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Testing Latitudinally Dependent Explanations of the Circulation Response to Increased CO_2 Using Aquaplanet Models

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Key Points:

- We test explanations of the circulation response to increased CO2 using aquaplanet models with latitudinally dependent CO2 concentration
- Increased CO2 in the tropics accounts for the subtropical jet response
- The response to increased CO2 is mostly linear, and increased CO2 in the subtropics dominates the circulation shift

Supporting Information:

- Figure S1

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Abstract The atmospheric circulation exhibits robust responses to increased CO_2 that emerge across the climate model hierarchy. Existing theoretical explanations of the circulation response can be grouped according to latitude. Here we test latitudinally dependent explanations of the circulation response to increased CO_2 using slab ocean aquaplanet models with latitudinally dependent CO_2 concentration. Quadrupling CO_2 in the tropics (0–20°) accounts for the strengthening and upward shift of the subtropical jet but does not account for the poleward shift of the Hadley cell edge or extratropical circulation. The tropical response is dominated by regions of descent. When CO_2 is quadrupled in high latitudes (60–90°), there is a negligible circulation response. The response to latitudinally dependent increased CO_2 is mostly linear and increased CO_2 in the midlatitudes (20–60°) dominates. Within the midlatitudes, the subtropics (20–40°) dominate. Thus, story lines explaining the circulation shift in response to increased CO_2 should focus on the thermodynamic response in the subtropics.

Plain Language Summary The atmospheric circulation controls the regional response to global warming. There are several robust responses to global warming according to state-of-the-art climate models: (1) the subtropical jet will strengthen and shift upward and (2) the Hadley cell edge, storm tracks, and jet stream will shift poleward. In contrast to the thermodynamic response to climate change, which includes warming of the troposphere, cooling of the stratosphere, warming aloft in the tropics, and Arctic amplification at the surface, robust physically based story lines of the circulation response are lacking. The lack of robust story lines occurs in part because there are many explanations put forward in the literature to explain the circulation response, which have not been properly compared. Here we test latitudinally dependent explanations of the circulation response to increased CO_2 using idealized simulations with latitudinally dependent CO_2 concentration. The results show that increased CO_2 in the tropics accounts for the strengthening and upward shift of the subtropical jet and increased CO_2 in midlatitudes accounts for the poleward shift of the Hadley cell edge, storm track, and jet stream. Within the midlatitudes the subtropics dominate.

1. Introduction

The atmospheric circulation exhibits robust responses to increased CO_2, including a strengthening and upward shift of the subtropical jet, poleward shift of the Hadley cell edge, eddy-driven jet, and storm tracks (Shaw et al., 2016; Vallis et al., 2015). These responses emerge across the climate model hierarchy (Medeiros et al., 2014; Vallis et al., 2015). In contrast to the thermodynamic response to increased CO_2, robust physically based story lines explaining the circulation response are lacking (Bony et al., 2015; Vallis et al., 2015). The lack of robust story lines occurs in part because there are many explanations (scaling arguments or simulations with idealized models) put forward in the literature to explain the circulation response, which have not been systematically compared in aquaplanet models. The explanations can be grouped according to latitude.

In the tropics, the thermodynamic response to increased CO_2 involves (1) rising of the tropopause, (2) increased dry static stability, and (3) an upward shift of high clouds. Rising of the tropical tropopause leads to a poleward shift of the Hadley cell edge according to axisymmetric theories (Held & Hou, 1980). Increased dry static stability via imposed changes in tropical lapse rate or diabatic heating in dry dynamical core models leads to a poleward shift of the Hadley cell edge and storm tracks (Butler et al., 2010; Mbengue & Schneider, 2013; Tandon et al., 2013). Furthermore, increased tropical stability implies a strengthening of the subtropical jet via thermal wind balance, which has been argued to induce circulation shifts via changes in potential vorticity (Lu et al., 2014). The upward shift of tropical high clouds, which dominates the longwave cloud radiative effect and mostly follows the fixed-anvil temperature hypothesis (Hartmann & Larson, 2002), shifts the Hadley cell edge and eddy-driven jet poleward in prescribed sea surface temperature (SST) aquaplanet models (Voigt & Shaw, 2015, 2016).

In high latitudes, the thermodynamic response to increased CO_2 involves Arctic amplification, which is mainly due to lapse rate and albedo feedbacks (Pithan & Mauritsen, 2014). Imposed surface diabatic heating in high latitudes shifts the eddy-driven jet equatorward in dry dynamical core simulations (Butler et al., 2010). In addition, imposed shortwave cloud radiative changes, which are assumed to be driven by local warming and dominate the cloud radiative effect in high latitudes in response to increased CO_2, shift the midlatitude circulation poleward in a slab ocean aquaplanet model (Ceppi & Hartmann, 2016).

Finally, in midlatitudes, the thermodynamic response to increased CO_2 involves (1) rising of the tropopause, (2) increased dry static stability, (3) strengthening of the near-surface moist static energy (MSE) gradient, and (4) an upward shift of high clouds. Increased midlatitude tropopause height and dry static stability have been connected to Hadley cell expansion via a scaling relationship that assumes that the Hadley cell is terminated at the latitude of the onset of baroclinic instability (Frierson et al., 2007; Held, 2000; Levine & Schneider, 2015; Lu et al., 2007). Increased dry static stability has been connected to the importance of convection and eddy latent heat transport in determining the midlatitude lapse rate (Frierson, 2006, 2008; O'Gorman, 2011; Schneider & O'Gorman, 2008; Schneider et al., 2010). The strengthening of the MSE gradient in response to warming shifts the midlatitude circulation poleward following diffusive energy balance arguments (Shaw & Voigt, 2016). Finally, the upward and poleward movement of midlatitude high clouds shifts the jet poleward in prescribed SST aquaplanet models (Voigt & Shaw, 2016).

