Interactions between the Hadley cell and the mid-latitude storm track in an idealized GCM

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The correlation between unforced variability in the latitude of the edge of the Hadley cell ($\Phi_{\text{Hadley}}$) and latitude of the surface westerlies ($\Phi_{\text{jet}}$) is examined using a simplified moist general circulation model that has gray radiation and no orography. The correlation can be determined by the time-mean separation of the two features. When the separation is small there is a positive correlation, and as the separation between them increases, a weak negative correlation emerges. Diagnostics of the eddy momentum flux convergence ($-|\partial_y u'v'|$) and the eddy heat flux ($v'T'$) show that regardless of whether the two features are correlated, the changes in eddy activity associated with $\Phi_{\text{Hadley}}$ variability form self-similar patterns. Associated with a poleward displacement of $\Phi_{\text{Hadley}}$ is a decrease in $-|\partial_y u'v'|$ in the sub-tropics, and an increase in $-|\partial_y u'v'|$ in mid-latitudes. The affect on $\Phi_{\text{jet}}$ appears to depend on the time-mean position relative to $\Phi_{\text{Hadley}}$. If the two features are close, the increase in $-|\partial_y u'v'|$ in mid-latitudes lies poleward of the time-averaged $\Phi_{\text{jet}}$ and draws $\Phi_{\text{jet}}$ poleward, giving a positive correlation between the $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$. Conversely, when the two features are well separated in the time-mean, the same increase in $-|\partial_y u'v'|$ in mid-latitudes draws $\Phi_{\text{jet}}$ equatorward, resulting in a negative correlation.
1. Introduction

The Hadley cell and the mid-latitude storm track are characteristic features of Earth’s atmosphere. The thermally direct meridional overturning of the Hadley cell gives rise to a tropical climate zone with wet deep-tropics and dry sub-tropics. In the mid-latitudes the baroclinic eddies that give rise to the the eddy-driven jet and surface westerlies also play a dominant role in determining local climate characteristics. Projections of future climate under increasing greenhouse gasses (GHGs) suggest that the latitude of the edge of the Hadley cell ($\Phi_{\text{Hadley}}$), and the latitude of the storm tracks and surface westerlies ($\Phi_{\text{jet}}$) will shift poleward in the coming century [Fyfe et al., 1999; Meehl et al., 2007].

In the Southern Hemisphere (SH) during summer, the magnitude of the projected shift $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ is correlated across different models [Lu et al., 2008]. Models that shift $\Phi_{\text{Hadley}}$ further poleward also shift $\Phi_{\text{jet}}$ further poleward, with the ratio of the projected changes in $\Phi_{\text{Hadley}}$ to $\Phi_{\text{jet}}$ of about 1:2.

It has also recently emerged that, in the SH during summer, the unforced variability of $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ is correlated [Kang and Polvani, 2011]. This is true for both the real atmosphere and in a suite of state of the art GCMs. As with the forced response examined by Lu et al. [2008], Kang and Polvani [2011] found a ratio of the movement of $\Phi_{\text{Hadley}}$ to $\Phi_{\text{jet}}$ of 1:2 during periods when they were correlated. Further work on this phenomenon has often been addressed through the viewpoint of the El Niño southern oscillation (ENSO) teleconnections. ENSO is also known to affect both $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ in the SH during austral summer [L’Heureux and Thompson, 2006; Seager et al., 2005; Fogt and Bromwich, 2006; Lu et al., 2008].
These relationships have led to research on the dynamical links between the $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$, with several researchers positing that the speed of the thermally driven subtropical jet, located at the edge of the Hadley cell, affects $\Phi_{\text{jet}}$ through the impact of the background wind-speed on the dissipation of equatorward-propagating eddies [Robinson, 2002; L’Heureux and Thompson, 2006; Seager et al., 2005; Lu et al., 2008].

