Seasonal sensitivity of the Hadley cell and cross-hemispheric responses to diabatic heating in an idealized GCM

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Key Points:

- The Hadley cells in an idealized model display seasonally varying sensitivities to localized diabatic forcing.
- Heating in one hemisphere forces the Hadley cell and eddy-driven jet in the other hemisphere.
- The seasonal differences in cross-hemispheric responses to heating arise due to the behavior of the dominant winter cell.

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Abstract

The seasonal sensitivity of the Hadley cell to localized diabatic forcing is studied using a dry idealized atmospheric general circulation model. Sensitivities are broadly consistent with responses of the Hadley cell in observations and climate models to ENSO and global warming-like forcings. However, the exact seasonal sensitivity patterns highlight the importance of reducing the uncertainty in the size and position of expected anthropogenic forcings to understand how the atmospheric circulation will respond. The sensitivities reveal cross-hemispheric responses of the Hadley cells which project onto the eddy-driven jets and storm tracks. For heating in the summer hemisphere, the winter Hadley cell extent and jet latitude responses are highly correlated. For heating in the winter hemisphere, the summer Hadley cell extent and jet speed responses are highly correlated. These seasonal differences arise due to the contrast between the dominant winter Hadley cell and weaker summer Hadley cell.

1 Introduction

An expansion of the tropical belt is one of the robust observed [*Seidel et al.*, 2008] and simulated [*Lu et al.*, 2007] effects of anthropogenic climate change. This expansion could have societal impacts due to changes in precipitation [*Seidel et al.*, 2008]. Impacts are not limited to the tropical regions, but extend into the extratropics too, due to the interdependence of the Hadley cells and eddy-driven jets. The tropical belt expansion has been connected to changes in the extratropical circulation [*Previdi and Liepert*, 2007], with idealized studies suggesting an interactive relationship between tropics and extratropics [*Becker et al.*, 1997; *Schneider*, 2004; *Walker and Schneider*, 2006; *Mbengue and Schneider*, 2013].

In summer, eddy-driving is the dominant driver of variability in the Hadley cell (HC) [*Caballero*, 2007]. By considering the momentum budget in the upper branch of the HC, *Schneider and Bordoni* [2008] show that winter HC changes are less affected by eddies and hence more thermally driven. In summer, a smaller local Rossby number is consistent with a poleward-shifted HC compared to the winter HC [*Kang and Lu*, 2012]. This is associated with seasonal dependencies in the relationship between the HC and the eddy-driven jet; the winter cell is less affected by extratropical eddies compared to the summer cell [*Schneider and Bordoni*, 2008; *Kang and Polvani*, 2011].

Studies using coupled models find seasonal differences in the response to climate change forcing of the tropical circulation and its connection to the eddy-driven jets [*Kang and Polvani*, 2011; *Ceppi and Hartmann*, 2013]. However, many idealized modeling studies investigating HC responses to ENSO and global warming-like forcings are conducted under hemispherically symmetric conditions [e.g., *Frierson et al.*, 2007; *Levine and Schneider*, 2011; *Sun et al.*, 2013; *Tandon et al.*, 2013]. Idealized modeling studies in non-equinoctial conditions allow us to investigate how the seasonal response of the HC behaves in response to climate forcings. It has been suggested that the solstitial cell is the dominant component of the HC [*Lindzen and Hou*, 1988], and the equinoctial pattern is ephemeral [*Hu et al.*, 2007], implying that results from studies run under equinoctial conditions may not hold throughout the annual cycle.

Under equinoctial conditions, *Frierson et al.* [2007] find the HC expands under increases in global mean temperature. For tropically confined heating the HCs contract, it is only when the heating has a wider meridional extent the HCs expand [*Tandon et al.*, 2013]. Heating with a wider meridional extent when eddy-feedbacks are not present causes the HCs to contract instead of expand [*Sun et al.*, 2013], suggesting the eddy-driven jets drive the expansion of the HCs when the heating is outside the tropics. *Lu et al.* [2008] propose that HC expansion is driven by changes in meridional temperature gradient modifying eddy phase speeds. However, *Schneider and Walker* [2006] postulate HC extent is governed by the latitude at which baroclinic eddies become deep enough to reach the upper troposphere and so the eddy flux divergence of angular momentum changes sign.

