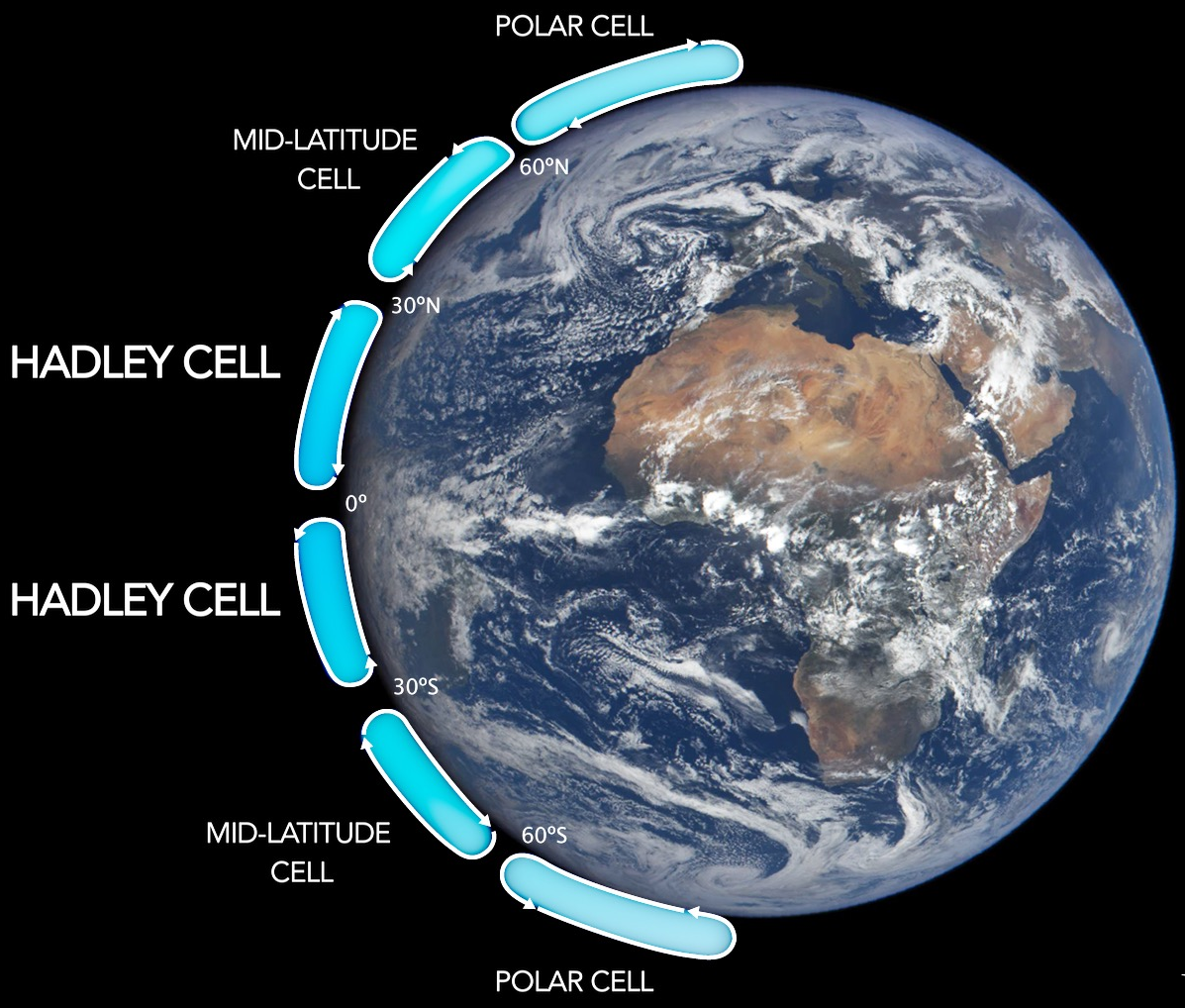
Expansion of the Hadley cell under global warming
(Lu *et al.* 2007)