Many of the explanations discussed above were examined via imposed latitudinally dependent diabatic perturbations (heating perturbations in dry dynamical core models or cloud radiative and ocean heat transport perturbations in aquaplanet models). Diabatic perturbations are problematic because they cannot be imposed a priori; they require knowledge of the equilibrium response to increased CO_2, which involves nonlocal effects (via the circulation). A more straightforward test of latitudinally dependent explanations of the circulation response to increased CO_2 is to perturb the CO_2 concentration in different latitudinal regions. Here we perform such a test using slab ocean aquaplanet models with latitudinally dependent CO_2 concentration. If tropical explanations dominate the circulation response, then increasing CO_2 only in the tropics should capture the response when CO_2 increases everywhere. Analogous arguments can be made for other regions. The results of these tests help to rule out latitudinally dependent explanations and quantify the importance of nonlocal effects. Further progress, including formulating robust physically based story lines for the circulation response to increased CO_2, can then be achieved by testing the mechanisms operating within the latitudinal region that dominate the response when CO_2 increases everywhere.

2. Model Simulations

We use two slab ocean aquaplanet models: (1) MPI-ESM-LR, hereafter MPI (Stevens, 2013) and (2) GFDL-AM2, hereafter GFDL (Anderson et al., 2004). The climatological aquaplanet simulations are configured as follows: (1) diurnal cycle but no seasonal cycle (eccentricity and obliquity are zero), (2) slab ocean depth is 50 m with no ocean heat transport, (3) greenhouse gases are $CO_2 = 348$ ppmv, $CH_4 = 1,650$ ppbv, $N_2O = 306$ ppbv, CFC-11 = 0, CFC-12 = 0, (4) ozone is identical to that in the Aquaplanet Experiment (Blackburn & Hoskins, 2013), and (5) no sea ice (surface temperatures can drop below freezing). This configuration follows previous simulations (Ceppi & Hartmann, 2016; Voigt et al., 2016). All simulations are run for 40 years with 10 years of spin up with results averaged over both hemispheres.

Climate change is simulated by increasing CO_2 to 4 times its climatological value ($CO_2 = 1,392$ ppmv). The aquaplanets are configured to include latitudinally dependent CO_2 concentration, that is, the CO_2 concentration is prescribed separately in each grid column following Shaw and Voigt (2016) and Huang et al. (2017). CO_2 is increased separately in the tropics (0–20°), high latitudes (60–90°), and midlatitudes (20-60°). In practice, the regional CO_2 increase is a step function with the CO_2 increased within the latitudinal regions.

We focus on the following circulation responses to increased CO_2: (1) strengthening and upward shift of the subtropical jet, (2) shift of the Hadley cell edge defined as the latitude where the surface zonal mean zonal