It is important to understand the broad range of possible HC changes due to the changing climate. We conduct a systematic set of experiments applying heating in all possible locations to build up sensitivity plots of the HC response to heating. Changes in the poleward extent of the HC may result from the expansion of the tropical belt, but also from shifts in the inter-tropical convergence zone (ITCZ) for fixed HC width. We examine the sensitivities of the ITCZ position and HC width, extent and strength to localized diabatic heating in a dry idealized model with perpetual winter and summer hemispheres. Theories in dry atmospheres are important because they provide the limits to which moist theories must converge.

The hypothesized response of the storm tracks to HC extent shifts [*Mbengue and Schneider*, 2017] leads us to investigate how the eddy-driven jets respond to forced HC changes. We find cross-hemispheric responses to diabatic heating; when heating is applied in one hemisphere, there is a response in the opposite hemisphere's HC branch and eddy-driven jet. We argue the dominant behavior of the winter cell is important for understanding the mechanisms of the inter-hemispheric responses.

2 Methods

2.1 Model

Simulations are conducted using the Geophysical Fluid Dynamics Laboratory's Flexible Modeling System dry dynamical core. The model solves the primitive equations on a sphere using a spectral transform method at T42 resolution with 37 unevenly spaced sigma levels ($\sigma = p/p_{surface}$, the model's vertical coordinate). The model includes a quasi-equilibrium convection scheme that relaxes temperatures in an atmospheric column to a prescribed lapse rate in an energetically consistent way. A full description of the model can be found in *Schneider and Walker* [2006] and the configuration used here is detailed in *Baker et al.* [2017].

The model streamfunction and jets are qualitatively similar to Earth's southern hemisphere (Fig. S1). Comparing the model southern hemisphere with the JJA southern hemisphere and the model northern hemisphere with the DJF southern hemisphere illustrates this.

We use the simulations conducted in *Baker et al.* [2017], who ran the model in perpetual winter (southern hemisphere) and summer (northern hemisphere) conditions with no diurnal or seasonal cycle. Following a ten year spin-up period to allow the model to reach a statistically steady state, we run a six year control simulation and 306 six year tropospheric heating experiments, all starting from the end of the spin-up simulation. Each simulation has a constant zonally uniform Gaussian heating, with a maximum of 2K/day, applied at a specific location in the latitude-sigma plane. The 306 simulations cover heating across a grid of 34 different latitudes and 9 sigma levels.

2.2 Indices

We define the ITCZ location as the latitude at which the zonally and vertically (σ between 0.4-0.8) averaged streamfunction changes sign between the winter and summer branches of the HC. Likewise the winter and summer HC extents are defined as the latitude at which the zonally and vertically averaged streamfunction changes sign between the respective HC and Ferrel cell branches. The strength of each HC branch is defined as the maximum of the streamfunction in the branch. The eddy-driven jet is defined as the latitude of the maximum zonal-mean zonal wind at $\sigma = 0.85$.

The sensitivities of each index are calculated as the difference between the time-average of the monthly indices in the forced simulations and the control simulation. As in *Baker et al.* [2017], we test for significance using a Student's t-test at the 1% level.

