Response of the Hadley Circulation to Climate Changes, Past and Future

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There are many suppositions concerning how the Hadley Cell responds to climate changes, and the implications for the paleo/future climate of such responses. We explore the general rules governing Hadley Cell changes in the context of the various thermal and momentum forcing terms contributing to the mass streamfunction. We compare general circulation model experiments for the Paleocene (58 million years ago), the Last Glacial Maximum (21k BP), and the doubled CO_2 climate with respect to the current climate. In addition to the standard experiments, each simulation is also run with an altered prescription of sea surface temperatures (SSTs) incorporating a greater tropical sensitivity. Finally, we comment on what the Hadley Cell changes actually mean with respect to soil moisture variations that might appear in the paleo-record.

The results show that across the suite of experiments neither the Hadley Cell intensity nor the poleward extent is simply related to global or equatorial temperatures. In the Southern Hemisphere for these particular experiments, the intensity is actually *inversely* related to tropical SSTs. The largest correlation of intensity is with the SST gradient between the tropics and subtropics; correlations are almost as large with the precipitation gradient between these latitudes, representing the primary diabatic heat source driving the Hadley Cell (and also responding to the vertical motion field associated with the circulation). This positive feedback leads to a latitudinal structure of the precipitation field that magnifies the effect of the SST gradients. As the SST structure can differ in the two solstice seasons, there is no significant correlation between the Hadley Cell intensity changes in the two winter hemispheres.

The poleward extent of the Hadley Cell shows no simple relationship with either the SST gradients or the intensity. It is negatively correlated with the tropical/subtropical precipitation gradient in the sense that when the Hadley Cell is expanded, subsidence in the subtropics weakens, and thus the precipitation gradient is weakened. The poleward extent is not correlated with the eddy energy, which through heat and momentum transports acts to generate the Ferrel Cell. The only obvious correlation for the extent (in the Northern Hemisphere) is with the parameterized topographical gravity wave drag (65% of the variance) , whose impact on the angular momentum field alters the sea level pressure and surface friction (with greater gravity wave drag, the extent increases).

The Hadley Cell extent has implications for the extratropical circulation, in the sense that when its poleward extent increases, higher pressure occurs further poleward, and the Arctic Oscillation phase is more negative. We have previously shown in other experiments for the $2xCO_2$ climate that with greater Hadley Cell intensity, there is greater energy convergence at lower mid-latitudes, increased west winds in the extratropical upper troposphere, more equatorward planetary wave refraction, and a more positive AO phase. This effect is not apparent in these runs due to the large range of topographic forcing and latitudinal temperature gradients included in these different climate regimes.

Finally, how does the Hadley Cell response relate to actual soil moisture changes in the different climates? As noted, the Hadley Cell intensity is related to the change in precipitation gradient, although variations in longitudinal cells and convection also influence precipitation. However, the latitudinal precipitation change accounts for just 30% of the variance in soil moisture in the two solstice seasons in the different experiments. Soil moisture is affected by evaporation changes as well, a function of the temperature and humidity, and the soil moisture values in individual seasons are affected by precipitation/soil moisture changes in other seasons. The results suggest the importance of Hadley Cell changes for paleo-moisture variations should not be overestimated.