Here we investigate the correlation between $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ using an idealized GCM. We find that the correlation depends on the time-mean separation of the two features, which suggests underlying dynamics that have not been expounded in the literature. The eddy dynamics associated with changes in $\Phi_{\text{Hadley}}$ appear to be unchanged across a wide parameter range, and remain the same when $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ are uncorrelated. The picture that emerges is of relatively constant eddy dynamics controlling the variability in $\Phi_{\text{Hadley}}$, and $\Phi_{\text{jet}}$ being affected by these changes according to the time-mean separation of the two features.

2. Methods

We use the simplified grey-radiation GCM described in Frierson et al. [2006]. The resolution is $2.8^\circ \times 2.8^\circ$, with 25 vertical levels, and the incoming solar flux is set by

$$S(\phi) = S_0 \left(1 + \frac{\Delta}{4} (1 - 3 \sin^2(\phi))\right) \tag{1}$$

where $\phi$ is latitude, and the flux is only absorbed at the surface. The parameter $\Delta$ sets the latitudinal variation of insolation, with stronger meridional temperature gradients resulting from higher $\Delta$. This is the main parameter varied in this study, and the
model is run for ∆ equall to 0.5, 0.8, 1.0, 1.2, 1.4, 1.7 and 2.0. The simulations are
generally run for 6000 days, and the first 1500 days have been discarded.

In addition to varying ∆, runs were also performed where the polar stratosphere was
cooled. This can be thought of as simulating the affect of Ozone depletion, and it is known
to shift Φ_{jet} poleward [Polvani and Kushner, 2002; Haigh et al., 2005]. A diabatic heating
term was added to the temperature tendency of the form

\[ \frac{\partial T}{\partial t} = C_0 e^{-\left(\frac{p-p_0}{p_h}\right)^2} e^{-\left(\frac{\phi-\phi_0}{\phi_h}\right)^2} \]  

(2)

where \( p \) is pressure, the 0 subscripts indicate reference pressure/latitude, and the h sub-
scripts indicate the pressure/latitude scale over which the heating anomaly decays. The
value of \( \phi_0 \) was set to \( \pm 90^\circ \), and the value of \( p_0 \) was set to 0 hPa, with \( \phi_h = 20^\circ \) and
\( p_h = 50 \) hPa. The value of \( C_0 \) was varied in order to give a reasonable shift of \( \Phi_{jet} \) (See
Table 1).

The streamfunction is computed from the zonally-averaged wind data. The edge of
the Hadley cell is then indexed as the first zero-crossing of the streamfunction going
poleward from the equator at a pressure level of 600 hPa. For added precision, the data
points around the zero-crossing are fitted with a second-order polynomial which is then
evaluated on a high-resolution grid (0.01°), and \( \Phi_{Hadley} \) is taken as the latitude of the
zero-crossing of the polynomial on this grid. The value of \( \Phi_{jet} \) is inferred from the latitude
of the maximum of the surface zonal-mean zonal wind-speed. The data points either side
of the maximum are fitted with a second-order polynomial, and this is evaluated on the
high-resolution grid.
3. Results

3.1. Mean State

As $\Delta$ increases, the climate moves from summer-like to winter-like conditions. The area-weighted global-mean surface temperature ($T_G$), shown in Table 1, drops by 5 K over the range of $\Delta$ considered, while the pole-equator surface temperature difference $(d_y T)$ increases by over 50 K.

In qualitative agreement with Lu et al. [2010] and Walker and Schneider [2006], both $\Phi_{\text{jet}}$ and $\Phi_{\text{Hadley}}$ (where $\ldots$ indicates the time-average) increase as $\Delta$ increases and the equator-pole temperature difference increases (Figure 1 (a)). The relationship is highly non-linear. For summer-like conditions (small $\Delta$), the ratio of $\delta \Phi_{\text{Hadley}}$ to $\delta \Phi_{\text{jet}}$ (where $\delta$ is the difference operator) is approximately 1:2. This is the same as was found in Lu et al. [2008] for the response of state-of-the-art GCMs to increasing GHGs during SH summer.

