Hadley cell bias in climate models linked to extratropical eddy stress

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[1] Recent theoretical and observational work shows that the Reynolds stresses due to large-scale extratropical eddies play a key role in determining Hadley cell strength. This implies that errors in the representation of extratropical eddies in climate models could force a bias in the tropical circulation. Here, this hypothesis is assessed using output from 17 coupled climate models, focusing on Northern Hemisphere winter. Inter-model variability in Hadley cell strength, tropical temperature and tropical humidity is found to be significantly correlated with inter-model differences in stationary eddy stress. Thus, a significant fraction of the tropical climate bias found in current climate models may be forced from the extratropics. **Citation:** Caballero, R. (2008), Hadley cell bias in climate models linked to extratropical eddy stress, *Geophys. Res. Lett.*, *35*, L18709, doi:10.1029/2008GL035084.

1. Introduction

[2] The zonal-mean transport of mass, energy and momentum in the atmosphere is dominated in the tropics by the divergent Hadley circulation, and in the extratropics by quasi-geostrophic, zonally asymmetric eddies [*Schneider*, 2006]. To give a credible representation of the atmospheric general circulation, climate models should capture both the Hadley cell and the extratropical macro-turbulence accurately and robustly. It is disturbing therefore to find that the current generation of coupled climate models exhibits a large inter-model spread in climatological Hadley cell intensity [*Tanaka et al.*, 2005] and extratropical eddy amplitude [*Lucarini et al.*, 2006; *Boyle*, 2006].

[3] There is reason to think that the two problems may be linked. Recent work [*Becker et al.*, 1997; *Becker and Schmitz*, 2001; *Kim and Lee*, 2001; *Walker and Schneider*, 2006; *Caballero*, 2007; *Schneider and Bordoni*, 2008] shows that forcing by extratropical eddies can play a key role in determining Hadley cell strength. On the other hand, tropical diabatic forcing can also play an important role. The purpose of this paper is to assess what fraction, if any, of the biases in Hadley cell strength is related to biases in extratropical eddy stresses. To facilitate comparison with previous observational work [*Caballero*, 2007], the study is restricted to boreal winter, defined as December–February (DJF).

[4] In the subtropical upper troposphere, the observed zonal- and climatological-mean zonal momentum balance is, to leading order,

$$(f + \zeta)v - S_{st} - S_{tr} \approx 0 \tag{1}$$

[see, e.g., *Dima et al.*, 2005]. This is a balance between zonal acceleration by the poleward transport of absolute vorticity $f + \zeta$ and deceleration by the stationary and transient eddy stresses, denoted S_{st} and S_{tr} respectively (a detailed definition is given below). If balance (1) is to hold in a general circulation model, any bias in v (and thus in Hadley cell mass flux) must be offset by a corresponding bias either in eddy stress, in ζ (and hence in subtropical jet strength), or in both. The chief result of this paper is that inter-model variability in DJF Hadley cell strength is significantly correlated with variability in S_{st}, but is uncorrelated with variability in S_{tr} and ζ.

2. Model Data

[5] This study is based on model output archived by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) for the World Climate Research Programme (WCRP) Coupled Model Intercomparison Project phase 3 (CMIP3) [*Meehl et al.*, 2007]. The following 17 models are considered: (1) BCCR-BCM2.0, (2) CCCMA-CGCM3.1-T47, (3) CCCMA-CGCM3.1-T63, (4) CNRM-CM3, (5) CSIRO-Mk3.0, (6) GFDL-CM2.0, (7) GFDL-CM2.1, (8) GISS-EH, (9) GISS-ER, (10) IAP-FGOALS-g1.0, (11) INGV-SXG, (12) INM-CM3.0, (13) IPSL-CM4, (14) MIROC3.2-hires, (15) MIROC3.2-medres, (16) MPI-ECHAM5 and (17) MRI-CGCM2.3.2. For each model, data were obtained for a single realisation of the 20th century coupled simulations (20C3M). Daily u and v (available on mandatory pressure levels only up to 200 hPa) were used to compute the eddy stresses $S_{st} = (a\cos^2 \varphi)^{-1} \partial(\cos^2 \varphi[\overline{u^*}\overline{v^*}])/\partial\varphi$ and $S_{tr} = (a\cos^2 \varphi)^{-1} \partial(\cos^2 \varphi \ [\overline{u'^*v'^*}])/\partial\varphi$, where seasonal and zonal averages are represented by overbars and square brackets respectively, while primes and asterisks indicate the respective anomalies. Monthly data for the same period were used to compute all other quantities presented below. The zonal-mean mass flux streamfunction on isobars was computed following *Oort and Yienger* [1996]. A 1962–1999 DJF climatology was computed for each model and interpolated onto a common grid to facilitate the analysis.

