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Width of the Hadley cell in simple and comprehensive general circulation models

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[1] The width of the Hadley cell is studied over a wide range of climate regimes using both simple and comprehensive atmospheric general circulation models. Aquaplanet, fixed sea surface temperature lower boundary conditions are used in both models to study the response of the Hadley cell width to changes in both global mean temperature and pole-to-equator temperature gradient. The primary sensitivity of both models is a large expansion of the Hadley cell with increased mean temperature. The models also exhibit a smaller increase in width with temperature gradient. The Hadley cell widths agree well with a scaling theory by Held which assumes that the width is determined by the latitude where baroclinic eddies begin to occur. As surface temperatures are warmed, the latitude of baroclinic instability onset is shifted poleward due to increases in the static stability of the subtropics, which is increased in an atmosphere with higher moisture content. **Citation:** Frierson, D. M. W., J. Lu, and G. Chen (2007), Width of the Hadley cell in simple and comprehensive general circulation models, *Geophys. Res. Lett.*, *34*, L18804, doi:10.1029/2007GL031115.

1. Introduction

[2] Many of the driest locales on Earth are situated in similar latitude bands, between 15–30 degrees latitude in the Northern and Southern Hemispheres. In these arid regions, downward motion from the subsiding branch of the Hadley cell fluxes moisture away from these locations and into the moist deep tropics. Baroclinic eddies from midlatitudes are additionally important in fluxing moisture away from this region. As the regions that border these deserts are often among the most tenuous of ecosystems, there are important implications for possible changes with global warming.

[3] Climate models show a general drying of the subtropics (and moistening of the deep tropics) in simulations of global warming, a fact that is relatively well-understood from basic theoretical arguments [*Allen and Ingram*, 2002; *Held and Soden*, 2006]. However, the location of the dry zones can shift as well. A poleward expansion of the Hadley cell could have a dramatic impact on locations such as Southwestern North America, the Mediterranean, southern South America, and Australia.

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[4] Such a shift of the edges of the Hadley cell has recently been identified in simulations in the WCRP CMIP3 multi-model data set [*Lu et al.*, 2007]. A similar poleward shift with global warming has been identified in the storm tracks in midlatitudes [*Kushner et al.*, 2001; *Yin*, 2005; *Bengtsson et al.*, 2006]. The Hadley cell expansion has been pointed to as important in determining the predicted Southwestern North American drought [*Seager et al.*, 2007] in global warming simulations. A widening of the Hadley cell has also been seen in recent satellite observations [*Fu et al.*, 2006].

[5] However, climate models vary to some extent in their predicted response. Therefore, it is important to understand the mechanisms behind the Hadley cell expansion, for interpreting model predictions, determining robustness, and for improving model discrepancies as well. The goal of this work is to improve our understanding by examining the width of the Hadley cell over a wide range of idealized boundary conditions.

[6] Much of our understanding of the Hadley cell comes from simple theories. For instance, *Held and Hou* [1980] (hereafter HH80) showed that the Hadley cell has a finite width even without the presence of baroclinic eddies in midlatitudes, and calculated a scaling for this width. On the other hand, in the HH80 model, the winds reach large values in the subtropics. Such large shears may become baroclinically unstable before the cell terminates according to the HH80 scaling. The resulting momentum fluxes would induce a Ferrel cell of the opposite direction which would end the Hadley cell prematurely. *Held* [2000] (hereafter H00) provides an alternate scaling for the Hadley circulation width based on this concept. The theory, which assumes angular momentum conservation to the latitude where the Phillips' criterion for baroclinic instability [*Phillips*, 1951; *Pedlosky*, 1987] is first satisfied, can be written as the following:

$$\phi_H \sim (H\Delta_v)^{1/4} \tag{1}$$

where ϕ_H is the Hadley cell latitude, H is tropopause height, and Δ_v is the gross dry static stability (the difference in potential temperature between the surface and the tropopause). A similar scaling can be derived by assuming a critical Eady growth rate for baroclinic instability, which results in a change of exponent from 1/4 to 1/6. The H00 scaling has been shown to be accurate for simulations of global warming [*Lu et al.*, 2007], as well as a set of idealized dry simulations in the study of *Walker and Schneider* [2006]. Idealized moist simulations also show a poleward shift of the storm tracks with increased moisture content [*Frierson et al.*, 2006, 2007], but it is clear in these simulations that the subtropical jet can separate quite far from the eddy driven jet in midlatitudes, a situation that would presumably preclude the H00 theory from working (if baroclinic instability does not occur in the vicinity of the Hadley cell edge).