For more winter-like conditions, the ratio of $\delta \Phi_{\text{Hadley}}$ to $\delta \Phi_{\text{jet}}$ decreases, with $\Phi_{\text{Hadley}}$ only increasing by around 1° for a 10° increase in $\Phi_{\text{jet}}$ between $\Delta = 1.4$ and $\Delta = 1.7$. It appears that there is a regime shift around $\Delta = 1.4$. Support for this idea is found in the values of the time-mean zonal-mean values of the zonal wind-speed at 300 hPa ($\tilde{u}_{300}$) shown in Figure 1 (b). For the low-$\Delta$, summer-like conditions, there is a single maximum in $\tilde{u}_{300}$, whereas for more winter-like conditions, when $\Delta \geq 1.4$, there is a double maximum. This behaviour is similar to the real SH atmosphere, where the thermally- and eddy-driven jets are coincident during summer but well separated during winter Bals-Elsholz et al. [2001]; Hoskins and Hodges [2005]; Yang and Chang [2006]. The picture that arrises from the idealized model is that the poleward shift of $\Phi_{\text{jet}}$ is relatively constant for a given increase in $\Delta$ or $d_y T$, whereas the sensitivity of $\Phi_{\text{Hadley}}$ to $\Delta$ or $d_y T$ is much higher when
the two features are close together and form a single upper level jet. The reason for this nonlinearity is beyond the scope of this manuscript.

3.2. Unforced Variability

In order to investigate the unforced variability of $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$, their values were averaged over 30-day periods, and these values will be labelled with a monthly superscript. A scatter plot of the values of $\Phi_{\text{monthly Hadley}}$ against $\Phi_{\text{monthly jet}}$ shows that both the slope of the regression, and the correlation between the two features decreases as the conditions move from summer-like to winter-like (Figure 2 (a)). When $\Delta$ is small, and conditions are summer-like, $\Phi_{\text{monthly Hadley}}$ and $\Phi_{\text{monthly jet}}$ are highly correlated, with $R=0.8$. As the conditions become more winter-like, the correlation decreases and even becomes negative when $\Delta$ is large.

One of the changes that occurs as $\Delta$ is increased is that the separation of $\hat{\Phi}_{\text{Hadley}}$ and $\hat{\Phi}_{\text{jet}}$ increases, as is clear from Figure 1 (a) and Table 1. When $\Delta$ is small, the two features are close together and essentially form a single upper level jet, as seen in Figure 1 (b). When $\Delta$ increases, the two features are well separated and there is a double maximum in $\hat{u}_{300}$.

To test the idea that the correlation between $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ depends on their separation, the features can be separated by a mechanism other than changing $\Delta$. It is well known that cooling the polar stratosphere causes the eddy-driven to shift poleward in GCMs [Kushner and Polvani, 2004; Haigh et al., 2005; Lorenz and DeWeaver, 2007]. As seen in Table 1, cooling the polar stratosphere in this model shifts $\hat{\Phi}_{\text{jet}}$ much more than $\hat{\Phi}_{\text{Hadley}}$ and acts to separate the two features. The only run where there is a large $\hat{\Phi}_{\text{Hadley}}$
response is the run with $\Delta = 0.5$. When $\Phi_{\text{jet}}$ and $\Phi_{\text{Hadley}}$ are relatively well separated in the control run, as when $\Delta = 1.0, 1.4$, the Hadley cell shows minimal response to polar stratospheric cooling. The stratospheric cooling does not extend to the surface, so $d_y T$ is essentially unchanged, implying that the thermodynamic changes in the mean state induced by stratospheric cooling different to when $\Delta$ is altered. In simplified GCMs, $\Phi_{\text{jet}}$ shifts poleward in response to either polar stratospheric cooling or increasing $d_y T$, independently. As such changing $C_0$ provides a test for the idea that the separation of $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ determines their correlation.