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Met 205B
March 3, 2008

History

VI. *Concerning* the Cauſe *of the* General Trade-Winds: *By* Geo. Hadley, *Eſq; F. R. S.*

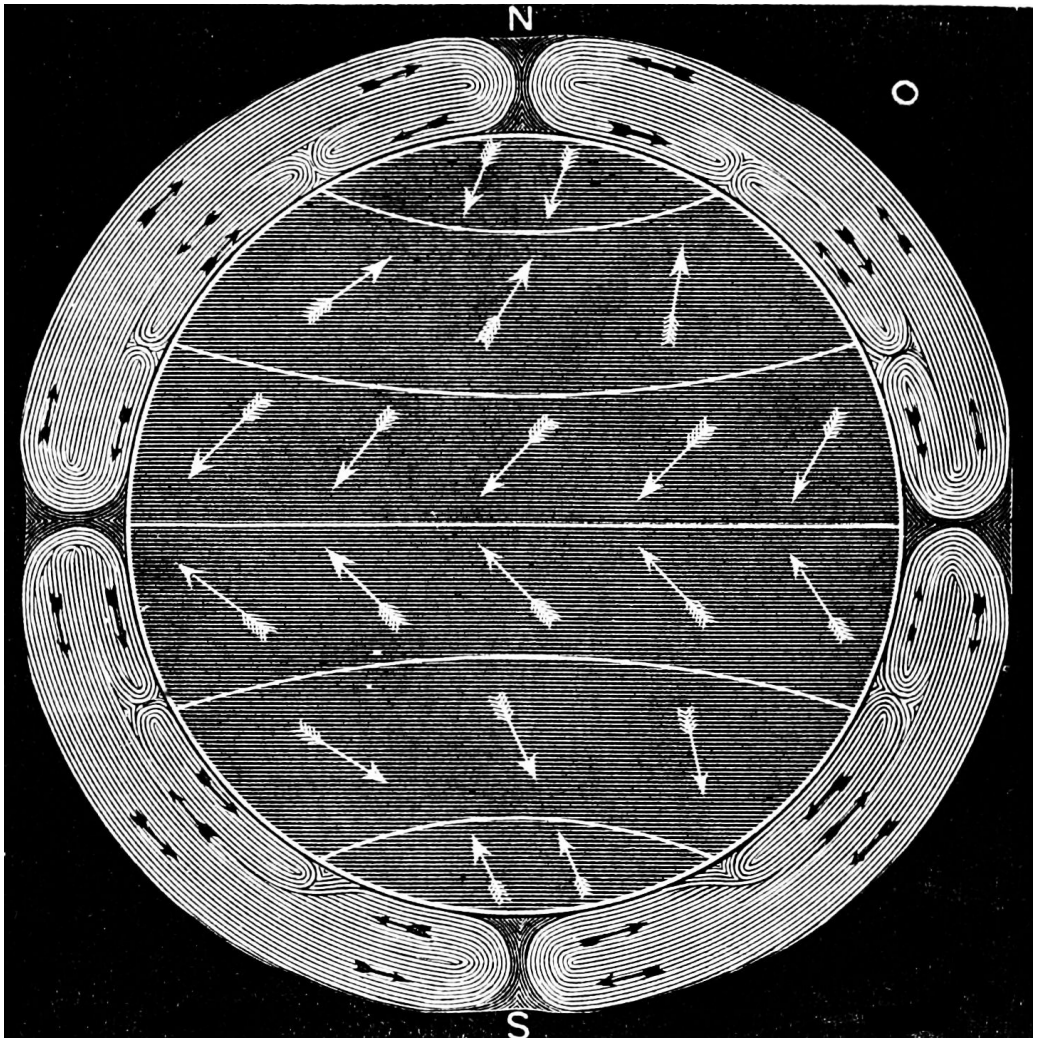
I Think the Cauſes of the General Trade-Winds have not been fully explained by any of thoſe who have wrote on that Subject, for want of more particularly and diſtinctly conſidering the Share the diurnal Motion of the Earth has in the Production of them: For although this has been mention'd by ſome amongſt the Cauſes of thoſe Winds, yet they have not proceeded to ſhew how it contributes to their Production; or elſe have applied it to the Explication of theſe Phænomena, upon ſuch Principles as will appear upon Examination not to be ſufficient.