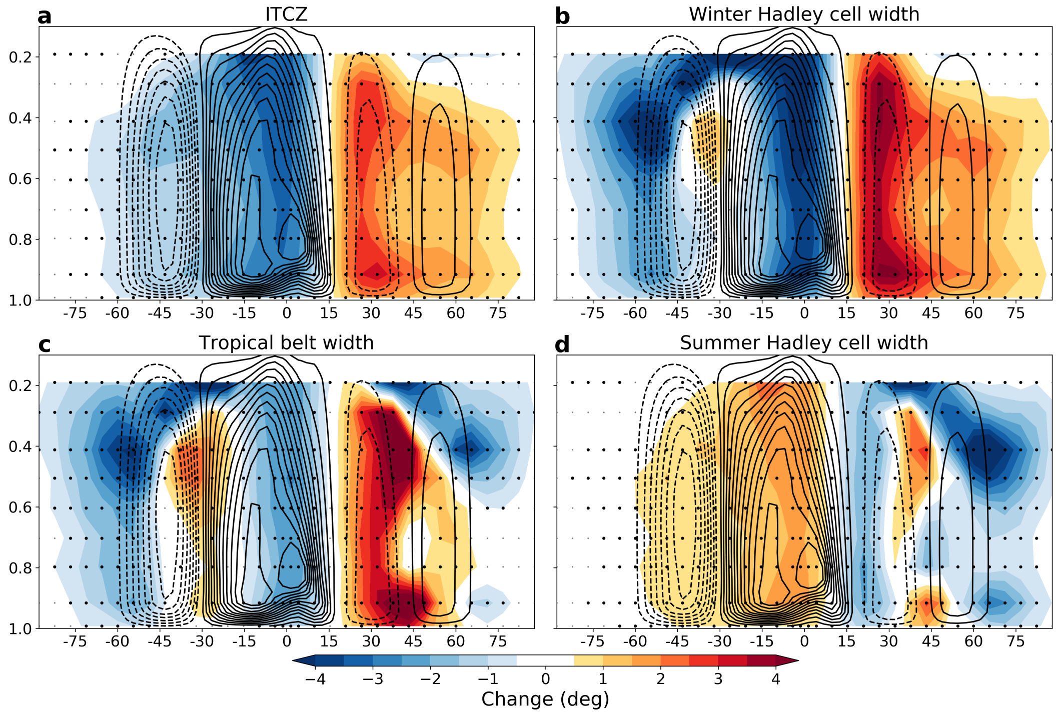

Figure 1. ITCZ, tropical belt and Hadley cell width sensitivities to heating experiments (colors) in the latitude-sigma plane. Contours show the zonal-mean control streamfunction. Black dots mark where the difference between the perturbed and control simulations are statistically significant. For the ITCZ, positive values correspond to a shift towards 90°N.

3 Results

3.1 Sensitivities

Shifts in the ITCZ in response to diabatic heating are shown as a sensitivity plot in Fig. 1a. Each dot summarizes a forced simulation with heating at that location in the latitude-sigma plane. Colors show the response of the ITCZ (warm colors indicate a northward shift of the ITCZ). Black dots mark statistically significant runs. The contours show the control streamfunction. Statistically significant shifts in the ITCZ arise from heating throughout the atmosphere in both hemispheres. For reference, the standard deviation of the monthly ITCZ position in the control run is 0.51°, so many responses are large compared to the variability. ITCZ position is determined by the flux across the equator and the net energy input to the equatorial atmosphere [*Bischoff and Schneider*, 2014]. Therefore, heating on either side of the ITCZ causes a shift in latitude towards the heating.

Fig. 1c shows the sensitivity of the tropical belt width (summer HC to winter HC extent). Heating confined to the winter cell in the deep tropics acts to contract the tropical belt, whilst upper-tropospheric heating in the subtropics can cause an expansion of the tropical belt. Heating on the poleward extent of the Ferrel cell in both hemispheres acts to contract the tropical belt. Patterns are similar to the eddy-driven jet sensitivities in Fig. 3 of *Baker et al.* [2017], suggesting that when forcing at high latitudes, it is the dynamics of extratropical eddies that affect the tropical belt width. The HC widths (Fig. 1b,d) display a similar behavior, with high latitude forcing contracting the HCs in the same hemisphere. In contrast, the response to forcing in the deep tropics appears to be dominated by the shifts in the ITCZ.

