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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

Supporting Information:

- Supporting Information S1

Correspondence to:
H. S. Baker,
hugh.baker@physics.ox.ac.uk

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Seasonal Sensitivity of the Hadley Cell and Cross-Hemispheric Responses to Diabatic Heating in an Idealized GCM

Hugh S. Baker[1], Cheikh Mbengue[1], and Tim Woollings[1]

[1] Atmospheric, Oceanic and Planetary Physics, University of Oxford, Oxford, UK

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 Hadley cell responses in observations and climate models to El Niño–Southern Oscillation 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 Hadley cell responses that project onto the eddy-driven jets and storm tracks. For summer hemisphere heating, the winter Hadley cell extent and jet latitude responses are highly correlated. For winter hemisphere heating, 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.

Plain Language Summary This study analyzes changes in the Hadley cell circulation to locally applied heating in the atmosphere in a simple model. The aim is to further understanding about how circulation responds to changes in the climate, for example, global warming. We find differences between the circulation changes in summer and winter, which highlight how important it is to understand exactly how global warming will heat the atmosphere so that we can predict how weather and climate will change. We also observe changes in the Hadley cell, and consequently the jet stream, in one hemisphere from heating in the other hemisphere. The relationship between the Hadley cell and jet stream depends on the season when these cross-hemisphere responses are observed. The implications of this are that we must ensure that studies looking at circulation changes do so using a seasonal cycle, instead of just considering annual average changes. The results also point to specific areas in the atmosphere (e.g., high in the troposphere over the tropics) where we need to better understand how heating due to global warming will affect the atmosphere. This will give us greater confidence in predicting how climates will change in the future.

1. Introduction

The tropical belt expansion 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 Hadley cell and eddy-driven jet interdependence. The tropical belt expansion has been connected to extratropical circulation changes (Previdi & Liepert, 2007), with idealized studies suggesting an interactive relationship between tropics and extratropics (Becker et al., 1997; Mbengue & Schneider, 2013; Schneider, 2004; Walker & Schneider, 2006). It is therefore important to understand the broad range of circulation changes and their seasonal dependencies that may occur due to the range of forcings associated with a changing climate.

Seasonal dependencies exist in the Hadley Cell (HC) and eddy-driven jet relationship (Ceppi & Hartmann, 2013; Kang & Polvani, 2011). By considering the momentum budget in the HC's upper branch, Schneider and Bordoni (2008) show the winter cell is less affected by extratropical eddies and is more thermally driven compared to the summer cell. In the summer, the HC is further poleward than winter, consistent with a smaller local Rossby number (Kang & Lu, 2012), which means eddy-driving is the dominant driver of HC variability (Caballero, 2007). Despite these seasonal dependencies, many idealized modeling studies investigating HC responses to El Niño–Southern Oscillation and global warming-like forcings are conducted under hemispherically symmetric conditions (e.g., Frierson et al., 2007; Levine & Schneider, 2011; Sun et al., 2013; Tandon et al., 2013). Idealized modeling studies in nonequinoctial conditions allow us to investigate how the HC seasonal response to climate forcings behaves. It has even been suggested that the solstitial cell is the dominant component of the HC (Lindzen & Hou, 1988), and the equinoctial pattern is ephemeral (Hu et al., 2007), implying results from studies run under equinoctial conditions may not hold throughout the annual cycle. It is therefore necessary to test HC and eddy-driven jet responses and their relationship to one another to verify results from equinoctial studies apply in different seasons.

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 HC expansion when the heating is outside the tropics. Using experiments with locally applied diabatic heating, it is possible to test these results hold in nonequinoctial conditions. Several mechanisms for understanding HC expansion have been proposed. Lu et al. (2008) find 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. Ceppi et al. (2013) find a cross-hemispheric relationship between the HC and jets under equinoctial conditions, and we aim to explore the relationship's seasonality and mechanisms in a solstitial setup.