That the Action of the Sun is the original Cauſe of theſe Winds, I think all are agreed; and that it does it by cauſing a greater Rarefaction of the Air in thoſe Parts upon which its Rays falling perpendicularly, or nearly ſo, produce a greater Degree of Heat there than in other Places; by which means the Air there becoming ſpecifically lighter than the reſt round about, the cooler Air will by its greater Denſity and Gravity, remove it out of its Place to ſucceed into it its ſelf, and make it riſe upwards. But it ſeems, this Rarefaction will have no other Effect than to cauſe the Air to ruſh in from all Parts into the Part where 'tis moſt rarefied, eſpecially from the North and South, where the Air is cooleſt, and not more from the Eaſt than the Weſt, as is commonly ſuppoſed: So that, ſetting aſide the diurnal Motion of the Earth, the Tendency of the Air would be from every Side towards that Part where the Sun's Action is moſt intenſe at the Time, and ſo a N. W. Wind be produced in the Morning, and a N. E. in the Afternoon, by Turns, on this Side of the Parallel of the Sun's Declination, and a S. W. and S. E. on the other.

That the perpetual Motion of the Air towards the Weſt, cannot be derived meerly from the Action of the Sun upon it, appears more evidently from this: If the Earth be ſuppoſed at Reſt, that Motion of the Air will be communicated to the ſuperficial Parts, and by little and little produce a Revolution of the Whole the ſame Way, except there be the ſame Quantity of Motion given the Air in a contrary Direction in other Parts at the ſame Time, which is hard to ſuppoſe. But if the Globe of the Earth had before a Revolution towards the Eaſt, this by the ſame means muſt be continually retard-

H 2 ed:

George Hadley proposed a mechanism for the trade winds in his 1735 paper, "On the Cause of the General Trade Winds".



Overview

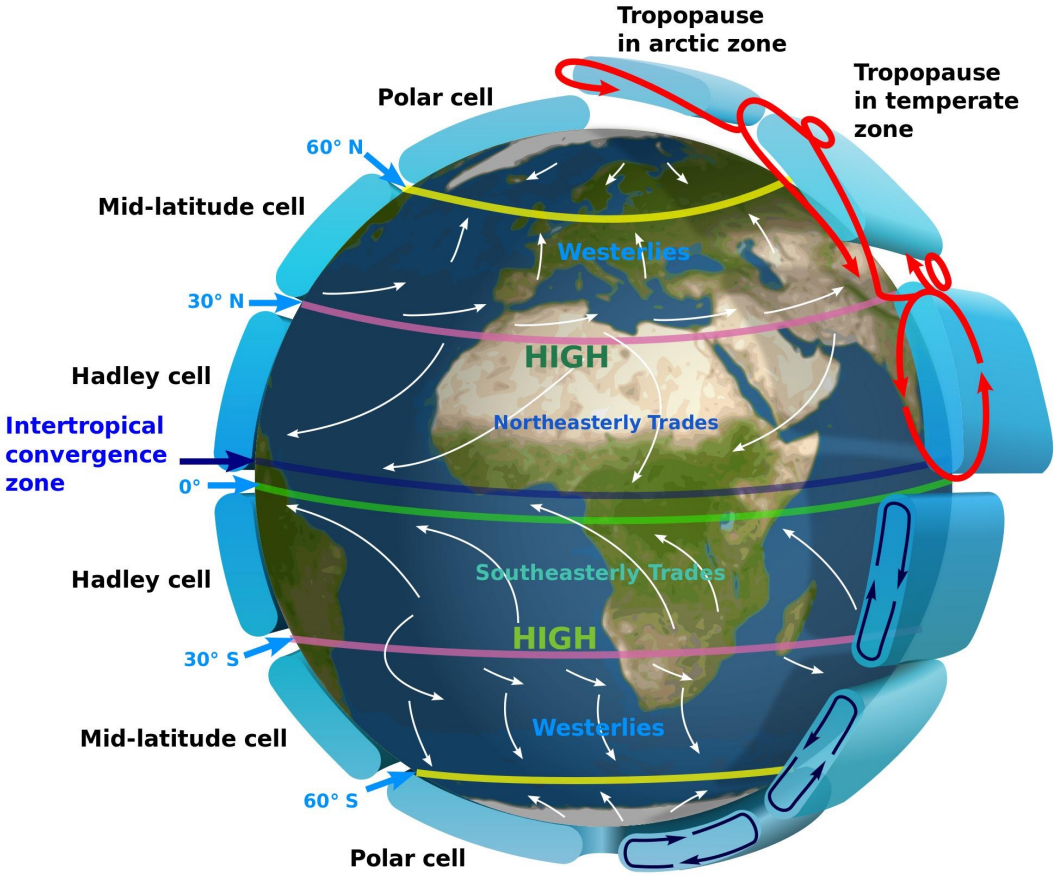
- A consistent weakening and poleward expansion of the Hadley circulation is diagnosed in the climate change simulations of the IPCC AR4 project.