[7] Additional physical effects can play a role in determining the Hadley cell width. For instance, changes in the properties of the momentum fluxes from midlatitudes can also lead to changes in the Hadley cell. G. Chen and I. M. Held (Phase speed spectra and the recent poleward shift of the Southern Hemisphere surface westerlies, submitted to *Geophysical Research Letters*, 2007) (hereinafter referred to as Chen and Held, submitted manuscript, 2007) have proposed a mechanism by which changes in phase speed spectra of baroclinic eddies can impact the position of the Southern Hemisphere surface westerlies; this mechanism can likely also impact the Hadley cell extent. Changes in the tropopause height has also been cited as a possible influence on the storm tracks *Lorenz and DeWeaver* [2007], although the full physical mechanism behind this is unclear.

[8] We investigate a wide range of fixed sea surface temperature (SST) aquaplanet simulations here, with both an idealized moist general circulation model (GCM) and a full GCM, to investigate the dependence of the Hadley circulation width on mean temperature and meridional temperature gradients. Classifying the dependence of the widths on these parameters can aid in our understanding of comprehensive climate simulations. The wide range of SSTs used can additionally help deduce whether any of the simple theories mentioned above are relevant for simulations with more complex models.

2. Model Descriptions

[9] The boundary conditions used in the simulations are from the study of *Caballero and Langen* [2005]. The surface is an aquaplanet (ocean-covered Earth) with no topography, and fixed, zonally symmetric SST distributions. The SSTs take the following functional forms, with two control parameters:

$$T_s(\phi) = T_m - \Delta T\left(3\sin^2\phi - 1\right)/3, \quad (2)$$

where T_m is the global mean temperature, ΔT is the equator-pole temperature difference, and ϕ is latitude. The functional form is chosen so that changes in ΔT cause no change in global mean temperature. We examine simulations with T_m between 0 and 35°C, and ΔT between 20 and 60 K. Simulations with surface temperatures above 45°C at the equator are omitted, due to uncertainties that the model physics can accurately simulate such warm climates. The full GCM simulations, which are the same simulations used in the *Caballero and Langen* [2005] study, are run at 5 K increments in both T_m and ΔT. To save computational expense, the idealized model simulations are run at 10 K increments for T_m and ΔT, with T_m = 35 C additionally run. It should be noted that due to the functional form of equation (2), the tropical temperatures increase with increases in both mean temperature and temperature gradient. All simulations are spun up for 1 year, and statistics are calculated over 3 subsequent years of integration. The time mean fields are calculated by averaging the Northern and Southern Hemispheres since the prescribed SST and the resulting model climatology are hemispherically symmetric.

2.1. Idealized Moist GCM

[10] The idealized GCM consists of various simplified physical parameterizations coupled to a spectral dynamical core which solves the primitive equations [*Frierson et al.*, 2006; *Frierson*, 2007a]. The model physics includes gray radiative transfer (which does not include water vapor or cloud radiative feedbacks), a simplified Monin-Obukhov surface flux scheme, a K-profile boundary layer scheme, and a simplified Betts-Miller convection scheme [*Betts*, 1986; *Betts and Miller*, 1986; *Frierson*, 2007a]. The idealized GCM is run at T42 resolution, with 25 vertical levels.

2.2. Full GCM

[11] The full GCM simulations in this paper are the same simulations originally used to study poleward heat transports in the study of *Caballero and Langen* [2005]. The model is a comprehensive GCM, with realistic parameterizations of clouds, radiation, convection, and other physics. The atmospheric model used for these simulations is PCCM3, which is the atmospheric component of the Fast Ocean-Atmosphere Model (FOAM) [*Jacob*, 1997]. The model uses the physical parameterizations of the NCAR CCM3.6 model [*Kiehl et al.*, 1996] and the dynamical core of the NCAR CCM2 model. The full GCM is run at T42 resolution, with 18 vertical levels. When the SST is below 0°C in the full GCM, sea ice is specified.

3. Results

[12] We first examine the width of the Hadley circulation for both the idealized GCM and the comprehensive GCM in Figure 1. We define the width based on the zonally averaged overturning stream function: the distance between the equator and the latitude where the 500 hPa stream function is 0. In Figure 1, the x-axes are the temperature gradient ΔT and the y-axes are the mean temperature T_m, with each box representing one simulation. The models agree to a large extent in their simulations of the edge of the Hadley cell, with the simulated widths within 1–3 degrees for nearly all the simulations. This suggests that the width of the Hadley circulation is likely not strongly sensitive to model physics. This result should be contrasted with the strength of the Hadley cell [*Frierson*, 2007a] and the location of the midlatitude jet [*Frierson*, 2007b], both of which we have found to be somewhat sensitive to the models used and their physical parameterizations. The idealized GCM tends to have a wider Hadley cell than the full GCM at the coldest and warmest temperatures, whereas the full GCM typically has a slightly wider Hadley cell for mean temperatures between 10 and 20 C.