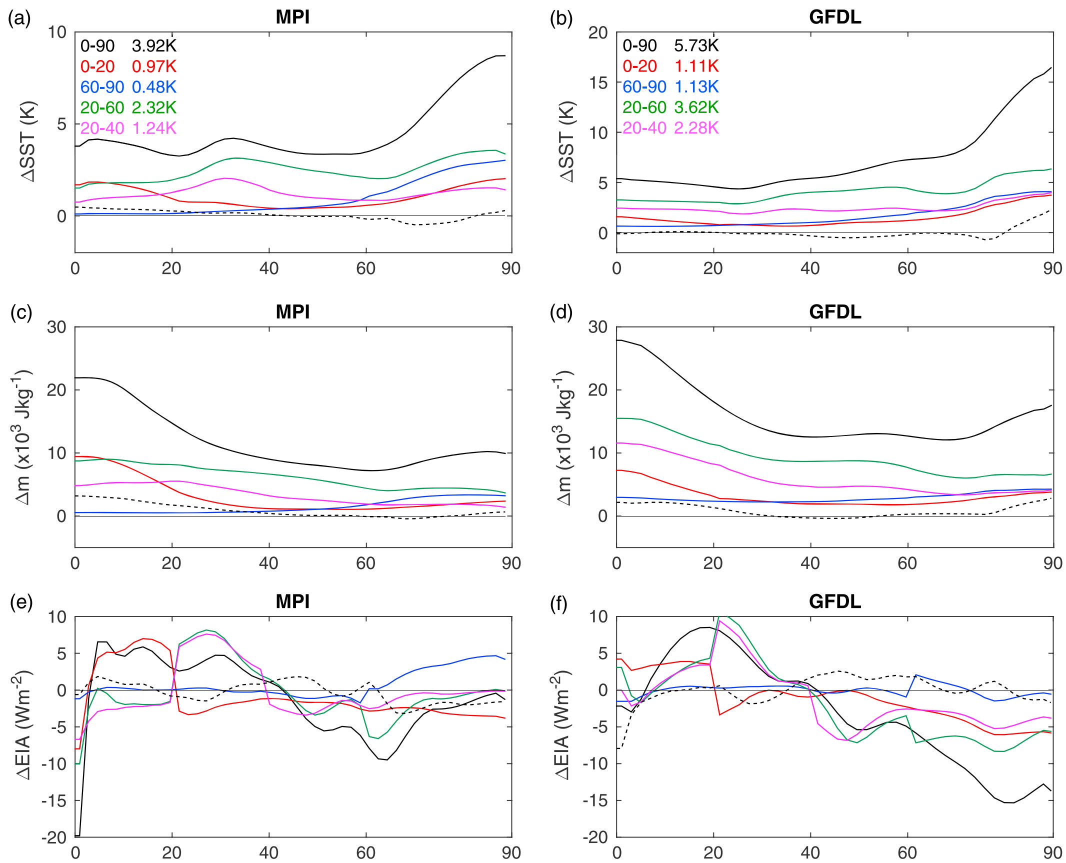

Figure 1. Response of time mean, zonal mean (a, b) sea surface temperature (SST), (c, d) near-surface MSE (m), and (e, f) energy input to the atmosphere (EIA) to latitudinally dependent 4xCO_2. Dashed black lines indicate the residual (sum of response to 0–20°, 60–90°, and 20–60° minus 0–90°). Global mean SST response shown in top-left of panels (a) and (b).

wind is zero ($\phi_{u=0}$) or where the 700-hPa Eulerian streamfunction is zero ($\phi_{\Psi=0}$) or where zonal mean precipitation minus evaporation is zero ($\phi_{P-E=0}$), (3) shift of the eddy-driven jet defined by the latitude of maximum cosine-weighted surface zonal mean zonal wind ($\phi_{\mathrm{u=max}}$), and (4) shift of the storm track defined as the latitude where zonal mean vertically integrated transient eddy MSE flux divergence is zero (ϕ_{st}, see Barpanda & Shaw, 2017; Shaw et al., 2018). Transient eddies are defined as deviations from the monthly mean. In all cases we focus on shifts whose absolute value is >1°, which is the amplitude of monthly internal variability in the models.

3. Results

The slab ocean aquaplanets exhibit the robust thermodynamic responses to increased CO_2 seen in prescribed SST aquaplanets (Medeiros et al., 2014) and coupled climate models (Vallis et al., 2015). In particular, there is global SST warming (3.9 K in MPI and 5.7 K in GFDL) and polar SST (60–90°) amplification (black lines, Figures 1a and 1b). The temperature response is amplified aloft in the tropics reflecting increased dry static stability (first column, Figure 2), consistent with the tropical troposphere remaining close to neutral stability relative to a moist adiabat. The near-surface MSE exhibits tropical amplification (black lines, Figures 1c and 1d) consistent with the dominance of changes in near-surface specific humidity and a strengthening of the climatological MSE gradient. Energy input to the atmosphere (EIA, i.e., top-of-atmosphere fluxes) increases in the tropics (except near the equator) and the subtropics but decreases in the extratropics (black lines, Figures 1e and 1f). The EIA changes are consistent with increased poleward energy transport due to the increase in atmospheric moisture content (Huang & Frierson, 2010). Finally, the tropopause rises globally (compare solid and dashed magenta lines in Figure 2, first column).

The slab ocean aquaplanets also exhibit a familiar circulation response. Aloft there is a strengthening and upward shift of the subtropical jet, and there is a dipole around the climatological maximum surface wind

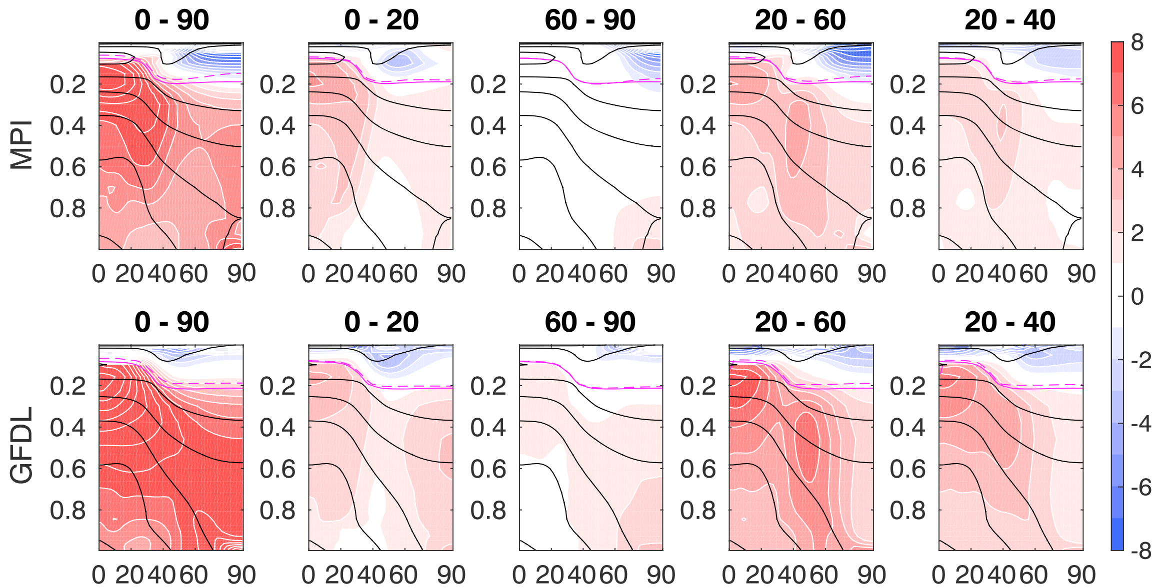

Figure 2. Response of time mean, zonal mean temperature (shading, contour interval 1 K) as a function of sigma level (pressure normalized by surface pressure) and latitude to latitudinally dependent 4xCO_2. Climatology indicated by black contours (contour interval 20 K up to 300 K). WMO tropopause for climatology and 4xCO_2 climate indicated by solid and dashed magenta lines, respectively.