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 HC sensitivity plots and the seasonality of these sensitivities. Changes in the HC's poleward extent may result from the tropical belt expansion but also from intertropical convergence zone (ITCZ) shifts for fixed HC width. We examine the ITCZ position and HC width, extent, and strength sensitivities 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 storm track response to HC extent shifts (Mbengue & 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 winter cell's dominant behavior is important for understanding the interhemispheric response mechanisms.

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 ($\sigma = p/p_{\mathrm{surface}}$, the model's vertical coordinate). The model includes a quasi-equilibrium convection scheme, relaxing 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). The configuration used here is detailed in Baker et al. (2017): a perpetual winter (Southern Hemisphere) and summer (Northern Hemisphere) state with no diurnal or seasonal cycle, in which temperatures are relaxed toward a solstitial profile using Newtonian relaxation.

The model stream function and jets are qualitatively similar to Earth's Southern Hemisphere (Figure 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). Following a 10 year spin-up period to allow the model to reach a statistically steady state, a 6 year control simulation and 306 six year tropospheric heating experiments were run, all starting from the end of the spin-up simulation. Each simulation has a constant zonally uniform heating applied at a specific location in the latitude-sigma plane. The heating has a 2-D Gaussian structure in this plane with a 2K/day maximum, 7.1° latitudinal standard deviation, and 0.053 sigma units vertical standard deviation. 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 and 0.8) averaged stream function changes sign between the winter and summer HC branches. Likewise the winter and summer HC extents are defined as the latitude at which the zonally and vertically averaged stream function changes sign between the respective HC and Ferrel cell branches. The strength of each HC branch is defined as the stream function maximum 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 monthly indices' time average 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.

3. Results

3.1. Sensitivities

ITCZ shifts in response to diabatic heating are shown as a sensitivity plot in Figure 1a following Baker et al. (2017). Each dot summarizes the response in a forced simulation with heating at that location in the latitude-sigma plane. Colors show the ITCZ response due to forcing at each location (warm colors indicate a northward ITCZ shift). Black dots mark statistically significant runs. The contours show the control stream function. Statistically significant ITCZ shifts arise from heating throughout the atmosphere in both hemispheres. For reference, the monthly ITCZ standard deviation 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 & Schneider, 2014). Therefore, heating on either side of the ITCZ causes a shift in latitude toward the heating.

Figure 1c shows the tropical belt width sensitivity (summer HC to winter HC extent). Heating confined to the winter cell in the deep tropics acts to contract the tropical belt, while subtropical upper-tropospheric heating can cause a tropical belt expansion. 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 Figure 3 of Baker et al. (2017), suggesting when forcing at high latitudes, it is the dynamics of extratropical eddies that affect the tropical belt width. The HC widths (Figures 1b and 1d) display a similar behavior, with high-latitude forcing contracting the HCs in the same hemisphere. In contrast, the response to deep tropical forcing appears to be dominated by ITCZ shifts.

We next consider the winter and summer HC poleward extent sensitivity (Figures 2a and 2c). For reference, the monthly poleward HC extent standard deviation 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 HC and jet latitudinal sensitivities in that same hemisphere display strong similarities (see Figure 3 in Baker et al., 2017) but with smaller HC shifts compared to the jet. This implies that the HC extent and eddy-driven jet are shifting in tandem, with a greater eddy-driven jet shift. This is analogous to the result of Mbengue and Schneider (2013), who find the HC extent and storm track often shift in tandem with a greater storm track shift. The shifts due to heating in the midlatitudes 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 an enhanced shift region found near the surface in summer in the extratropics (cf. Figure 3 in Baker et al., 2017).