[13] In terms of changes in the Hadley cell width with SST in Figure 1, the most prominent sensitivity is an increase in extent with increased mean temperature. This is present in both models, to a similar degree. On average, there is an approximately 0.2–0.25 degree widening per 1 K mean temperature increase in both models (although the expansion increases somewhat with mean temperature). This expansion is the same sign as the Hadley cell expansion with global warming identified in the WCRP CMIP3 multi-model data set [*Lu et al.*, 2007] and in recent

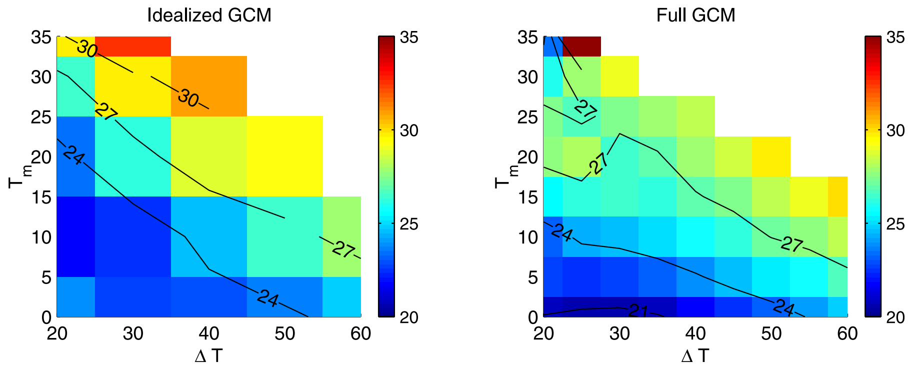

Figure 1. Width of the Hadley cell as defined by the zero line of the 500 hPa stream function for (left) the idealized GCM and (right) the full GCM.

observations [*Fu et al.*, 2006]. In addition, the widening in these experiments is similar in magnitude to [*Lu et al.*, 2007], who find an average expansion of $\sim$0.3 degrees latitude per 1 K warming in each hemisphere for the A2 scenario simulations.

[14] There is also a smaller increase in Hadley cell extent with temperature gradient in both models. This expansion is approximately 0.1 degrees latitude per 1 K increase in ΔT. It is important to recognize however that given the form of the SSTs in equation (2), the tropical temperatures are increased with larger ΔT (while latitudes poleward of 35.3 degrees are cooled). One might expect that this tropical warming may be at least partially responsible for the expansion with ΔT, by the same mechanism which causes the expansion with T_m. However, by comparing the average expansion with ΔT with the average expansion with T_m, taking into account the rates of SST increase in the tropics with ΔT, one can show that this cannot be the only cause of the sensitivity to ΔT. Since the equatorial SSTs increase only as $\frac{1}{3}$ ΔT and the rest of the tropics increases less (with 25 degrees latitude increasing as 0.15 ΔT), the Hadley cell width must be somewhat sensitive to the SST gradient across the Hadley cell as well as the mean tropical temperature. We discuss the reasons for the dependence on ΔT in more detail after comparing with the simple scalings.

[15] We next examine changes in the Hadley cell extent as compared with the theories presented in section 1. As discussed in that section, the H00 scaling (equation (1)) is most appropriate for situations in which the Hadley cell continues up to the latitude where baroclinic instability begins to occur. Such a situation would be especially expected in cases when the subtropical and eddy-driven jets are merged, which occurs in nearly all of the simulations presented here (with the exception of some of the warmest cases). In Figure 2 we compare with the H00 scaling as given by equation (1). We calculate the tropopause height H using the WMO criterion, where the lapse rate first hits 2 K/km, and calculate the bulk stability Δ_v averaged up to the tropopause height. Then we average over the subtropics between 20 and 40 degrees to create the scaling.

[16] As shown in Figure 2 (left), the H00 scaling works quite well for the idealized GCM, with only a few of the coldest and smallest temperature gradient simulations differing noticeably from the scaling. For the full GCM (Figure 2, right), the scaling again works well for the majority of the simulations. There is a similar tendency to underpredict the width for the coldest simulations, and additionally a tendency to overpredict the warmest simulations. We note that using a scaling which assumes a