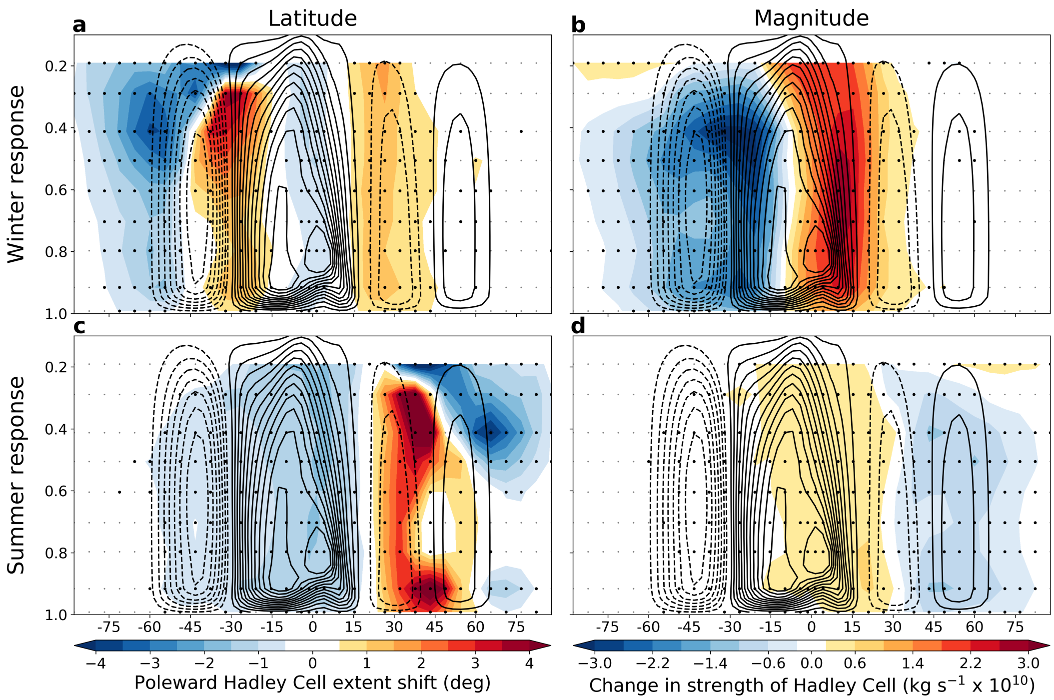

Figure 2. Hadley cell sensitivities to heating experiments (colors) in the latitude-sigma plane. Contours show the zonal-mean control streamfunction. Black dots mark where the difference between the perturbed and control simulations is statistically significant. Positive values correspond to poleward shift of the HC extent or strengthening of the Hadley cell in the target hemisphere (a,b: winter; c,d: summer)

We next consider the sensitivity of the poleward extent of the winter and summer HCs (Fig. 2a,c). For reference, the standard deviation of the monthly poleward HC extent in the control run is 0.63° in winter, and 0.84° in summer. When heating is applied in the extratropical and polar regions, the latitudinal sensitivities of the HC and jet in that same hemisphere display strong similarities (see Fig. 3 in *Baker et al.* [2017]), but with smaller HC shifts compared to the jet. This implies the HC extent and eddy-driven jet are shifting in tandem, with a greater shift of the eddy-driven jet. This is analogous to the result of *Mbengue and Schneider* [2013], who find that the HC extent and storm track often shift in tandem with a greater shift in the storm track. The shifts due to heating in the mid-latitudes increase with height due to static stability arguments: the higher the heating, the greater the increase in static stability and thus, by simple scaling arguments [*Lu et al.*, 2007], the greater the shift in HC extent. There is also a region of enhanced shift found near the surface in summer in the extratropics (cf. Fig. 3 in *Baker et al.* [2017]).

Corroborating *Lu et al.* [2008], tropical heating acts to contract the HCs, the "El Niño-like" response, whereas heating in the extratropics produces poleward HC expansion, the global warming-like response. This effect is also seen for the HC widths (Fig. 1b,d), but is not seen for the summer HC extent (Fig. 2d) due to the ITCZ shift towards 90°N.

Statistically significant cross-hemispheric responses exist, with a heating in the summer hemisphere (poleward of the ITCZ) causing the winter HC to expand poleward. In contrast, a heating in the winter hemisphere causes the summer HC to contract equatorward.

Changes in the magnitude of the HCs are governed by the location of the heating with respect to the ascending and descending branches of each cell (Fig. 2b,d). Heating in the ascending branch of each cell (i.e. across the ITCZ) acts to strengthen the overturning circulation in both HCs. Heating in the descending branches and the Ferrel cells acts to weaken the overturning circulation in that hemisphere. In both cases, the magnitude of the winter HC response is greater than that of the summer cell. For reference, the standard deviation of the monthly HC strength in the control run is 4.0×10^9 kg s^{-1} in winter, and 2.4×10^9 kg s^{-1} in summer.

Winter HC width and strength changes are greater than summer HC changes. This may be because the winter HC is in the regime where the angular momentum conserving model of the HC applies (a weaker cell can be wider before instability occurs) so local diabatic heating is balanced by HC changes. Weaker changes in the summer HC suggest in summer that local diabatic heating is balanced more strongly by eddy changes; the cell is in an eddy-driven regime, with a lower local Rossby number. This regime behavior of the HCs agrees with *Schneider and Bordoni* [2008], who find eddy-mediated regime transitions of the HC during the annual cycle.