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

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

HC strength changes are governed by the heating's location with respect to the cell's ascending and descending branches (Figures 2b and 2d). Heating in the cell's ascending branch (i.e., across the ITCZ) acts to strengthen the overturning circulation in both HCs. Heating in the descending branches and the Ferrel cells acts

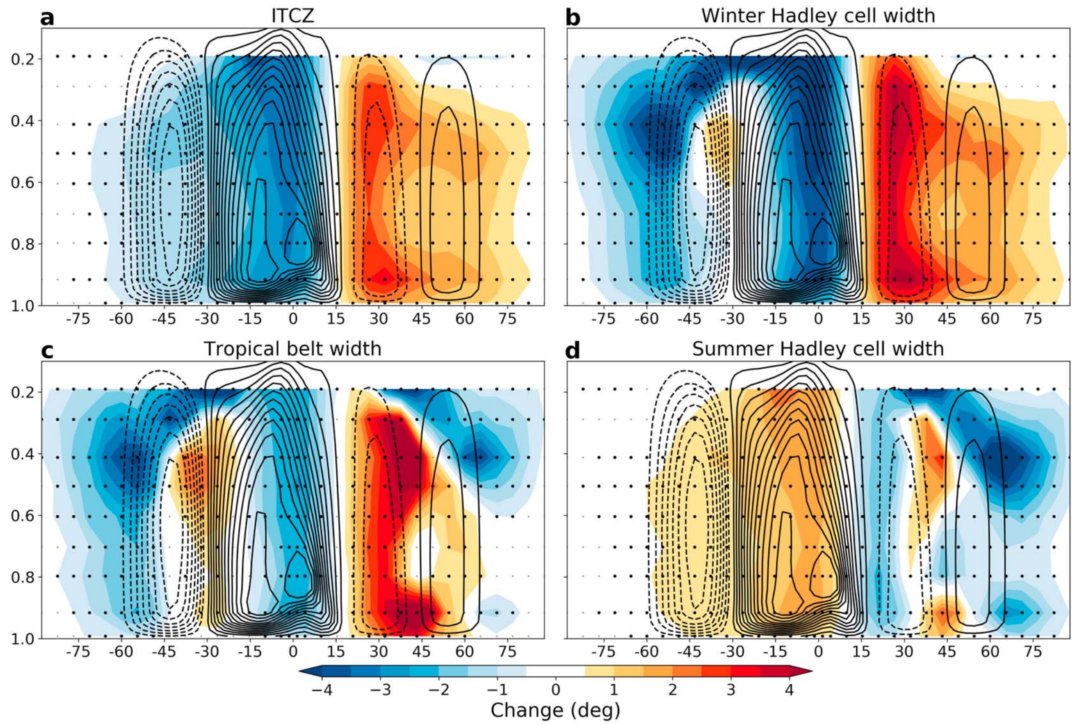

Figure 1. Intertropical convergence zone (ITCZ), tropical belt, and Hadley cell width sensitivities to heating experiments (colors) in the latitude-sigma plane. Contours show the zonal-mean control stream function. Black dots mark where the difference between the perturbed and control simulations is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