(first column, Figure 3). In addition, the Hadley cell weakens in the tropics (first column, Figure 4). In terms of circulation shifts, there is a robust poleward shift of the Hadley cell edge defined using surface winds, Eulerian streamfunction or precipitation minus evaporation and a poleward shift of the eddy-driven jet and storm track (black x, Figure 5).

3.1. Tropical CO_2 Increase

We begin by evaluating the response to increased CO_2 in the tropics (0–20°) and assess whether it captures the thermodynamic and circulation response when CO_2 increases everywhere. Increasing CO_2 in the tropics (0–20°) accounts for only 20–25% of the global SST warming when CO_2 increases everywhere (compare red and black lines, Figures 1a and 1b). The tropical CO_2 increase leads to polar amplification of SST, highlighting

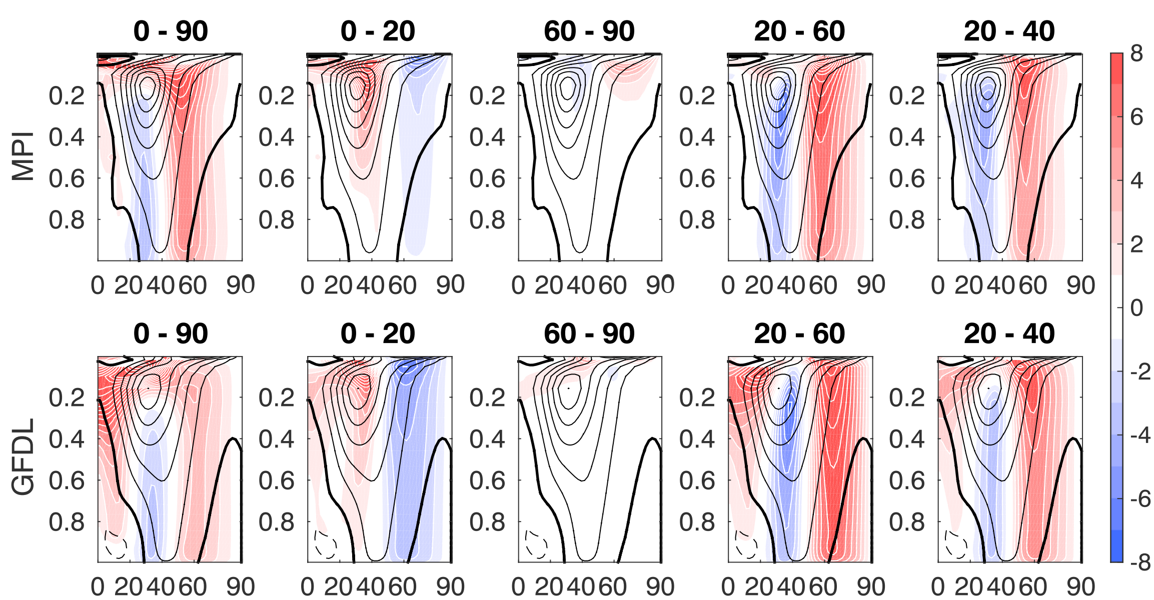

Figure 3. As in Figure 2 but for the response of zonal mean zonal wind (shading, contour interval 1 m/s, black contour interval 10 m/s, negative contours dashed).

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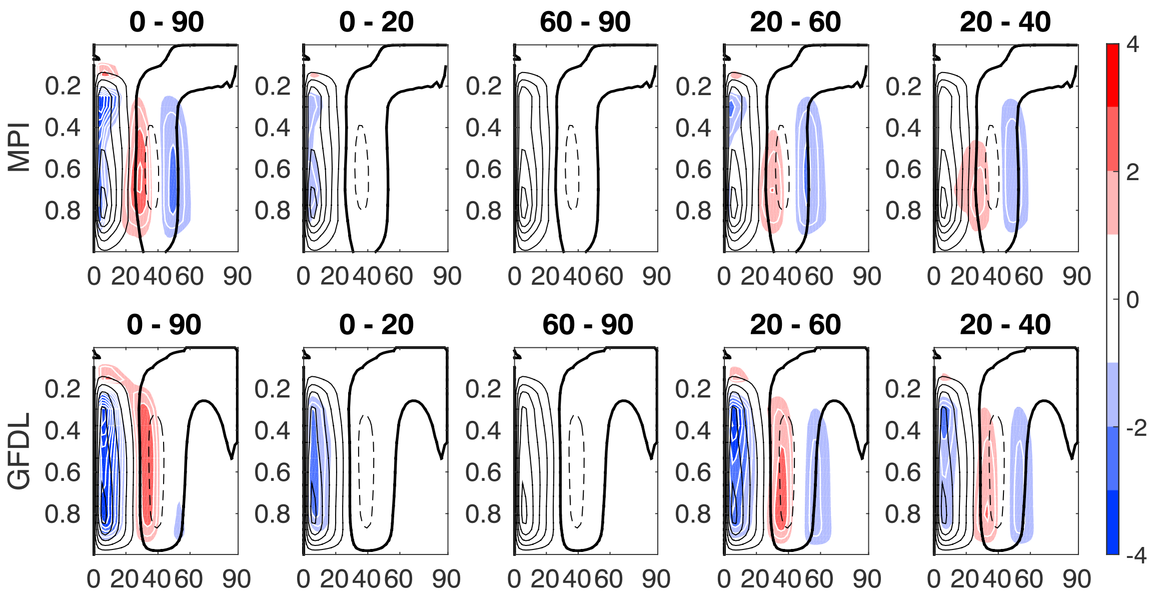