3. Multi-model Ensemble-Mean

[6] We first briefly examine the multi-model ensemble-mean (MMEM). Figure 1 compares the MMEM climatology with the corresponding fields in the ECMWF 40-year reanalysis (ERA40) [*Uppala et al.*, 2005] over the same period. The observed structure of the Hadley and Ferrel cells and of the eddy stresses is very well captured by the MMEM. A similar comparison using the NCEP reanalysis [*Kalnay et al.*, 1996] gives similar results (not shown).

[7] For a more quantitative comparison, we use a bulk measure of Northern Hemisphere (NH) Hadley cell strength

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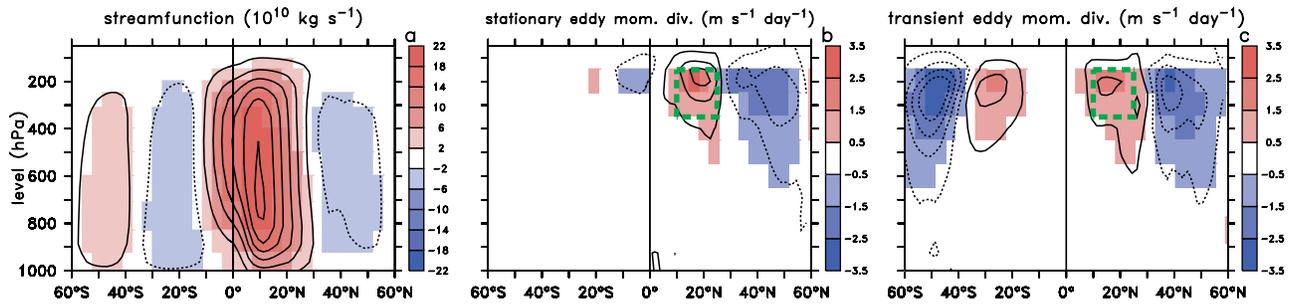
Figure 1. 1962–1999 DJF zonal-mean climatology of (a) isobaric mass streamfunction, (b) stationary eddy stress S_{st} and (c) transient eddy stress S_{tr}. Shading shows the MMEM, contours ERA40. Green boxes in Figures 1b and 1c show the region over which eddy stresses are averaged to obtain the indices plotted in Figure 2.

ψ^N defined as the maximum value of the streamfunction between 0° and 30°N [*Oort and Yienger*, 1996]. We also define indices of NH subtropical eddy stress variability S_{st}^N and S_{tr}^N as averages of S_{st} and S_{tr} over the region 10°–25°N, 200–300 hPa (outlined in green in Figures 1b and 1c). These indices are displayed in Figure 2. As noted in previous work [*Mitas and Clement*, 2005], there is a large discrepancy between climatological ψ^N in ERA40 (23 × 10^{10} kg s^{-1}) and NCEP (18 × 10^{10} kg s^{-1}). The Hadley cell is a purely divergent circulation, which is not well constrained by observations and is therefore sensitive to biases in the assimilating models [*Sardeshmukh and Hoskins*, 1987]. A well-documented problem with ERA40's tropical humidity leads to spurious latent heating, driving a strong Hadley cell which survives in the analysis [*Andersson et al.*, 2005]. On the other hand, both stationary and transient eddy stresses in ERA40 agree well those in NCEP (Figure 2c). This is not surprising, as the stresses result from large-scale, geostrophically balanced eddies which are well captured by the observational network. Eddy stresses are clearly not the sole control on Hadley cell strength, which should be borne in mind when considering the results below.

[8] The MMEM ψ^N agrees best with the ERA40 estimate, but given the uncertainty as to the true strength of the Hadley cell, this agreement must be considered fortuitous. Both stationary and transient MMEM eddy stresses agree well with the observational estimates—better in fact than any single model, as is commonly found [*Gleckler et al.*, 2008; *Reichler and Kim*, 2008].