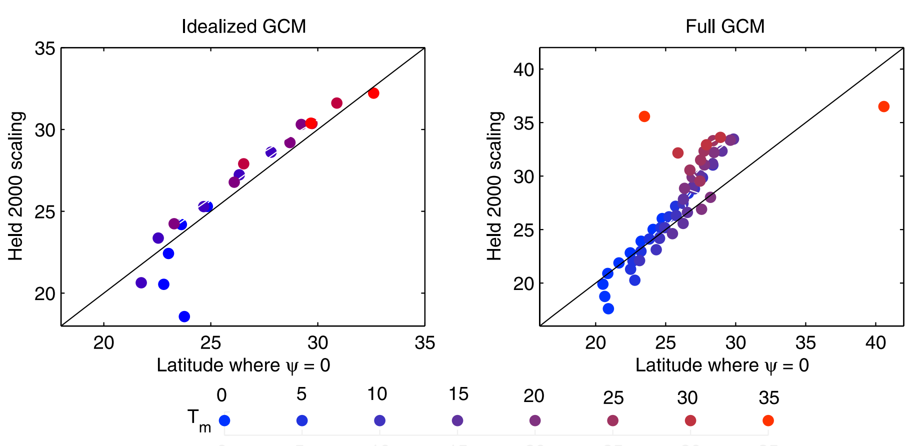

Figure 2. *Held* 2000 scaling for the Hadley cell width versus the actual cell width for (left) the idealized GCM and (right) the full GCM. Simulations are color-coded based on their global mean temperature value (T_m).

critical Eady growth rate for baroclinic instability [*Held*, 2000] works better in predicting the Hadley cell width for the full GCM, but not as well for the idealized GCM (not shown).

[17] Assuming that the H00 scaling does properly capture the dynamics of the Hadley cell width, what factors within this scaling cause the expansion with mean temperature and temperature gradient? Both the tropopause height and the gross static stability increase with mean temperature and temperature gradient, but within the scaling of equation (1), the static stability is the dominant factor. The tropopause heights vary by a factor of 2 from the lowest to the highest case, while the dry stabilities vary by a factor of 7. Increases in the tropical static stability with mean temperature are expected from simple application of the moist adiabatic lapse rate [*Xu and Emanuel*, 1989]. An increase in static stability in the subtropics and midlatitudes is also expected with increases in both mean temperature and meridional temperature gradients, as shown by recent examinations of observations [*Emanuel*, 1988; *Juckes*, 2000], idealized models [*Frierson et al.*, 2006], and the WRCP CMIP3 multi-model data set [*Frierson*, 2006]. For the simulations presented here, we have demonstrated a large increase in the midlatitude static stability with increases in T_m and a somewhat smaller increase in static stability with larger ΔT in the study of [*Frierson*, 2007b]. So, the increase in Hadley cell width with T_m and ΔT is interpreted as due to the increase in static stability, which reduces baroclinic growth rates and prevents the onset of baroclinic instability from occurring until higher latitudes (where the shear and the factor f/β in the Phillips' criterion are larger).

4. Conclusions

[18] We have shown that the width of the Hadley cell responds similarly to changes in SST distribution in idealized and full GCMs: both models respond with a widening of the Hadley cell in response to increases in global mean temperature, and to increases in meridional temperature gradients, to a lesser extent. These results provide a benchmark for comparing with Hadley cell extent changes in simulations with more comprehensive climate models. That the width increases similarly in the idealized moist GCM as in the full GCM suggests that the Hadley cell width does not strongly depend on model physics.

[19] We interpret the increase in width with mean temperature and temperature gradients with the theory of H00. With increases in SST and SST gradients, there are increases in the dry static stability, a result that is expected from previous studies [e.g., *Xu and Emanuel*, 1989; *Frierson*, 2007b]. The increased static stability then reduces baroclinic growth rates, which pushes the latitude of baroclinic instability onset (and therefore the edge of the Hadley cell) to a location that is farther poleward, where the shear and the factor of f/β in the Phillips' criterion are larger.

[20] The H00 scaling used here is based on the Phillips' criterion; however, a similar scaling can be derived assuming a critical Eady growth rate as the edge of the Hadley cell [*Held*, 2000]. Such a scaling produces qualitatively similar results to those presented in Figure 2. It is additionally important to recognize that when comparing with such a simple scaling, other physical effects, such as changes in phase speed spectra (Chen and Held, submitted manuscript, 2007), tropopause height [*Lorenz and DeWeaver*, 2007], and subtropical wind changes [*Seager et al.*, 2003; *Seager et al.*, 2005] should not be ruled out as factors that can influence the Hadley cell width. Some of these effects may be especially important when the changes in climate are of smaller magnitude than we force here, or when the changes are less global in scale (e.g., if temperature gradients are varied over a smaller band of latitudes). A more detailed study of the momentum, heat, and moisture budgets is warranted within these simulations, including eddy phase speed spectra for momentum fluxes. We are currently examining such diagnostics and constructing new simulations with the idealized GCM to further understand the dynamics of the Hadley cell width. However, given the accuracy of the H00 scaling in Figure 2, we find the H00 theory an appealing null hypothesis for explaining the widening of the Hadley cell with increased global mean temperatures.

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