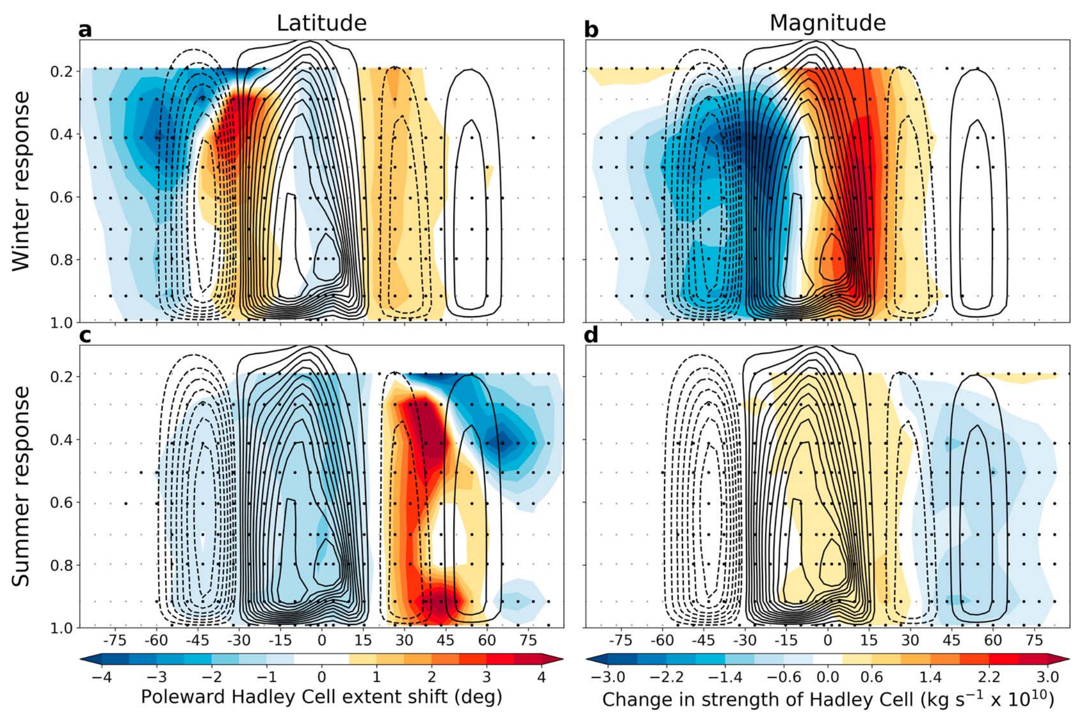

Figure 2. Hadley cell sensitivities to heating experiments (colors) in the latitude-sigma plane. Contours show the zonal-mean control stream function. Black dots mark where the difference between the perturbed and control simulations is statistically significant. Positive values correspond to poleward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