To quantify the changes in regime behavior, we compute the local Rossby numbers in each HC, following *Schneider and Bordoni* [2008]. This is done by taking the ratio of the local vorticity to the planetary vorticity in the upper troposphere above the maximum of the HC streamfunction. High Rossby numbers indicate the cell responds more to thermal driving, whereas lower Rossby numbers suggest eddy-driving is more dominant. The ratio of the local Rossby numbers in the winter to summer cells is 1.5, supporting the hypothesis that the changes in the winter cell are more thermally driven, compared to more eddy-driven changes in the summer cell. The winter to summer ratio of maximum shift of the HC divided by maximum shift of $\overline{v'T'}$ in each hemisphere is 1.7, supporting the idea that local diabatic heating is balanced more strongly by HC changes in winter and eddy changes in summer.

3.2 Cross-hemispheric connections

Both HC extents display a sensitivity to heating in the opposite hemisphere. The heating in one hemisphere also projects onto the eddy-driven jet in the other hemisphere, suggesting a cross-hemispheric jet response mediated by the HC [*Baker et al.*, 2017]. To see this we plot the response of the speed and latitude of the eddy-driven jet against the shift of the HC extent in each hemisphere (Fig. 3). Fig. 3a shows heating in the summer hemisphere (red dots) shifts the poleward extent of the winter HC, which is highly correlated with a poleward shift of the winter eddy-driven jet. The shifts are close to 1:1 (i.e. one degree of HC extent shift corresponds to one degree of jet shift). Fig. 3b shows a correlation between winter HC extent and winter eddy-driven jet speed when heating in the summer hemisphere. This correlation is less robust than the correlation between the HC extent and eddy-driven jet shift. Note a poleward shift in the jet here corresponds to a weakening of the jet. More commonly, a poleward shift of the jet would be associated with the jet strengthening (due to increases in eastward eddy phase speeds when the jet strengthens *Chen and Held* [2007]; *Lorenz* [2014]).

The response of the summer HC extent and summer eddy-driven jet (Fig. 3c,d) is similar to the winter case, but with a stronger relation to the jet speed than latitude this time. Heating in the winter hemisphere (blue dots) causes the summer HC extent and summer jet strength to change together. The summer jet shift is correlated with the summer HC extent shifts to a lesser degree (also a near 1:1 relationship). As the jet shifts equatorward it strengthens, analogous to the poleward shifted jet weakening in the winter jet case. Note the summer HC extent and ITCZ position are correlated with an r-squared value of 0.97 (not shown), indicating the dependencies found between the summer HC extent and summer jet when heating in the winter hemisphere also apply to the ITCZ position and jet.

To investigate the mechanisms behind the HC and jet responses, we analyze two forcing simulation case studies. The first of these is the simulation where heating in the summer hemisphere produces the greatest poleward shift of the winter HC extent and eddy-driven jet (Fig. 4). Heating acts to strengthen the winter branch of the HC and shift both the winter