The impact that the separation of $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ has on the correlation between $\Phi_{\text{Hadley}}^{\text{monthly}}$ and $\Phi_{\text{jet}}^{\text{monthly}}$ is summarised in Figure 2 (b). The correlation coefficient is shown for all of the runs in Table 1, and there are two points for each run (one for each hemisphere).

In the experiments with polar stratospheric cooling (red) and the runs where only $\Delta$ was altered (blue), the correlation is well determined by the time-mean separation, and both sets of experiments follow a similar relationship. The correlation between the features becomes negative at a similar separation for the two sets of experiments. For the runs where only $\Delta$ was changed, this occurs at $\Delta = 1.7$ or 2.0. The highest value of $\Delta$ for runs that also have polar stratospheric cooling is $\Delta = 1.4$. It can be inferred from Figure 2 (b) that the runs with polar stratospheric cooling and $\Delta = 1.4$ populate the same space as the runs with $\Delta = 1.2$ or 2.0, that have no imposed polar stratospheric cooling.

### 3.3. Hadley cell behaviour

In this section diagnostics are shown that suggest that the dynamics and teleconnections associated with variations in $\Phi_{\text{Hadley}}$ are unchanged regardless of whether $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$...
are correlated. If, when the two features are correlated, $\Phi_{\text{Hadley}}$ were controlled by changes originating with the mid-latitude jet, the changes in eddy activity associated with $\Phi_{\text{Hadley}}$ variability might be qualitatively different when the two features are correlated versus uncorrelated. This is not the case, and the dynamics associated with $\Phi_{\text{Hadley}}$ are relatively constant. This supports the view that $\Phi_{\text{Hadley}}$ can be thought of as being controlled by its own internal dynamics, and that these dynamics impact $\Phi_{\text{jet}}$ according to the time-mean separation of the two features.

As seen in Figure 3 (a), the hemispheric-scale correlation patterns of $\bar{u}_{300}^{\text{monthly}}$ with $\Phi_{\text{Hadley}}^{\text{monthly}}$ form self-similar patterns with respect to $\hat{\Phi}_{\text{Hadley}}$. The pattern shows a decrease in $\bar{u}_{300}^{\text{monthly}}$ in the sub-tropics and an increase in the midlatitudes. The latitudes of the maximum/minimum correlations shift poleward as $\hat{\Phi}_{\text{Hadley}}$ shifts poleward (i.e. with increasing $\Delta$). Examining the corresponding correlations for the meridional component of the wind-speed, $\bar{v}_{300}$, reveals that the changes in $\bar{u}_{300}^{\text{monthly}}$ must be eddy-driven (Figure 3 (b)). The changes in $\bar{v}_{300}^{\text{monthly}}$ are of the opposite sign to those required to drive the changes in $\bar{v}_{300}^{\text{monthly}}$ through the Coriolis torque.

The convergence of the meridional flux of zonal momentum ($-\partial_y \bar{u}'v'$) must drive the changes in $\bar{v}_{300}^{\text{monthly}}$. These $\bar{v}_{300}^{\text{monthly}}$ anomalies would drive the $\bar{v}_{300}^{\text{monthly}}$ anomalies in panel (b) through the Coriolis torque, thereby implying that the streamfunction anomalies associated with $\Phi_{\text{Hadley}}^{\text{monthly}}$ variability are eddy-driven in this model.

The value of $-\partial_y \bar{u}'v'$ was calculated from daily-means, and then vertically-averaged ($|...|$) and time-averaged to enable a relatively noise-free comparison with $\Phi_{\text{Hadley}}^{\text{monthly}}$. The relationship between $-|\partial_y \bar{u}'v'|^{\text{monthly}}$ and $\Phi_{\text{Hadley}}^{\text{monthly}}$ is shown in Figure 3 (c) and (d) for the
experiments with \( \Delta = 0.5 \) and 1.7 respectively. Just as with the \( \overline{u_{300}}^{\text{monthly}} \), the correlation patterns between \(-|\partial_y u'v'|^{\text{monthly}}\) and \(\Phi_{\text{Hadley}}^{\text{monthly}}\) are approximately self-similar with relation to \(\hat{\Phi}_{\text{Hadley}}\). There is a negative correlation at the latitude of \(\hat{\Phi}_{\text{Hadley}}\), and a positive correlation a few degrees poleward of \(\hat{\Phi}_{\text{Hadley}}\).