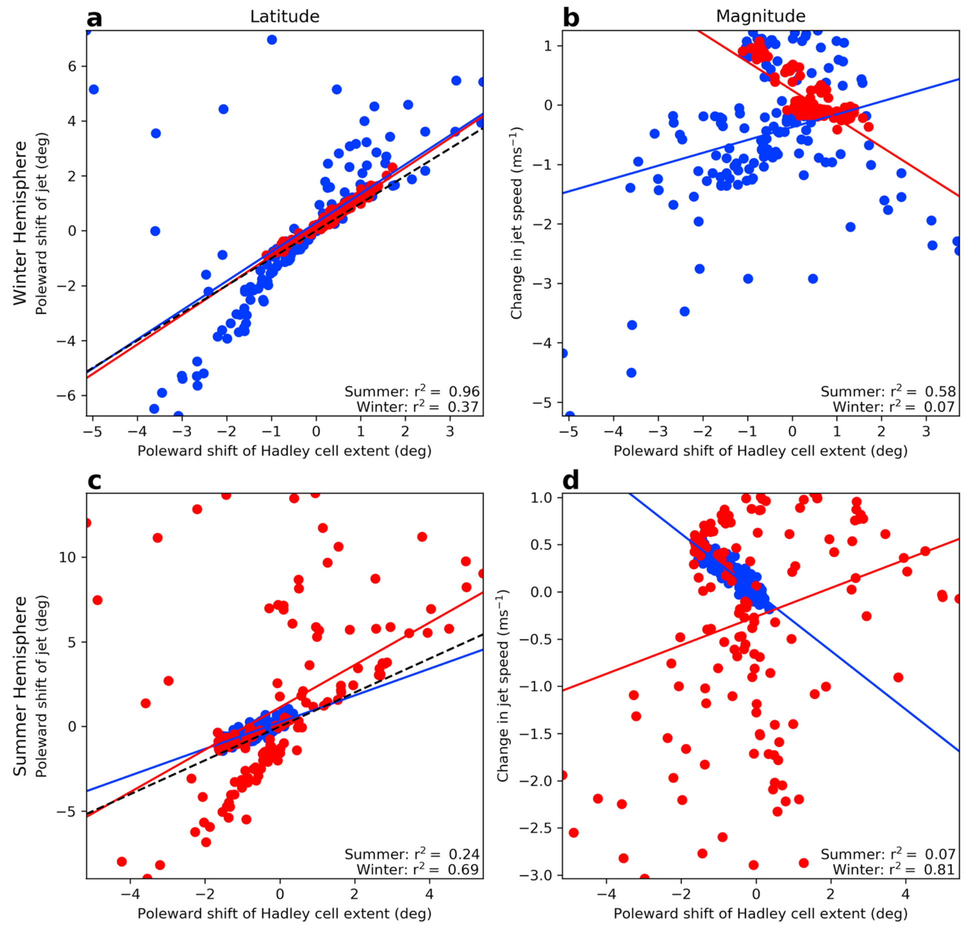

Figure 3. Scatter plots of changes in jet indices against changes in Hadley cell extent between the forced and control simulations. (a,b) Winter jet and Hadley cell response. (c,d) Summer jet and Hadley cell response. Blue dots show simulations where the heating is applied in the winter hemisphere, red 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.

to weaken the overturning circulation in that hemisphere. In both cases, the winter HC strength response is greater than the summer cell. For reference, the monthly HC strength standard deviation 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 that in summer, 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 HC regime behavior agrees with Schneider and Bordoni (2008), who find eddy-mediated HC regime transitions 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 HC stream function maximum. High Rossby numbers indicate that 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 HC shift divided by maximum $\overline{v'T'}$ shift in each hemisphere is 1.7, supporting the idea local diabatic heating is balanced more strongly by HC changes in winter and eddy changes in summer.