Figure 4. As in Figure 2 but for the response of zonal mean Eulerian streamfunction (shading, contour interval 0.5×10^{10} kg/s, black contour interval 5×10^{10} kg/s, negative contours dashed).

the importance of nonlocal effects and tropical amplification of MSE; however, it does not dominate the response when CO_2 increases everywhere (compare red and black lines, Figures 1a–1d). In response to increased CO_2 in the tropics the EIA response near the equator is not robust across the models. It dominates the tropical response when CO_2 increases everywhere for MPI but not GFDL (compare red and black lines, Figures 1e and 1f). Finally, increased CO_2 in the tropics leads to increased tropical dry static stability (second column, Figure 2) and a small rise of the tropopause (magenta lines, second column, Figure 2). Clearly, increased CO_2 in the tropics contributes to the thermodynamic response when CO_2 increases everywhere but it does not dominate overall.

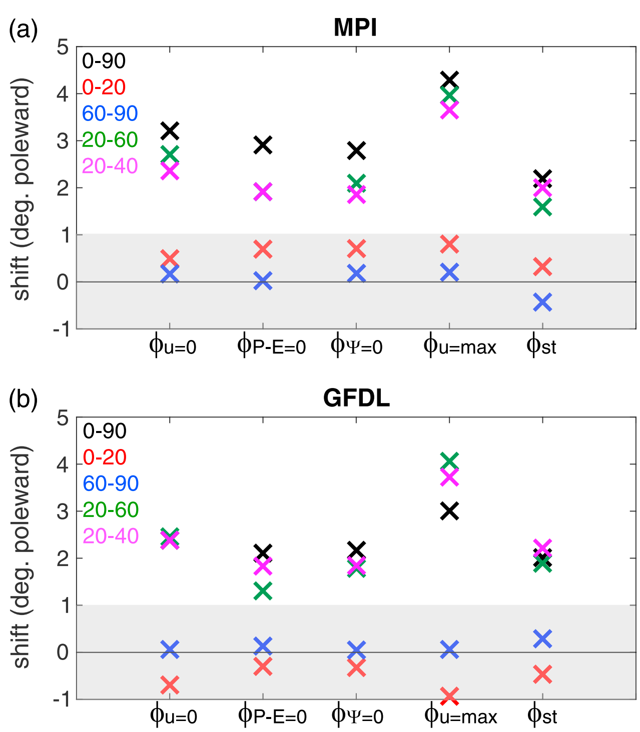

Figure 5. Circulation shift in response to latitudinally dependent $4xCO_2$ (see section 2 for more information). Gray shading indicates shifts whose absolute value is ≤1°. N.B. in panel (a) the green cross is hidden behind the magenta cross for $\phi_{P-E=0}$ and in panel (b) the black cross is hidden behind the magenta cross for $\phi_{u=0}$.

In terms of the circulation response, the tropical CO_2 increase dominates the strengthening and upward shift of the subtropical jet (compare first and second columns, Figure 3) and contributes to the weakening of the Hadley cell (second column, Figure 4). The dominance of the tropical CO_2 increase for the subtropical jet response is consistent with it dominating the upper tropospheric temperature gradient response in the subtropics (supporting information Figure S1). However, increased CO_2 in the tropics does not dominate the zonal wind response at the surface. Furthermore, the circulation shift is not robust: there is a weak (≲1°) poleward shift of the circulation in the MPI model and a weak equatorward shift in the GFDL model (red x, Figure 5).

The results show that increased CO_2 in the tropics dominates the response of the subtropical jet, suggesting that it is sufficient for explaining its strengthening and upward shift when CO_2 increases everywhere. However, increased CO_2 in the tropics does not dominate the circulation shift. Thus, we move on to assess the impact of regions outside the tropics to the circulation shift.

3.2. High-Latitude CO_2 Increase

Increasing CO_2 in high latitudes (60–90°) accounts for 10-20% of the global SST warming and contributes less than half of the polar warming when CO_2 increases everywhere (compare black and blue lines, Figures 1a and 1b and first and third columns, Figure 2). The fact that increased CO_2 in high latitudes does not dominate polar amplification highlights the importance of nonlocal effects (via the circulation). Increased CO_2 in high latitudes does not contribute significantly to the responses of near-surface MSE, EIA (compare black and blue lines, Figures 1c–1f) and tropopause height (compare magenta lines, first and third columns, Figure 2).

The circulation response to increased CO_2 in high latitudes is negligible and does not extend to the surface (third column, Figures 3 and 4). Consistently, the circulation shift is weak in response to increased CO_2 in high latitudes (blue x, Figure 5). The small circulation shift may be the result of opposing behavior induced by polar amplification at the surface (equatorward shift) and polar stratospheric cooling (poleward shift; Butler et al., 2010). There are several other examples of opposing influences on the circulation response to increased CO_2 (cf. Barnes & Screen, 2015; Harvey et al., 2014; Shaw et al., 2016). Overall, increased CO_2 in high latitudes is not sufficient to explain the circulation shift when CO_2 increases everywhere.

3.3. Midlatitude CO_2 Increase

Assuming the response to latitudinally dependent CO_2 is close to linear (confirmed below), the results suggest increased CO_2 in midlatitudes dominates the circulation shift when CO_2 increases everywhere.