One theory for the dynamical control on the Hadley cell extent is that the poleward extent of the axis-symmetric overturning is dictated by the latitudes where the flow becomes baroclinically unstable [Held, 2000; Lu et al., 2008]. There is net momentum flux convergence into the source latitudes of baroclinic instability, and so if this latitude moves poleward, the dipolar anomalies see in Figure 3 (c) and (d) would be expected. The sign of the \(-|\partial_y u'v'|^{\text{monthly}}\) correlations are those required to drive the \(\overline{u_{300}}^{\text{monthly}}\) anomalies seen in panel (a).

A similar analysis of the correlation between the eddy heat flux \((v'T')\) and \(\Phi_{\text{Hadley}}^{\text{monthly}}\) also shows dipolar anomalies, with a reduction in \(\overline{v'T'}^{\text{monthly}}\) at sub-tropical latitudes, and an increase in \(\overline{v'T'}^{\text{monthly}}\) in the mid-latitudes (Figure 3 (e) and (f)). Again, this is consistent with the idea that low-latitude baroclinic instability has shifted poleward, as baroclinic instability is inherently tied to an eddy heat flux.

The changes in \(-|\partial_y u'v'|^{\text{monthly}}\) associated with changes in \(\Phi_{\text{Hadley}}^{\text{monthly}}\) do not have a self-similar pattern with relation to \(\hat{\Phi}_{\text{jet}}\) or the time-averaged values of \(-|\partial_y u'v'|\) (dashed lines in Figure 3 (c) and (d)). When \(\Delta\) is low and \(\hat{\Phi}_{\text{jet}}\) is located towards the equator, the increase in \(|\partial_y u'v'|^{\text{monthly}}\) is on the poleward flank of the climatological maximum of \(|\partial_y u'v'|\), and poleward of \(\hat{\Phi}_{\text{jet}}\). Conversely, when \(\Delta\) is high, and \(\hat{\Phi}_{\text{jet}}\) is located towards the pole, the increase in \(-|\partial_y u'v'|^{\text{monthly}}\) is roughly coincident with the climatological
maximum of $-|\partial_y u'v'|$, and is slightly equatorward of $\Phi_{\text{jet}}$. Thus it appears that although changes in $-|\partial_y u'v'|_{\text{monthly}}$ associated with changes in $\Phi_{\text{Hadley}}^{\text{monthly}}$ are roughly constant with respect to $\Phi_{\text{Hadley}}$ (as is expected if $\Phi_{\text{Hadley}}$ variability is always eddy-driven), their location with respect to $\Phi_{\text{jet}}$ is determined by the separation of $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$. The position of the $-|\partial_y u'v'|_{\text{monthly}}$ anomalies relative to $\Phi_{\text{jet}}$ determines whether $\Phi_{\text{jet}}^{\text{monthly}}$ moves, and thus whether $\Phi_{\text{Hadley}}^{\text{monthly}}$ and $\Phi_{\text{jet}}^{\text{monthly}}$ are correlated. In this view of things, the weak negative correlations between $\Phi_{\text{Hadley}}^{\text{monthly}}$ and $\Phi_{\text{jet}}^{\text{monthly}}$ when $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ are well separated, seen in Figure 2 (a) and (b), make sense. When the separation between $\Phi_{\text{Hadley}}$ and $\Phi_{\text{jet}}$ is so large that the $-|\partial_y u'v'|_{\text{monthly}}$ anomalies lie equatorward of $\Phi_{\text{jet}}$, the two features become negatively correlated.