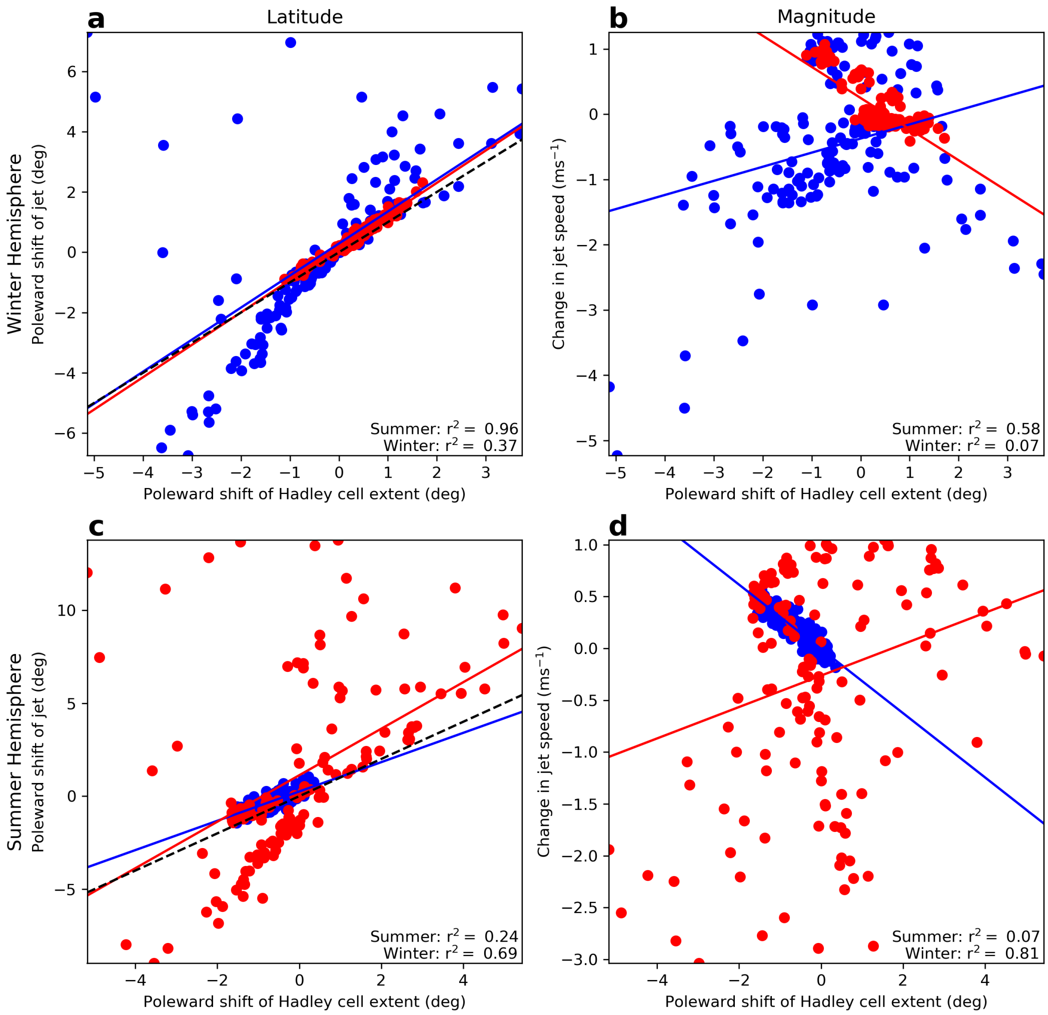

Figure 3. Scatter plots of changes in jet indices against changes in Hadley cell extent between the forced and control simulations. (a,b) Response of the winter jet and Hadley cell. (c,d) Response of the summer jet and Hadley cell. Blue dots show simulations where the heating is applied in the winter hemisphere, red dots where the heating is applied in the summer hemisphere. The 1:1 Hadley cell to jet shift is shown in the dashed black lines on the left-hand panels.

Hadley and Ferrel cells poleward. There are also poleward shifts of the winter heat and momentum fluxes on the same order of magnitude as the HC, and hence eddy-driven jet. The heating is conveyed to the winter hemisphere via the HC, and warms the upper troposphere near the maximum of the upper level winter heat flux (shown by the lowering of the isentropes near the tropopause). Heating here acts to shift the jet poleward (Fig. 3 of *Baker et al.* [2017]) by shifting the maximum of $\overline{v'T'}$ poleward (mechanism discussed in detail in *Baker et al.* [2017]).

The second case study is the simulation where the heating in the winter hemisphere causes the greatest increase in speed in the summer eddy-driven jet (Fig. 5). The heating causes both HC branches to shift towards the winter pole. Temperature gradients are decreased in the summer subtropics and a stronger subtropical jet allows eddies to penetrate further into the summer hemisphere tropics across a wider summer HC. This acts to barotropically strengthen the summer eddy-driven jet through increased eddy momentum convergence.