4. Inter-model Variability

[9] A large spread in Hadley cell and eddy stress intensities among models is evident in Figure 2, with ranges exceeding 50% of the MMEM in all cases. The stationary eddy stress index S_{st}^N has correlation coefficient $r = 0.66$ with ψ^N, explaining 44% of the variance (Figure 2a). This correlation is significant at the 99% confidence level, using
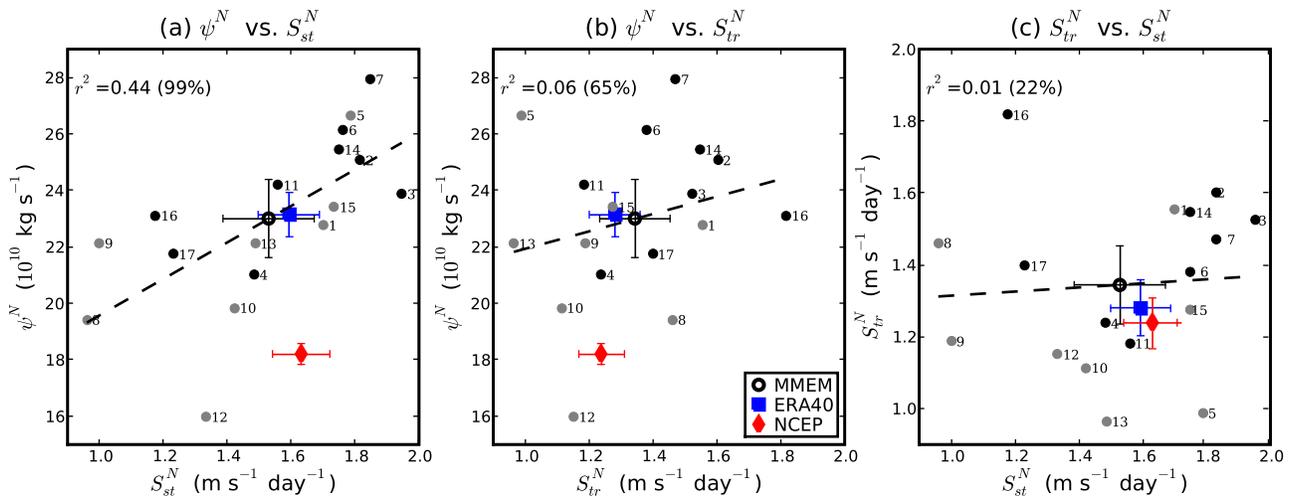
Figure 2. Scatter plots of Hadley cell strength index ψ^N and stationary and transient eddy stress indices S_{st}^N and S_{tr}^N, as indicated along the top of each figure. Solid dots indicate DJF climatologies for individual models, identified by numbers as in section 2; gray dots indicate models with poorer climatology (see text). Black circles indicate the MMEM. Squares and diamonds indicate ERA40 and NCEP climatologies respectively. Error bars show 2 standard errors based on the inter-model variance for the MMEM and on the inter-annual variance for the reanalyses. For clarity, errors have been omitted for individual models. Dashed lines show linear regressions, with r^2 indicated at the top left corner (statistical confidence level in parentheses).
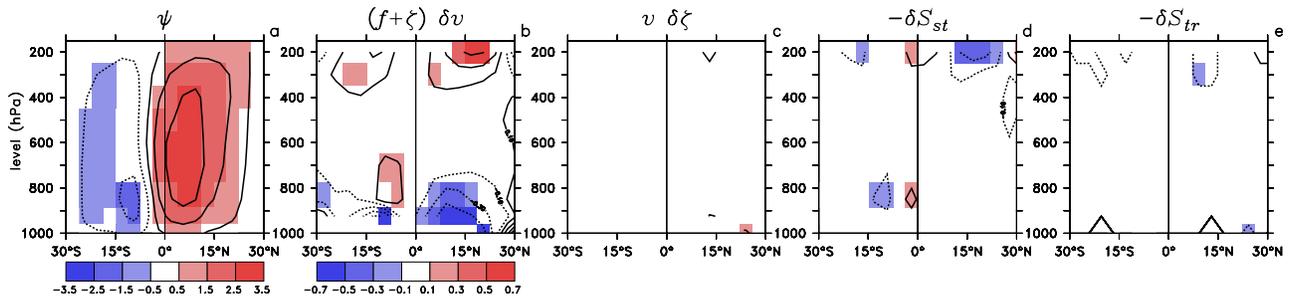
Figure 3. Regression of Hadley cell strength index ψ^N onto (a) the mass streamfunction and (b)−(e) the 4 terms in the linearised momentum budget (2), as indicated at the top of each figure. Regressions have been normalized to show the response to 1 standard deviation of ψ^N. Units are (a) 10^{10} kg s^{-1} and (b−e) m s^{-1} day^{-1}. Shading is shown only where the regression is statistically significant at the 95% level. Colour bar in Figure 3b applies to Figures 3b−3e.