- Associated with this widening is a poleward expansion of the subtropical dry zone.

- The expansion of the Hadley cell is caused by an increase in the subtropical static stability, which pushes poleward the baroclinic instability zone and hence the outer boundary of the Hadley cell.

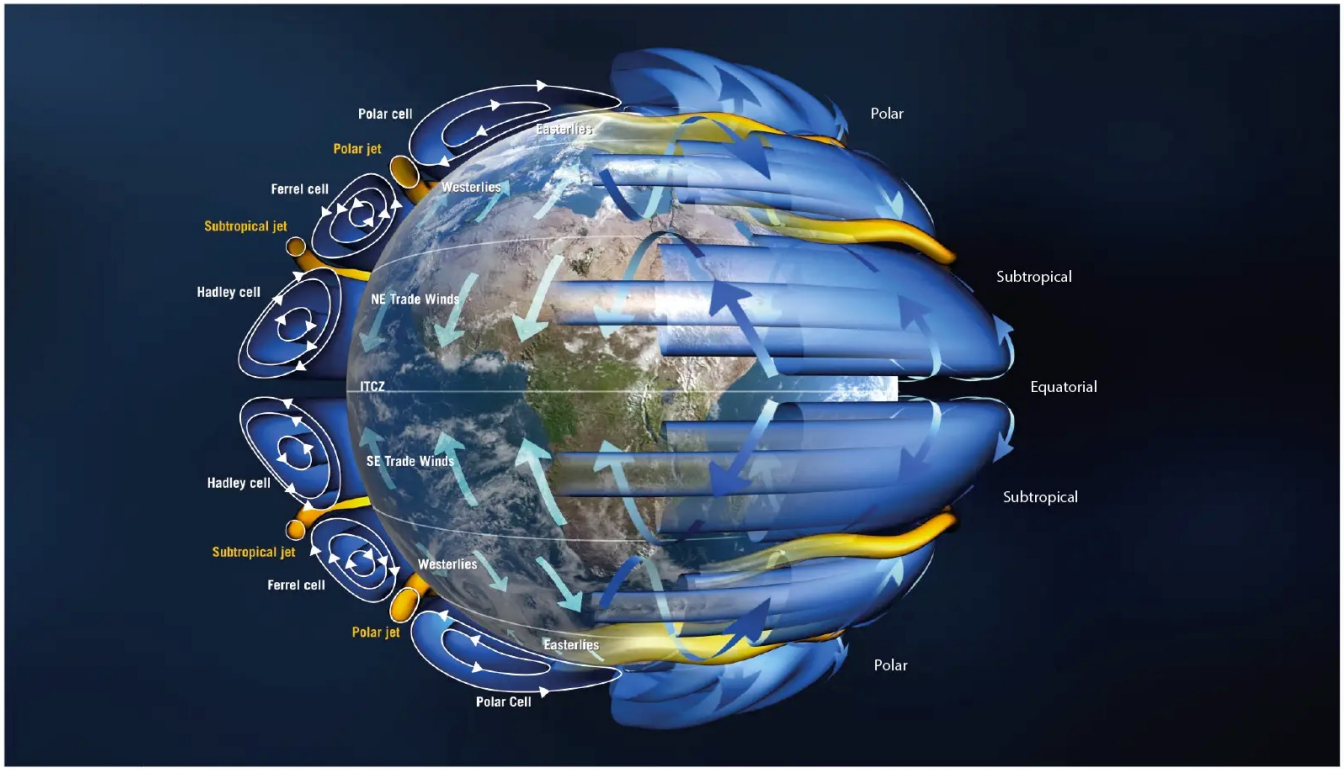
Hadley cell

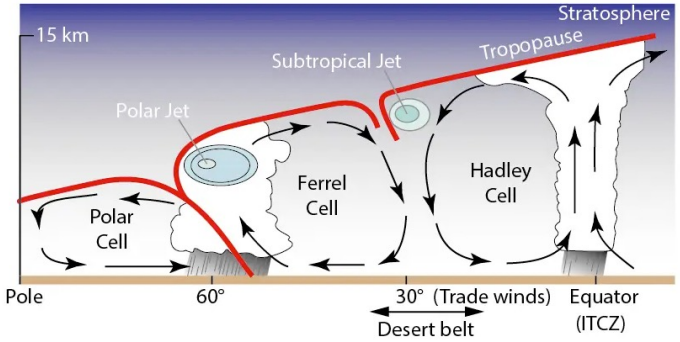
The Hadley cell (HC) plays a pivotal role in the earth's climate by transporting energy and angular momentum poleward and by organizing the three dimensional tropical atmospheric circulation.

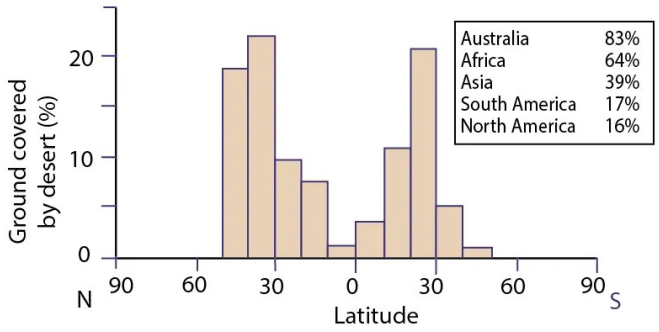


Hadley cell

The locations of the large-scale subtropical dry zones and the major tropical/ subtropical deserts of the globe are largely determined by the subsiding branches of the Hadley cell.







HC Influencing Factors

- Tropical heating processes (*e.g.,* Mitas and Clement 2006)
- Atmospheric stability (*e.g.,* Schneider 1977)
- Extra-tropical eddy dynamics
  (*e.g.,* Walker and Schneider 2006)
- Total atmospheric moisture (Frierson *et al.* 2006). To date, studies of the long term behavior of the HC, and the extent to which GHG forcing is relevant remain inconclusive.

Current understanding

- Studies of the long term behavior of the HC, and the extent to which GHG forcing is relevant remain inconclusive.

- Atmospheric reanalyses show a statistically significant intensification of their Hadley circulation throughout the second part of the 20th century (Mitas and Clement 2005).

- However, this intensification is not found in the rawinsonde data, nor in most 20th century simulations using both coupled or atmosphere-only general circulation models (GCMs) (Mitas and Clement 2005, 2006).

Observations

- Analysis of the satellite observations indicates a poleward expansion of the HC over the past 27 years (Fu *et al.* 2006).

- The extent to which this observed widening of the HC is primarily a response to GHG warming is not clear and warrants further investigation.

Data

- Gridded global monthly data from the AR4 archive website (www-pcmdi.llnl.gov):
  - precipitation
  - evaporation
  - surface air temperature
  - surface wind
  - meridional wind
  - 500hPa pressure velocity (ω_{500})
- Annual means were formed for the analysis.
- IPCC A2, A1B, and B1 scenarios were investigated

Hadley cell width

- To determine the poleward edges of the HC, Lu *et al.* computed the zonal-mean mass flux stream function (ψ) by vertically integrating the zonal-mean density-weighted meridional wind component from the top model level downward.