Increased CO_2 in midlatitudes (20–60°) accounts for 60% of the global SST warming when CO_2 increases everywhere. It also dominates the polar SST response (compare black and green lines, Figures 1a and 1b), the near-surface MSE response at most latitudes (compare black and green lines, Figures 1c and 1d) and the EIA response in midlatitudes (compare black and green lines, Figures 1e and 1f). In addition, it dominates the warming aloft in the tropics, including the increase in dry static stability (compare first and fourth columns, Figure 2), and the rising of the tropopause globally (compare magenta lines, first and fourth columns, Figure 2). Overall, the thermodynamic response to increased CO_2 in midlatitudes dominates the response when CO_2 increases everywhere (compare columns in Figure 2).

Increased CO_2 in midlatitudes also dominates the zonal wind response at the surface (compare first and fourth columns, Figure 3), the poleward shift of the Hadley and Ferrel cells and contributes to the weakening of the Hadley cell (compare first and fourth columns, Figure 4). Consistently, increased CO_2 in midlatitudes dominates the circulation shift when CO_2 increases everywhere (green x, Figure 5). Within the midlatitudes, increased CO_2 in the subtropics (20–40°) dominates over increased CO_2 in subpolar latitudes (40–60°) for the circulation shift response (compare fourth and fifth columns in Figures 3 and 4, green and magenta x in Figure 5, and supporting information Figures S2–S5).

3.4. Residual, Robustness, and Alternative Decompositions

The thermodynamic and circulation responses to the latitudinally dependent CO_2 increase are close to linear (dashed black line, Figure 1 and Figure S6). In general, the responses are more linear for (1) the troposphere than the stratosphere, (2) temperature than zonal wind, and (3) MPI than GFDL. Overall, the results confirm that increased CO_2 in the tropics dominates the strengthening and upward shift of the subtropical jet, whereas increased CO_2 in the subtropics dominates the poleward shift of the circulation.

The latitudinally dependent decomposition is robust to the inclusion of seasonal insolation. In particular, increased CO_2 in the tropics dominates the response of the subtropical jet, and increased CO_2 in the subtropics dominates the shift of the circulation for the annual mean response to increased CO_2 in the presence of a seasonal cycle (Figures S7–S12). In the presence of a seasonal cycle there is no polar amplification (Kim et al., 2018) and the latitudinally dependent decomposition is more linear.

The decomposition of increased CO_2 in the tropics (0–20°), high latitudes (60–90°), and midlatitudes (20–60°) was motivated by the explanations of the circulation response discussed in section 1. However, the latitudinal regions have different areas, which may play a role in their effectiveness at provoking a circulation response. To quantify the area effect, we follow Shaw and Voigt (2016) and rescale the CO_2 concentration relative to the tropical area, that is, 4xCO_2 in the tropics, 9.94xCO_2 in high latitudes, 2.38xCO_2 in the midlatitudes, and 4.13xCO_2 in the subtropics. When the CO_2 concentration is rescaled to account for area, the effectiveness of the different latitude regions in provoking a thermodynamic response changes. In particular, increased CO_2 in high latitudes dominates Arctic amplification at the surface and increased CO_2 in the tropics dominates the increase of tropical dry static stability in MPI (Figures S13–S14). However, the effectiveness of the different latitudinal regions in provoking a circulation response is independent of area. In particular, increased CO_2 in the tropics still dominates the subtropical jet response and increased CO_2 in the subtropics still dominates the circulation shift (Figures S15–S17).

Finally, Merlis (2015) showed that the weakening of the Hadley cell is consistent with a small direct CO_2 radiative forcing in regions of tropical ascent due to masking by climatological cloud and water vapor. This result motivates an alternative latitudinal decomposition. When CO_2 is increased in regions of climatological tropical ascent (0–5°), there is no significant circulation response (supporting information Figures S18–S21). Thus, the weakening of the Hadley cell and strengthening and upward shift of the subtropical jet are consistent with the response to increased CO_2 in regions of descent.

4. Conclusions

Explaining the circulation response to increased CO_2 is one of the grand challenges of climate science (Bony et al., 2015). Here we tested latitudinally dependent explanations of the circulation response (e.g., strengthening and upward shift of the subtropical jet, shift of the Hadley cell edge, eddy-driven jet, and storm track) to increased CO_2 using slab ocean aquaplanet models with latitudinally dependent CO_2 concentration. Our conclusions can be summarized as follows:

- Increased CO_2 in the tropics (0–20°) dominates the strengthening and upward shift of the subtropical jet; however, it does not contribute significantly to the circulation shift. Within the tropics, the response to increased CO_2 in regions of descent dominate over regions of ascent.
- Increased CO_2 in high latitudes (60–90°) does not contribute significantly to the circulation shift. The ineffectiveness of increased CO_2 in high latitudes at provoking a circulation response is not related to its small area.
- The response to latitudinally dependent CO_2 is mostly linear, thus increased CO_2 in midlatitudes (20–60°) dominates the circulation shift when CO_2 increases everywhere. Within the midlatitudes, the subtropics dominate.

The importance of increased CO_2 in midlatitudes (20–60°), and more specifically the subtropics (20–40°), is consistent with previous work that documented (1) a significant correlation between the rising of the extratropical (35–55°) tropopause and Hadley cell expansion in coupled models (Lu et al., 2007), (2) the dominance of prescribed midlatitude cloud changes in response to warming for the poleward jet shift in aquaplanet models (Voigt et al., 2016), and (3) the sensitivity of circulation shifts to imposed subtropical diabatic heating (Allen et al., 2012; Tandon et al., 2013). The unimportance of tropical CO_2 increase is also consistent with aquaplanet models that exhibit nonrobust Intertropical Convergence Zone responses to global warming but robust midlatitude circulation responses (Medeiros et al., 2014).