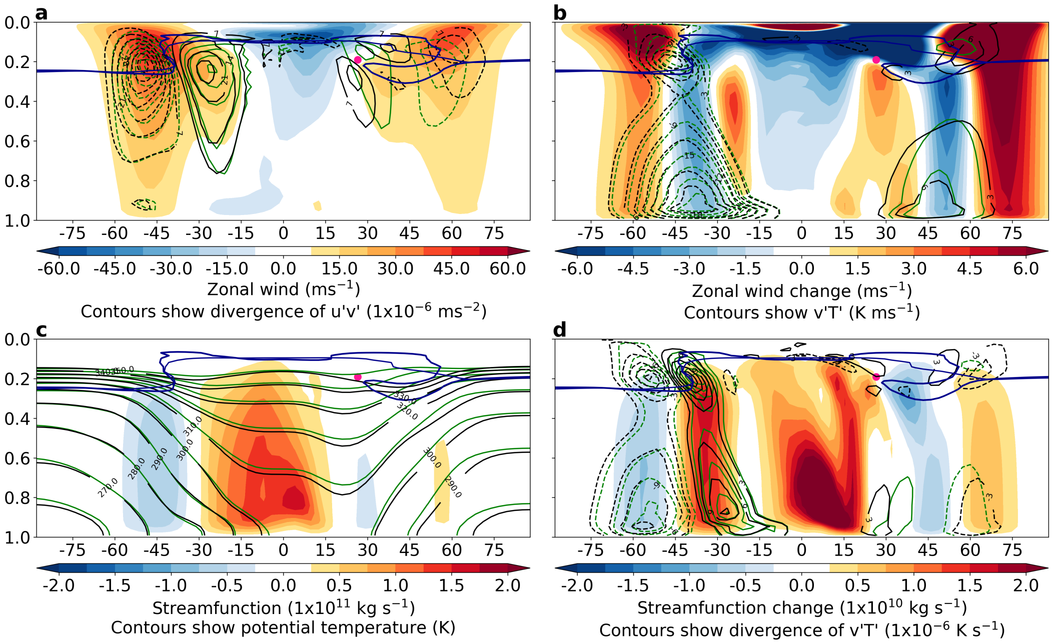

Figure 4. Summary plot for heating applied at $\sigma = 0.2$ and $\phi = -10^\circ$ (pink dot). (a) Simulation $\overline{u}$ (colors), $\nabla \cdot \overline{u'v'}$ (black contours for simulation, green for control). (b) Change in $\overline{u}$ (colors), $\overline{v'T'}$ (black contours for simulation, green for control). (c) Simulation streamfunction (colors), potential temperature (black contours for simulation, green for control). (d) Change in streamfunction (colors), $\nabla \cdot \overline{v'T'}$ (black contours for simulation, green for control). The thick blue line is the tropopause in the simulation and the thin blue line is the control tropopause.

Although the applied heating is near the top of the troposphere in both of these case studies, the response patterns in simulations where the heating is applied nearer the surface display the same features, but with smaller HC extent and jet shifts and smaller changes in jet speed (see Fig. 2). This suggests the mechanisms affecting the HC and jets are amplified at higher levels [*Yuval and Kaspi*, 2016].

Given the high correlation of the ITCZ and summer HC extent, it would appear that the correlations in the summer hemisphere in response to forcing in the winter hemisphere are dominated by how the ITCZ and hence how the winter HC is responding to the heating. This suggests the winter HC is most important for understanding the cross-hemispheric responses to forcing.

4 Discussion and Conclusions

We have shown the winter and summer HCs in a dry idealized GCM display different sensitivities to localized diabatic forcing. These seasonal sensitivities apply to HC width, extent and strength, and cause the ITCZ and tropical belt width sensitivities to vary depending on which hemisphere the heating is applied. The sensitivities are broadly barotropic in nature, with some increase in magnitude as the heating is applied higher in the troposphere.

We have also shown strong correlations between the HC and eddy-driven jet when forced from the opposing hemisphere. Winter hemisphere heating forces the summer HC