- The maximum of the absolute value of this stream function at 500 hPa (ψ_{500}) was determined, then identifying the edges of the HC as the first latitude poleward of the maximum at which ψ_{500} became zero.

- The edge of the subtropical dry zone in each hemisphere was identified as the latitude where the zonal mean precipitation minus evaporation (*P*-*E*) field crosses zero poleward of the subtropical minimum.

Results: global hydrological cycle

(a) Multi-model ensemble mean *P-E* in the A2 scenario. Shading indicates the difference between the first and the last 20 years of the 21st century and the black line denotes the 0-isopleths averaged from 2001 to 2020. The zonal mean averaged over 2001–2020 (black) and 2081–2100 (red) is shown; units are mm/day.

(b) Number count out of the total 15 models that simulate a moistening (i.e., $\Delta(P\text{-}E) > 0$) at each grid point.

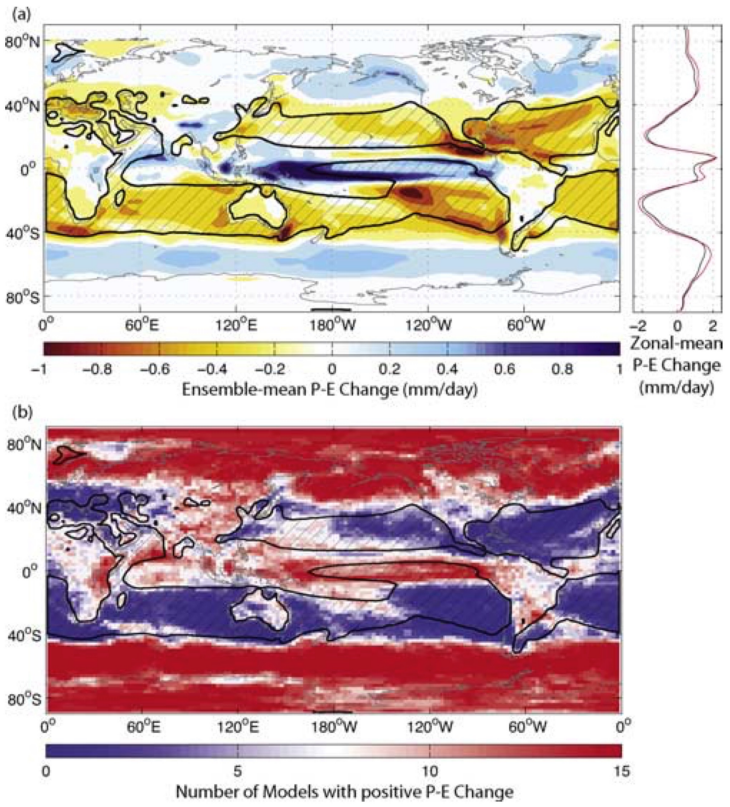


Figure 1. (a) Multi-model ensemble mean *P-E* in the A2 scenario. Shading indicates the difference between the first and the last 20 years of the 21st century and the black line denotes the 0-isopleths averaged from 2001 to 2020. The zonal mean averaged over 2001–2020 (black) and 2081–2100 (red) is shown; units are mm/day. (b) Number count out of the total 15 models that simulate a moistening (i.e., $\Delta(P\text{-}E) > 0$) at each grid point.

Results: Hadley cell expansion

- Poleward expansion of the subtropical dry zone is strongly tied to the poleward expansion of the HC.
- Based on the 38 simulations from the three scenarios (A2, A1B, B1), about 85% (72%) of the spread in the poleward displacement of the subtropical dry zones in the southern (northern) hemisphere can be explained by a linear relation to the displacements of the outer boundaries of the HC.
- The ensemble mean response of the A2 scenario (open circle) shows that the edges of the subtropical dry zone displace poleward by 1 in each hemisphere.