We used increased CO_2 concentration in different latitudinal regions to test explanations of the circulation response to increased CO_2. Increasing the CO_2 concentration in different latitudinal regions has many advantages over imposed latitudinally dependent diabatic perturbations. The first advantage is that it does not make any assumption regarding the amplitude of the perturbation and the connection between diabatic heating and temperature. Imposing latitudinally dependent diabatic heating perturbations requires knowledge of the equilibrium response to increased CO_2 and an assumption about the connection between the diabatic heating and temperature responses, which in reality is mediated by the circulation. The second advantage is that it accounts for nonlocal effects between the different regions, which are also mediated by the circulation. The results here have quantified the importance of nonlocal effects. In particular, increased CO_2 in the midlatitudes and subtropics have global impacts, including on tropical and polar amplification. This is consistent with Roe et al. (2015) who used a diffusive MSE balance model to show that subtropical feedbacks induce a global response, whereas polar feedbacks are locally confined. The final advantage is that the response to increased CO_2 in different latitudinal regions can be quantitatively compared and thus explanations of the circulation response can be ruled out.

Physically based story lines summarizing the circulation response to increased CO_2 should be the outcome of testing falsifiable predictions or explanations. The results of the tests performed here suggest that story lines of the response of the subtropical jet to increased CO_2 should focus on the thermodynamic response in the tropics and story lines of the circulation shift in response to increased CO_2 should focus on the thermodynamic response in the subtropics. However, the tests cannot confirm the mechanisms operating within those regions. The mechanism responsible for the subtropical jet response may be the thermal wind response to increased dry static stability via moist adiabatic adjustment. There are several possible subtropical responses to increased CO_2 that could be responsible for the circulation shift. In particular, (1) rising of the tropopause

(Lorenz & DeWeaver, 2007; Vallis et al., 2015), (2) increased dry static stability (Frierson, 2006, 2008; Schneider & O'Gorman, 2008), (3) upward shift of high clouds (Voigt & Shaw, 2016), and (4) the sharpening of the near-surface MSE gradient (Shaw & Voigt, 2016). Further progress in understanding the circulation response to increased CO_2, including formulating physically based story lines, depends on configuring model experiments to test these explanations.

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References

Allen, R. J., Sherwood, S. C., Norris, J. R., & Zender, C. S. (2012). The equilibrium response to idealized thermal forcings in a comprehensive GCM: Implications for recent tropical expansion. *Atmospheric Chemistry and Physics*, *12*, 4795–4816.

Anderson, J. L., Balaji, V., Broccoli, A. J., Cooke, W. F., Delworth, T. L., Dixon, K. W., et al. (2004). The new GFDL global atmosphere and Land Model AM2-LM2: Evaluation with prescribed SST simulations. *Journal of Climate*, *17*, 4641–4673.

Barnes, E. A., & Screen, J. A. (2015). The impact of Arctic warming on the midlatitude jetstream: Can it? has it? will it? *WIREs Climate Change*, *6*, 277–286.

Barpanda, P., & Shaw, T. A. (2017). Using the moist static energy budget to understand storm-track shifts across a range of time scales. *Journal of the Atmospheric Sciences*, *74*, 2427–2446.

Blackburn, M., & Hoskins, B. J. (2013). Context and aims of the aqua-planet experiment. *Journal of the Meteorological Society of Japan*, *91A*, 1–15.

Bony, S., Stevens, B., Frierson, D. M. W., Jakob, C., Kageyama, M., & Pincus, R. (2015). Clouds, circulation and climate sensitivity. *Nature Geoscience*, *8*, 261–268. https://doi.org/10.1038/NGEO2398

Butler, A. H., Thompson, D. W. J., & Heikes, R. (2010). The steady-state atmospheric circulation response to climate change-like thermal forcings in a simple general circulation model. *Journal of Climate*, *23*, 3474–3496.

Ceppi, P., & Hartmann, D. L. (2016). Clouds and the atmospheric circulation response to warming. *Journal of Climate*, *29*, 783–799.

Frierson, D. M. W. (2006). Robust increases in midlatitude static stability in simulations of global warming. *Geophysical Research Letters*, *33*, L24816. https://doi.org/10.1029/2006GL027504

Frierson, D. M. W. (2008). Midlatitude static stability in simple and comprehensive general circulation models. *Journal of the Atmospheric Sciences*, *65*, 1049–1062.

Frierson, D. M. W., Lu, J., & Chen, G. (2007). Width of the Hadley cell in simple and comprehensive general circulation models. *Geophysical Research Letters*, *34*, L18804. https://doi.org/10.1029/2007GL031115

Hartmann, D. L., & Larson, K. (2002). An important constraint on tropical cloud—Climate feedback. *Geophysical Research Letters*, *29*, 1951. https://doi.org/10.1029/2002GL015835

Harvey, B. J., Shaffrey, L. C., & Woollings, T. J. (2014). Equator-to-pole temperature differences and the extra-tropical storm track responses of the CMIP5 climate models. *Climate Dynamics*, *43*, 1171–1182.

Held, I. M. (2000). *The general circulation of the atmosphere*. Paper presented at 2000 Woods Hole Oceanographic Institute Geophysical Fluid Dynamics Program, Woods Hole Oceanogr. Inst., Woods Hole, MA. Retrieved from http://gfd.whoi.edu/proceedings/2000/PDFvol2000.html

Held, I. M., & Hou, A. Y. (1980). Nonlinear axially symmetric circulation in a nearly inviscid atmosphere. *Journal of the Atmospheric Sciences*, *37*, 515–533.