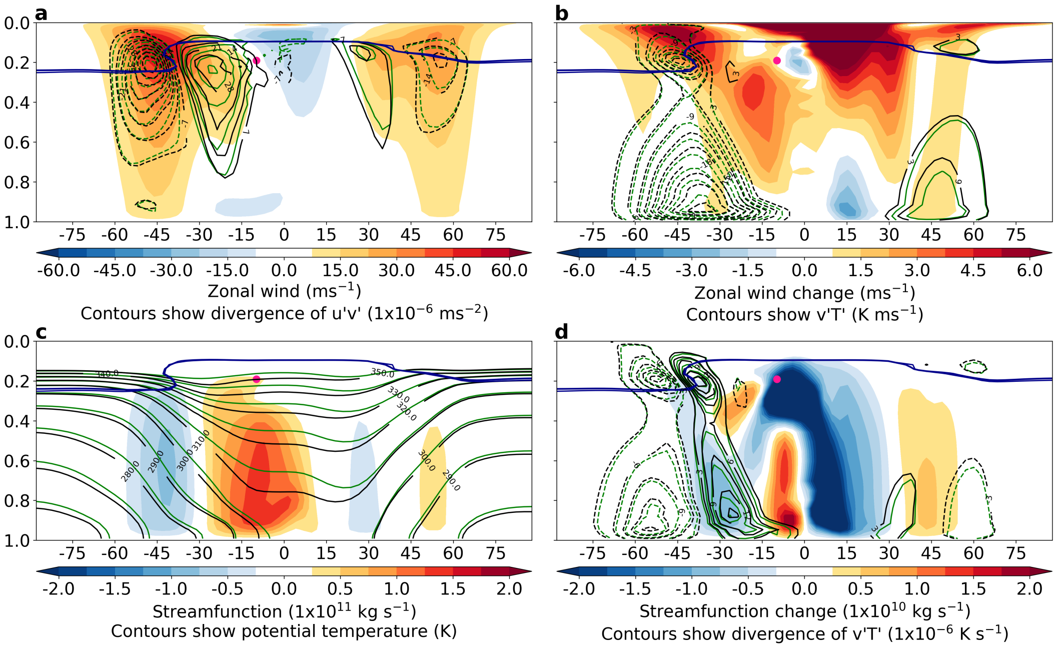

Figure 5. Summary plot for heating applied at $\sigma = 0.2$ and $\phi = 27°$ (pink dot). (a) Simulation $\overline{u}$ (colors), $\nabla \cdot \overline{u'v'}$ (black contours for simulation, green for control). (b) Change in $\overline{u}$ (colors), $\overline{v'T'}$ (black contours for simulation, green for control). (c) Simulation streamfunction (colors), potential temperature (black contours for simulation, green for control). (d) Change in streamfunction (colors), $\nabla \cdot \overline{v'T'}$ (black contours for simulation, green for control). The thick blue line is the tropopause in the simulation and the thin blue line is the control tropopause.

extent, which is highly correlated with summer jet speed changes; summer hemisphere heating forces the winter HC extent which is highly correlated with winter jet shifts. Summer HC responses are highly correlated with the ITCZ response, implying HC and jet correlations are dictated by shifts in the ITCZ via the response of the dominant winter cell.

The ITCZ shift sensitivities agree with idealized [*Kang et al.*, 2008] and more complex modeling studies [*Chiang and Bitz*, 2005; *Broccoli et al.*, 2006], with a shift in position towards the location of heating/away from cooling. The responses of the HC widths, extents, and tropical belt width are all consistent with a range of studies looking at HC changes in simple and complex models [*Frierson et al.*, 2007; *Previdi and Liepert*, 2007; *Lu et al.*, 2007, 2008; *Sun et al.*, 2013; *Tandon et al.*, 2013], showing at least the sign of responses from equinoctial studies apply in the solstitial case. Heating produces similar sensitivity patterns for the eddy-driven jets and HCs when the forcing is in the same hemisphere as the jets, supporting the idea the midlatitude eddies feed back onto the HC [*Becker et al.*, 1997; *Walker and Schneider*, 2006; *Caballero*, 2007; *Kang et al.*, 2008; *Kang and Polvani*, 2011; *Ceppi and Hartmann*, 2013].

The correlations between HC and jet from heating in the opposing hemisphere appear to be governed by the behavior of the dominant winter HC. The responses see the eddy-driven jets weaken and shift poleward in tandem, or strengthen and shift equatorward. This suggests the mechanism by which the HCs force the jets is not via changes in eddy phase speeds [*Chen and Held*, 2007], which would see a strengthening and poleward shift of the jet occur in tandem. We postulate a simple mechanistic understanding of how the jets may respond to the HC changes through the modifications of the overturning circulation projecting onto the heat fluxes and subtropical jets, but leave a full diagnosis of the mechanism for future work.

Our findings suggest it is important to study the nature of the solstitial HCs and conduct studies in an annual cycle framework, investigating the different seasonal responses of the HCs. There are also clear implications given the uncertainty in the size and spatial extent of the anthropogenic forcing due to climate change. Areas where the uncertainty of the anthropogenic forcing is high and the sensitivity of the HCs response is high (e.g., in the tropical upper troposphere) are clearly areas that need further study to better constrain the nature of the anthropogenic forcing.

Acknowledgments

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