4. Discussion

The correlation between the Hadley cell extent and latitude of the eddy-driven jet has been examined using a simplified GCM. It appears that the correlation can be determined by the time-mean separation of the two features. When they are close together there is a positive correlation, and as the separation between them increases, the correlation decreases, with a weak negative correlation emerging at large separation. Diagnostics of the eddy momentum flux convergence show that regardless of whether the two features are correlated, the eddy dynamics and teleconnections associated with changes in the Hadley cell extent form self-similar patterns, and the same is true of the eddy heat flux. This can be interpreted as meaning the internal variability of the Hadley cell extent is driven by changes in baroclinic eddy activity, and that the eddy-driven jet responds to these changes. Associated with a poleward displacement of the Hadley cell is a decrease
in the eddy momentum flux convergence and heat flux in the sub-tropics, and an increase
at mid-latitudes. This is consistent with the picture that the Hadley cell extent is set
by the latitudes where the flow first becomes baroclinically unstable, and that this is
subject to variability. The affect on the mid-latitude jet then depends on the time-mean
position relative to the Hadley cell. If they are close, the change in eddy activity at
mid-latitudes will draw the eddy-driven jet poleward, resulting in a positive correlation
between the Hadley cell extent and eddy-driven jet latitude. Conversely, if there is a
broad baroclinic zone and the two jets features are well separated, the same increase in
eddy activity in mid-latitudes will draw the eddy-driven jet equatorward, resulting in a
negative correlation.

The question of whether these same relationships and dynamics are relevant to more
realistic atmospheres in full GCMs is the subject of ongoing work.

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Table 1: A summary of the experiments. The first column gives the value of $\Delta$, used in Equation 1. The second column gives the value of $C_0$, used in Equation 2 for the stratospheric cooling experiments, and this was set to zero for the control experiments, who’s values are bolded. The variables shown for each experiment are the global-mean surface temperature ($T_G$), the difference in surface temperature between the equator and the pole ($d_y T$), and the time-averaged values of the latitude of the edge of the Hadley cell ($\hat{\Phi}_{\text{Hadley}}$) and the latitude of the surface westerlies ($\hat{\Phi}_{\text{jet}}$).
Figure 1. (a) Scatter plot of $\tilde{\Phi}_{\text{Hadley}}$ and $\tilde{\Phi}_{\text{jet}}$ for the runs were $\Delta$ was altered (see text). (b) Time-mean zonal-mean upper-tropospheric (250 hPa) zonal winds for each run.
Figure 2. (a) Scatterplot of $\phi_{\text{Hadley}}^{\text{monthly}}$ and $\phi_{\text{jet}}^{\text{monthly}}$ for each of the runs where $\Delta$ was altered. (b) The correlation coefficient for $\phi_{\text{Hadley}}^{\text{monthly}}$ and $\phi_{\text{jet}}^{\text{monthly}}$ plotted as a function of the separation of $\hat{\phi}_{\text{Hadley}}$ and $\hat{\phi}_{\text{jet}}$. The data from the runs with polar stratospheric cooling are plotted in red, and those from the uncooled runs are plotted in blue.
Figure 3. (a) The correlation coefficient between $\Phi_{\text{Hadley}}^{\text{monthly}}$ and the monthly-mean zonal wind-speed at 300 hPa ($u_{300}^{\text{monthly}}$), for the experiments where only $\Delta$ was altered. (b) The same as (a) but for the meridional component of the wind-speed ($v_{300}^{\text{monthly}}$). (c) The correlation coefficient between $\Phi_{\text{Hadley}}^{\text{monthly}}$ and the eddy momentum flux convergence ($|\partial_y u'v'|^{\text{monthly}}$, solid line, see text), and the time-averaged eddy momentum flux convergence ($\langle|\partial_y u'v'|\rangle$, dashed line) for the control run with $\Delta = 0.5$. (c) The same as (b) but for the run with $\Delta = 1.7$. (d), (e) The same as (c) and (d) but for the eddy heat flux, $|v'T|^{\text{monthly}}$ (solid lines), and $\langle|v'T|\rangle$ (dashed lines).