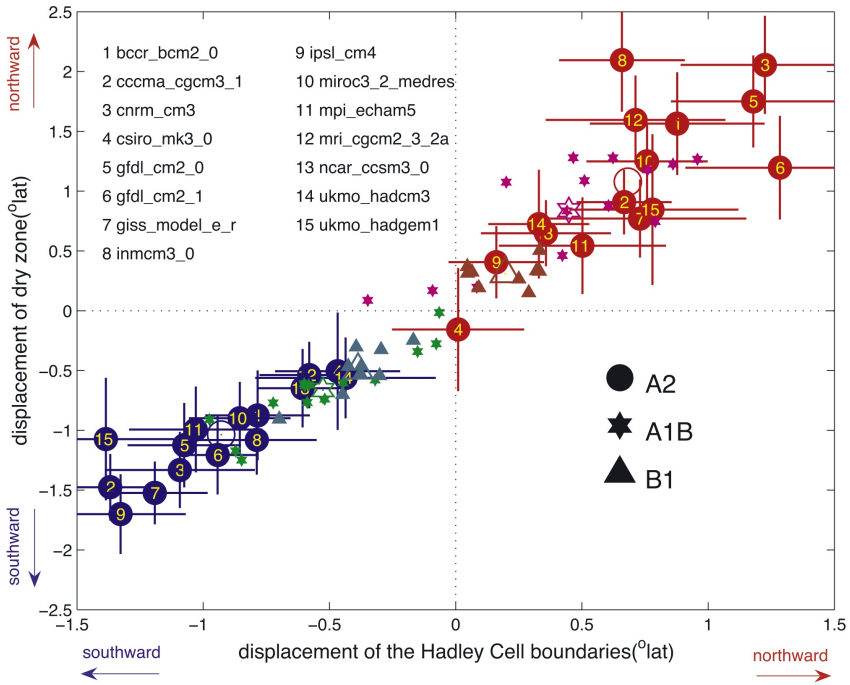


Figure 2. The breakdown by models and scenarios of the displacement of the northern (warm colors) and southern (cold colors) edges of the subtropical dry zone (y-axis) versus that of the HC (x-axis). The circles, hexagrams, and triangles denote the changes (2081–2100 minus 2001–2020) estimated from the A2, A1B, and B1 scenarios, respectively. The open symbols denote the multi-model ensemble mean values. The cross on each circle shows the 95% confidence interval of the estimated displacements using Student's t-test.

Results: Hadley cell weakening

- Another important aspect of the Hadley cell response to global warming is the reduction of its intensity (auxiliary material Figure S1)

- Weakening at rates between 0–4% K^{-1}, with a mean of 1.2% K^{-1}.

Results: HC –tropopause height

The extratropical tropopause height (ETH, averaged over 35°–55° N & S), is found to be closely related to the variation of the HC extent not only within each model (below), but also in the comparison of the long-term trend among models (top).