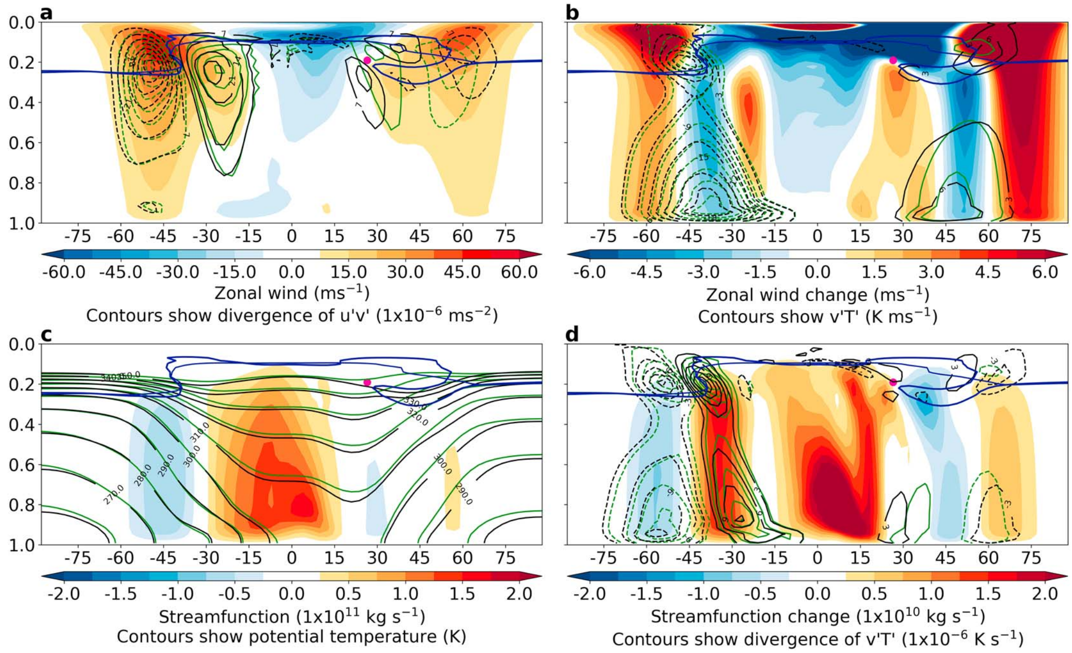

Figure 4. Summary plot for heating applied at $\sigma = 0.2$ and $\phi = 27°$ (pink dot). (a) Simulation $\bar{u}$ (colors), $\nabla \cdot \overline{u'v'}$ (black contours for simulation, green for control). (b) Change in $\bar{u}$ (colors), $\overline{v'T'}$ (black contours for simulation, green for control). (c) Simulation stream function (colors), potential temperature (black contours for simulation and green for control). (d) Change in stream function (colors), $\nabla \cdot \overline{v'T'}$ (black contours for simulation and green for control). The thick blue line is the tropopause in the simulation, and the thin blue line is the control tropopause.

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; Ceppi et al., 2013). To see this, we plot the eddy-driven jet speed and latitude response against the HC extent shift in each hemisphere (Figure 3). Figure 3a shows heating in the summer hemisphere (red dots) shifts the winter HC's poleward extent, which is highly correlated with a poleward shift of the winter eddy-driven jet. The shifts are close to 1:1 (i.e., 1° of HC extent shift corresponds to 1° of jet shift). Figure 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 here a poleward jet shift corresponds to a jet weakening. More commonly, a poleward jet shift would be associated with the jet strengthening due to increases in eastward eddy phase speeds when the jet strengthens (Chen & Held, 2007; Lorenz, 2014), suggesting a different mechanism in the cross-hemispheric response cases.

The summer HC extent and summer eddy-driven jet responses (Figures 3c and 3d) are 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 is the simulation where heating in the summer hemisphere produces the greatest poleward shift of the winter HC extent and eddy-driven jet (Figure 4). Heating acts to strengthen the HC winter branch and shift both the winter Hadley and Ferrel cells poleward. There are also winter heat and momentum flux poleward shifts 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 upper level