a 2-tailed t test and assuming the data points to be independent. It is worth inquiring into the validity of the independence assumption, whose failure would imply a spuriously inflated correlation. Many of the models in the sample actually come in pairs: they are either the same model run at different resolution (pairs 2−3 and 14−15), or they are different versions of the same model family (6−7 and 8−9). It may be argued that these pairs are not truly independent. To test this argument, we can eliminate from the sample a random member from each of the 4 pairs, and recompute the correlation. Doing so for all possible combinations gives a mean r of 0.62 and a significance level which averages 97% and never drops below 95%. This should be compared against the null case in which 4 random models are eliminated from the sample, which gives a mean r of 0.67 and a mean significance level of 99%. It appears that including pairs of closely related models in the sample does lead to somewhat inflated correlations. However, we have also shown that when the dependencies are eliminated, the correlation between ψ^N and S_{st}^N remains statistically significant at least at the 95% level.

[10] The transient eddy stress index S_{tr}^N has no statistically significant correlation with Hadley cell strength (Figure 2b). Consistently, S_{st}^N and S_{tr}^N are also uncorrelated with each other (Figure 2c).

[11] For a more detailed view of the relation between Hadley cell mass flux and eddy stresses, we examine the linearised zonal momentum balance

$$(f + \langle \zeta \rangle)\delta v + \langle v \rangle \delta \zeta - \delta S_{st} - \delta S_{tr} \approx 0 \qquad (2)$$

where $\langle \cdot \rangle$ indicates the MMEM and δ a deviation therefrom. Figure 3 shows regressions of ψ^N onto the terms in (2), as well as onto the streamfunction itself. This latter regression (Figure 3a) shows a dipole pattern, indicating a strengthening not only of the northern (winter) cell but also of the southern (summer) cell. This dipole perturbs the momentum balance by inducing increased poleward transport of absolute vorticity at upper levels in both hemispheres (Figure 3b). In both hemispheres, the perturbation is compensated mostly by an increase in stationary eddy stress (Figure 3d), with only a small contribution from the transient eddies (Figure 3e). Changes in ζ—and thus in jet structure—play no significant role (Figure 3c). At low levels, surface friction plays an essential role in the momentum balance and (2) breaks down; this is why there is nothing in Figures 3c−3e to balance the increased low-level vorticity advection seen in Figure 3a.

[12] Finally, it is interesting to assess the relation between the eddy stress and Hadley cell biases seen above and other aspects of the tropical climate. Figure 4 shows regressions of stationary eddy stress onto tropical temperature and
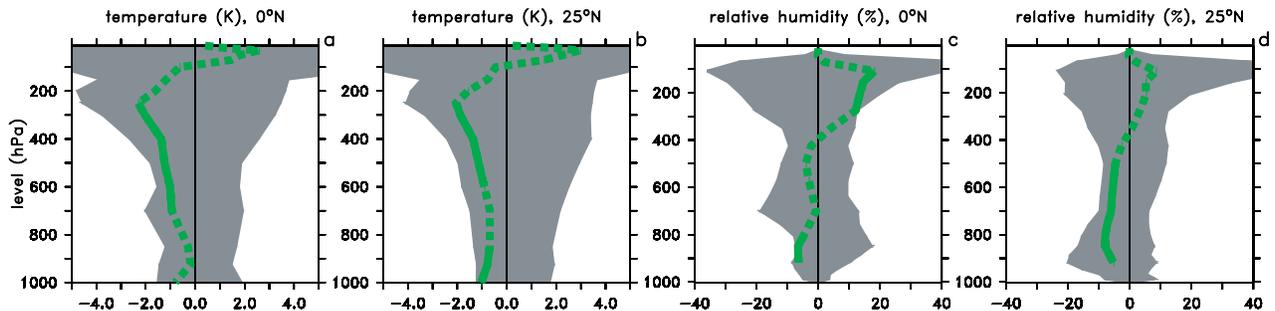
Figure 4. Inter-model variability of zonal-mean (a,b) temperature and (c,d) relative humidity at (a,c) the equator and (b,d) 25°N. Gray shading shows the maximum positive and negative anomalies from the MMEM at each level. Green lines show a regression onto the stationary eddy stress index S_{st}^N. The lines are solid where the correlation is significant at the 95% level. The regression has been scaled to show the response to a positive 2-standard-deviation anomaly of S_{st}^N.