Huang, Y.-T., & Frierson, D. M. W. (2010). Increasing atmospheric poleward energy transport with global warming. *Geophysical Research Letters*, *37*, L24807. https://doi.org/10.1029/2010GL045440

Huang, Y., Xia, Y., & Tan, X. (2017). On the pattern of CO_2 radiative forcing and poleward energy transport. *Journal of Geophysical Research: Atmospheres*, *122*, 10,578–10,593. https://doi.org/10.1002/2017JD027221

Kim, D., Kang, S. M., Shin, Y., & Feldl, N. (2018). Sensitivity of polar amplification to varying insolation conditions. *Journal of Climate*, *31*, 4933–4947.

Levine, X., & Schneider, T. (2015). Baroclinic eddies and the extent of the Hadley circulation: An idealized GCM study. *Journal of the Atmospheric Sciences*, *72*, 2744–2761.

Lorenz, D. J., & DeWeaver, E. T. (2007). Tropopause height and zonal wind response to global warming in the IPCC scenario integrations. *Journal of Geophysical Research*, *112*, D10119. https://doi.org/10.1029/2006JD008087

Lu, J., Sun, L., Wu, Y., & Chen, G. (2014). The role of subtropical irreversible PV mixing in the zonal mean circulation response to global warming-like thermal forcing. *Journal of Climate*, *27*, 2297–2316.

Lu, J., Vecchi, G. A., & Reichler, T. (2007). Expansion of the Hadley cell under global warming. *Geophysical Research Letters*, *34*, L06805. https://doi.org/10.1029/2006GL028443

Mbengue, C., & Schneider, T. (2013). Storm track shifts under climate change: What can be learned from large-scale dry dynamics. *Journal of Climate*, *26*, 9923–9930.

Medeiros, B., Stevens, B., & Bony, S. (2014). Using aquaplanets to understand the robust responses of comprehensive climate models to forcing. *Climate Dynamics*, *44*, 1957–1977. https://doi.org/10.1007/s00382-014-2138-0

Merlis, T. M. (2015). Direct weakening of tropical circulations from masked CO_2 radiative forcing. *Proceedings of the National Academy of Sciences*, *112*, 13,167–13,171.

O'Gorman, P. A. (2011). The effective static stability experienced by eddies in a moist atmosphere. *Journal of the Atmospheric Sciences*, *68*, 75–90.

Pithan, F., & Mauritsen, T. (2014). Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nature Geoscience*, *7*, 181–184. https://doi.org/10.1038/NGEO2071

Roe, G. H., Feldl, N., Armour, K. C., Hwang, Y.-T., & Frierson, D. M. W. (2015). The remote impacts of climate feedbacks on regional climate predictability. *Nature Geoscience*, *8*, 135–139. https://doi.org/10.1038/NGEO2346

Schneider, T., & O'Gorman, P. A. (2008). Moist convection and the thermal stratification of the extratropical troposphere. *Journal of the Atmospheric Sciences*, *65*, 3571–3583.

Schneider, T., O'Gorman, P. A., & Levine, X. J. (2010). Water vapor and the dynamics of climate changes. *Reviews of Geophysics*, *48*, RG3001. https://doi.org/10/2009RG000302

Shaw, T. A., & Voigt, A. (2016). What can moist thermodynamics tell us about circulation shifts in response to uniform warming? *Geophysical Research Letters*, *43*, 4566–4575. https://doi.org/10.1002/2016GL068712

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y.-T., et al. (2016). Storm track processes and the opposing influences of climate change. *Nature Geoscience*, *9*, 656–664. https://doi.org/10.1038/NGEO2783

Shaw, T. A., Barpanda, P., & Donohoe, A. (2018). A moist static energy framework for zonal-mean storm-track intensity. *Journal of the Atmospheric Sciences*, *75*, 1979–1994.

Shaw, T. A., & Voigt, A. (2016). Land dominates the regional response to CO_2 direct radiative forcing. *Geophysical Research Letters*, *43*, 11,383–11,391. https://doi.org/10.1002/2016GL071368

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., et al. (2013). Atmospheric component of the MPI-M earth system model: ECHAM6. *Journal of Advances in Modeling Earth Systems*, *5*, 146–172. https://doi.org/10.1002/jame.20015

Tandon, N., Gerber, E. P., Sobel, A. H., & Polvani, L. M. (2013). Understanding Hadley cell expansion versus contraction: Insights from simplified models and implications for recent observations. *Journal of Climate*, *26*, 4304–4321.

Vallis, G. K., Zurita-Gotor, P., Cairns, C., & Kidston, J. (2015). Response of the large-scale structure of the atmosphere to global warming. *Quarterly Journal of the Royal Meteorological Society*, *141*, 1479–1501.

Voigt, A., Biasutti, M., Scheff, J., Bader, J., Bordoni, S., Codron, F., et al. (2016). The tropical rain belts with an annual cycle and a continent model intercomparison project: TRACMIP. *Journal of Advances in Modeling Earth Systems*, *8*, 1868–1891. https://doi.org/10.1002/2016MS000748

Voigt, A., & Shaw, T. A. (2015). Circulation response to warming shaped by radiative changes of clouds and water vapour. *Nature Geoscience*, *8*, 102–106. https://doi.org/10.1038/NGEO2345

Voigt, A., & Shaw, T. A. (2016). Impact of regional atmospheric cloud radiative changes on shifts of the extratropical jet stream in response to global warming. *Journal of Climate*, *29*, 8399–8421.