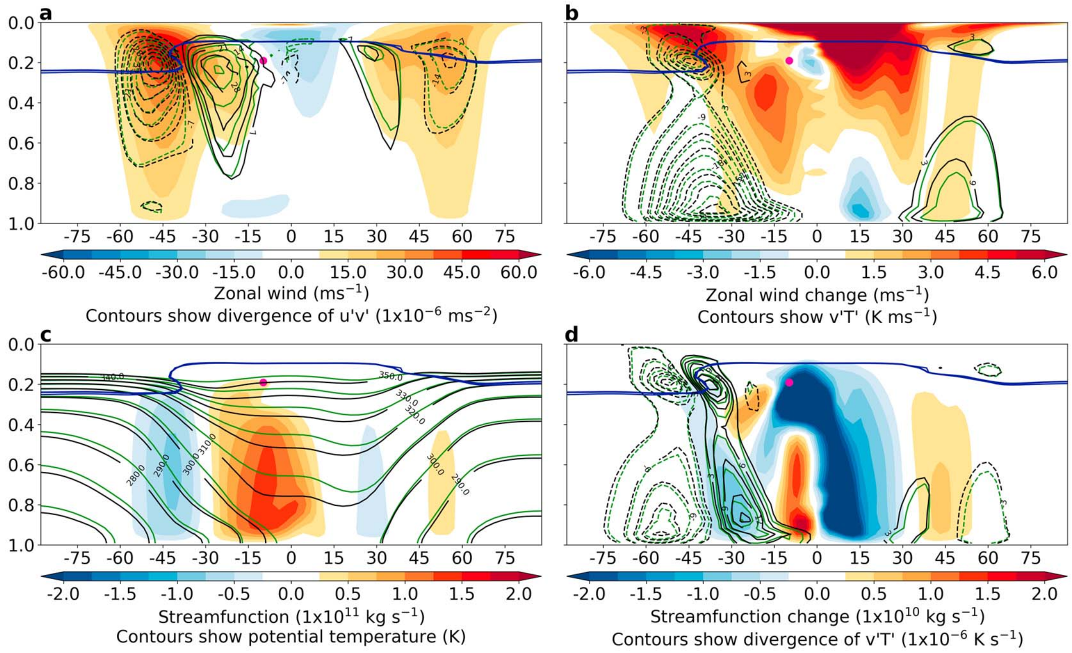

Figure 5. Summary plot for heating applied at $\sigma = 0.2$ and $\phi = -10°$ (pink dot). (a) Simulation $\bar{u}$ (colors), $\nabla \cdot \overline{u'v'}$ (black contours for simulation and green for control). (b) Change in $\bar{u}$ (colors), $\overline{v'T'}$ (black contours for simulation and green for control). (c) Simulation stream function (colors), potential temperature (black contours for simulation, green for control). (d) Change in stream function (colors), $\nabla \cdot \overline{v'T'}$ (black contours for simulation and green for control). The thick blue line is the tropopause in the simulation and the thin blue line is the control tropopause.

winter heat flux (shown by the lowering of the isentropes near the tropopause). Heating here acts to shift the jet poleward (Figure 3 of Baker et al., 2017) by shifting the $\overline{v'T'}$ maximum 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 speed increase in the summer eddy-driven jet (Figure 5). The eddy-driven jet strengthening is barotropic (Figure 5b), implying it is caused by changes in the eddies. The heating weakens summer subtropical temperature gradients (Figure 5c), strengthening the subtropical jet (Figure 5b). Eddies can then penetrate further into the summer tropics, demonstrated by the divergence increase on the equatorward flank of the summer eddy momentum divergence (Figure 5a). The extra eddy momentum diverged from the tropics results in increased eddy momentum convergence into the jet (Figure 5a), barotropically strengthening it.

Although the applied heating is near the top of the troposphere in both 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 Figure 2). This suggests that the mechanisms affecting the HC and jets are amplified at higher levels (Yuval & 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 shift and tropical belt width 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 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 ITCZ shifts via the dominant winter cell response.

The ITCZ shift sensitivities agree with idealized (Kang et al., 2008) and more complex modeling studies (Broccoli et al., 2006; Chiang & Bitz, 2005), with a shift in position toward the location of heating/away from cooling. The HC width, extent, and tropical belt width sensitivities are broadly consistent with a range of studies looking at HC changes in simple and complex models (Frierson et al., 2007; Lu et al., 2007, 2008; Previdi & Liepert, 2007; Sun et al., 2013; Tandon et al., 2013), showing at least the signs of responses from equinoctial studies match the solstitial case. Tandon et al. (2013) study the “El Niño-like” heating in the equinox case; El Niño peaks in NH winter, and our results corroborate the response they find but with a more relevant background state. For the eddy-driven jets and HCs, heating produces similar sensitivity patterns when the forcing is in the same hemisphere as the jets, supporting the idea that the midlatitude eddies feed back onto the HC (Becker et al., 1997; Caballero, 2007; Ceppi & Hartmann, 2013; Kang & Polvani, 2011; Kang et al., 2008; Walker & Schneider, 2006).

The correlations between HC and jet from heating in the opposing hemisphere appear to be governed by the dominant winter HC behavior. The responses see the eddy-driven jets weaken and shift poleward in tandem or strengthen and shift equatorward. This suggests that the mechanism by which the HCs force the jets is not via changes in eddy phase speeds (Chen & Held, 2007), which would see a strengthening and poleward jet shift 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 that it is important to study the nature of the solstitial HCs and conduct studies in an annual cycle framework, investigating the different HC seasonal responses. 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 HC sensitivity is high (e.g., in the tropical upper troposphere) are clearly areas needing further study to better constrain the nature of the anthropogenic forcing.

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