humidity profiles. We see large inter-model differences in both temperature and relative humidity, of up to 8 K and 40% respectively. Significant biases in these fields have been documented previously [*John and Soden*, 2007]. The question here is to what extent the inter-model variability may be accounted for by differences in eddy forcing of the Hadley cell. Figure 4 shows statistically significant association between temperature, humidity and stationary eddy stress anomalies in much of the troposphere. Where correlations are significant, S_{st}^N explains 30–45% of the temperature and humidity variance. The sign of the regressions indicates that models with stronger eddy stress have tropical tropospheres which are everywhere colder, are moister around the equatorial tropopause and drier in the subtropical lower troposphere. The humidity response is consistent with a stronger Hadley cell, which would promote convection in the deep tropics and thus moisten the tropopause outflow region, and would dry the lower part of the subsiding branch through increased advection of dry upper-level air. The cooling observed throughout the troposphere is tied to surface cooling: dividing the regression profiles in Figures 4a and 4b by the surface value yields vertical amplification profiles consistent with the moist adiabat [*Santer et al.*, 2005]. The reasons for the surface cooling are not clear; it might result from an overall change in the radiative budget of the tropics, or from a rearrangement of the ocean/atmosphere heat transports. Further analysis is required to elucidate this point.

5. Summary and Discussion

[13] The main results of this study can be summarised as follows:

[14] 1. There are large model-to-model differences in DJF subtropical eddy stress, spanning a range of over 50% of the mean. However, the multi-model mean agrees very well with reanalysis data, suggesting that the multi-model mean may more accurately capture some aspects of the climate system than any individual model.

[15] 2. There are large differences in DJF Hadley cell strength among models and also among reanalysis data sets. Thus, there currently appears to be no useful observational constraint on the strength of the Hadley cell.

[16] 3. Inter-model variability of Hadley cell strength is significantly correlated with that in stationary eddy stress, but is uncorrelated with transient eddy stress.

[17] 4. Model bias in eddy stress—and thus in Hadley cell strength—is associated with significant bias in tropical temperature and humidity.

[18] How do the above results depend on the overall quality of model climatology? *Gleckler et al.* [2008] and *Reichler and Kim* [2008] have recently introduced model performance indices which measure the overall fidelity to the observed climatology of a suite of fields (which does not include the Hadley circulation or eddy stresses). The 8 models with the worst climatologies, as measured by Reichler and Kim's metric, are shown in gray in Figure 2 (models 1, 5, 8, 9, 10, 12, 13 and 15). Removing these models from the sample reduces the spread in ψ^N and S_{st}^N somewhat (standard deviations drop by 29% and 12% respectively), but interestingly the correlation between the two hardly changes (it

increases slightly to $r = 0.68$). This implies that our main conclusions apply even to the subset of the "best" models.

[19] The weak Hadley cell response to transient eddies (found also in observations [*Caballero*, 2007]) is puzzling, since the variabilities of transient and stationary eddy stresses are comparable (Figure 2c). One may also wonder what happens in the Southern Hemisphere (SH), where stationary waves are very weak. Defining SH cell strength and eddy stress indices analogous to those in section 4 but using the region 10°S to 30°S and the June-August season, we find that the roles of transient and stationary eddies are reversed: fluctuations in transient eddy stress explain around 40% of the variance in cell strength, while stationary eddy stresses play no role. Why transient eddy stresses should be effective in the SH but ineffective in the NH, given their comparable magnitudes, is not clear.

[20] Another issue left open here is the direction of causality. Do model errors in the extratropics lead to bias in subtropical eddy stress, forcing biases in the tropics [e.g., *Abiodun et al.*, 2008]? Or do biases intrinsic to the tropics affect extratropical wave propagation into the tropics and hence subtropical eddy stress [e.g., *Seager et al.*, 2003; *L'Heureux and Thompson*, 2006]? Both scenarios are possible.

[21] Pinning down the precise direction of causality is of considerable practical importance. If it turns out that tropical biases are in fact mostly forced from the extratropics, then "tuning" of model parameterisations locally in the tropics will, at best, give the right climate for the wrong reasons. On the other hand, efforts directed at correcting the extratropical circulation could have the added bonus of improving the tropical circulation as well.

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