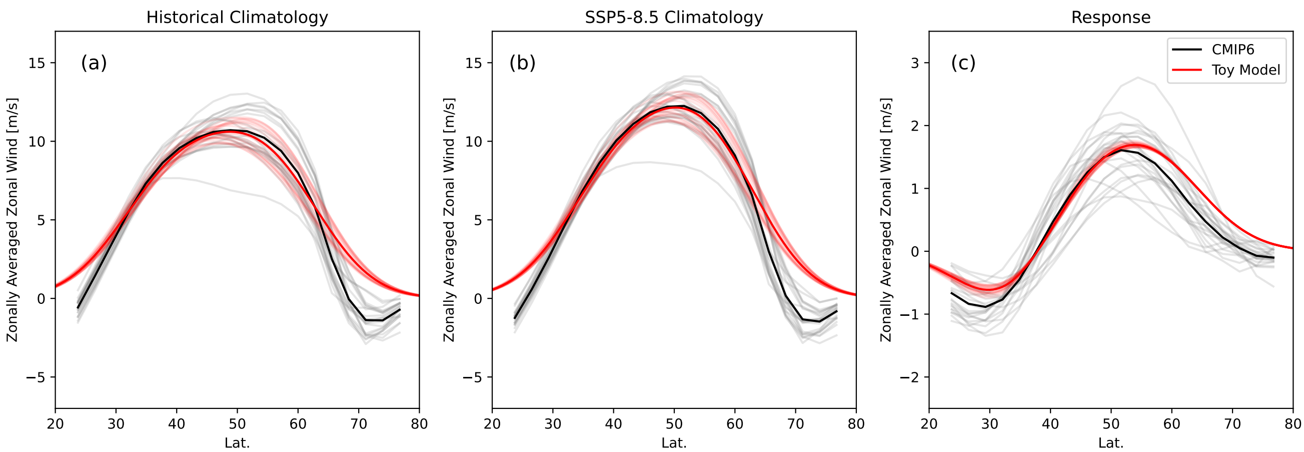

Figure A2. As in Fig. 4 but for the full-hemispheric zonal mean.

165 ## Appendix A: Toy Model

Here we show the same comparison of zonal mean zonal winds from the CMIP6 ensemble with the toy model as in Fig. 4, but for the Atlantic/Indian sector (Fig. A1) and the full hemispheric zonal mean (Fig. A2).

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

Acknowledgements. We are grateful to Camille Li for a helpful discussion. Philipp Breul was supported by the Centre for Doctoral Training in Mathematics of Planet Earth. This research has been supported by the Engineering and Physical Sciences Research Council (grant no. EP/L016613/1), the Imperial College London, and the Natural Environment Research Council (grant no. NE/T006250/1)

https://doi.org/10.5194/wcd-2022-42
Preprint. Discussion started: 26 July 2022

Weather and Climate Dynamics Discussions
Open Access EGU

References

Barnes, E. A. and Polvani, L.: Response of the Midlatitude Jets, and of Their Variability, to Increased Greenhouse Gases in the CMIP5 Models, Journal of Climate, 26, 7117–7135, https://doi.org/10.1175/JCLI-D-12-00536.1, 2013.

Breul, P., Ceppi, P., and Shepherd, T. G.: Relationship between southern hemispheric jet variability and forced response: the role of the stratosphere, Weather and Climate Dynamics, 3, 645–658, https://doi.org/10.5194/wcd-3-645-2022, 2022.

Codron, F.: Relations between Annular Modes and the Mean State: Southern Hemisphere Winter, Journal of the Atmospheric Sciences, 64, 3328–3339, https://doi.org/10.1175/JAS4012.1, 2007.

Curtis, P. E., Ceppi, P., and Zappa, G.: Role of the mean state for the Southern Hemispheric jet stream response to CO2 forcing in CMIP6 models, Environmental Research Letters, 15, 064 011, https://doi.org/10.1088/1748-9326/ab8331, publisher: IOP Publishing, 2020.

Goltz, H. H. and Smith, M. L.: Yule-Simpson's Paradox in Research, https://doi.org/10.7275/DGCC-JV81, publisher: University of Massachusetts Amherst, 2010.

Hall, A., Cox, P., Huntingford, C., and Klein, S.: Progressing emergent constraints on future climate change, Nature Climate Change, 9, 269–278, https://doi.org/10.1038/s41558-019-0436-6, 2019.

Inatsu, M. and Hoskins, B. J.: The Zonal Asymmetry of the Southern Hemisphere Winter Storm Track, Journal of Climate, 17, 4882–4892, https://doi.org/10.1175/JCLI-3232.1, 2004.

Kidston, J. and Gerber, E. P.: Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology, Geophysical Research Letters, 37, https://doi.org/10.1029/2010GL042873, 2010.

Kubo, R.: The fluctuation-dissipation theorem, Rep. Prog. Phys, p. 31, 1966.

Leith, C. E.: Climate Response and Fluctuation Dissipation, Journal of the Atmospheric Sciences, 32, 2022–2026, https://doi.org/10.1175/1520-0469(1975)032<2022:CRAFD>2.0.CO;2, publisher: American Meteorological Society, 1975.

Ring, M. J. and Plumb, R. A.: The Response of a Simplified GCM to Axisymmetric Forcings: Applicability of the Fluctuation–Dissipation Theorem, Journal of the Atmospheric Sciences, 65, 3880–3898, https://doi.org/10.1175/2008JAS2773.1, 2008.

Shepherd, T. G.: Atmospheric circulation as a source of uncertainty in climate change projections, Nature Geoscience, 7, 703–708, https://doi.org/10.1038/ngeo2253, 2014.

Simpson, I. R. and Polvani, L. M.: Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes, Geophysical Research Letters, 43, 2896–2903, https://doi.org/10.1002/2016GL067989, 2016.

Simpson, I. R., McKinnon, K. A., Davenport, F. V., Tingley, M., Lehner, F., Al Fahad, A., and Chen, D.: Emergent constraints on the large scale atmospheric circulation and regional hydroclimate: do they still work in CMIP6 and how much can they actually constrain the future?, Journal of Climate, pp. 1–62, https://doi.org/10.1175/JCLI-D-21-0055.1, 2021.