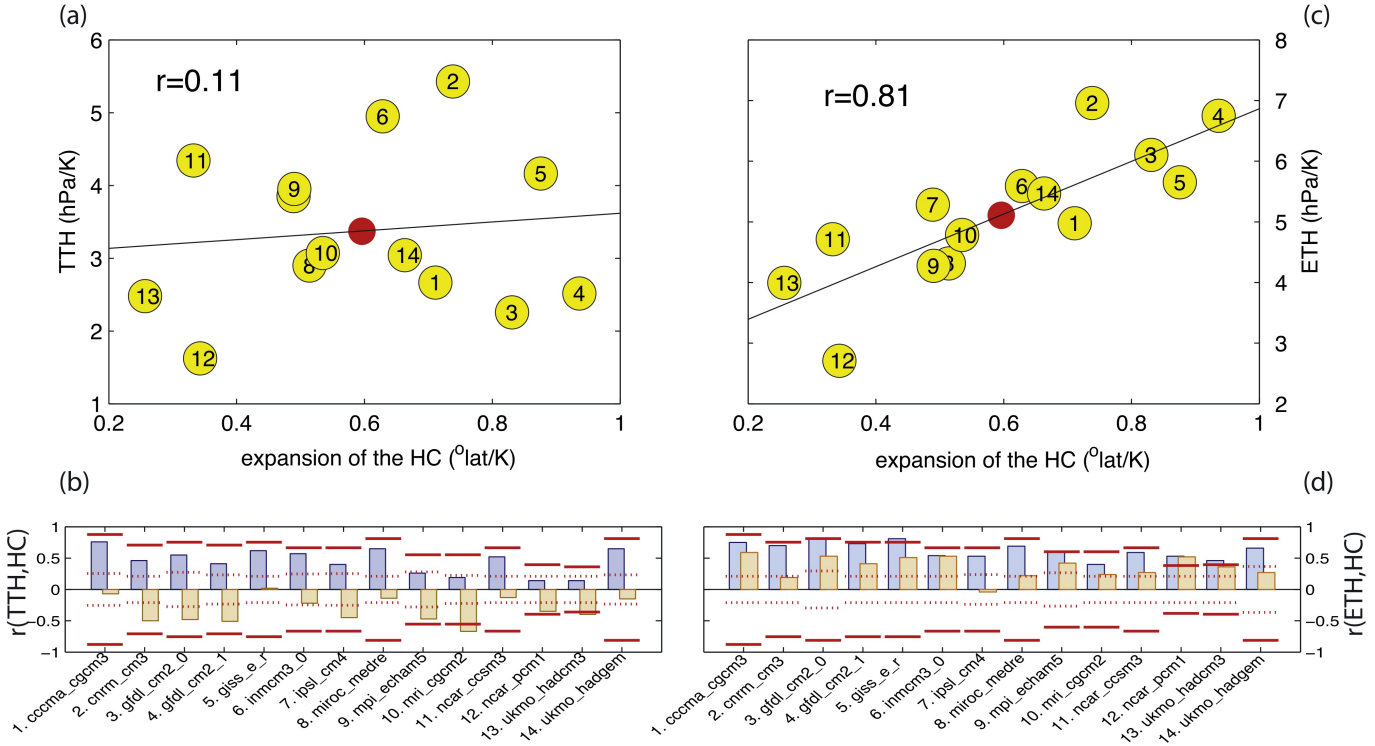


Figure 3. The relationship of (a–b) the tropical (20°S–20°N) tropopause height (TTH); (c–d) the extra-tropical (35°S–55°S and 35°N–55°N) tropopause height (ETH) with the extent of the HC for 14 models from the A2 scenario. Positive tropopause height value represents rise of tropopause. Figures 3a and 3c show the differences between (2081–2100) and (2001–2020), normalized by the corresponding change in the global mean temperature. The red dots denote the multi-model ensemble mean values. Figures 3b and 3d show the correlation coefficients between the full (blue bars) and detrended (sandy bars) time series of the HC extent and TTH (Figure 3b) and ETH (Figure 3d). The horizontal lines indicate the P = 0.05 confidence level of the correlation for each model based on Student's t-test. During the computation of the confidence levels, the reduction of effective degrees of freedom due to the autocorrelations of the time series has been considered following formula (30) by *Bretherton et al.* [1999]. The solid (dotted) lines are estimated from the full time series containing trend (detrended time series).

Possible mechanisms for HC expansion

Held and Hou (1980) formulate a scaling relationship which suggests no dependence on static stability, and is derived by assuming that:

1. the zonal wind in the upper branch of the HC is angular-momentum conserving.

2. the HC is energetically closed, so that the diabatic heating in the ascent regions is balanced by the diabatic cooling in the descent regions.

$$\phi_H \sim \left(\frac{gH_t}{\Omega^2 a^2} \frac{\Delta_h}{\theta_0} \right)^{\frac{1}{2}}$$

Possible mechanisms for HC expansion

Solving the equation between the angular momentum conserving zonal wind and the baroclinically critical zonal wind yields an alternative scaling for the width of the HC:

$$\phi_H \propto \left(\frac{NH_e}{\Omega^2 a} \right)^{\frac{1}{3}}$$

Conclusions

- In response to increased GHG forcing, Lu *et al.* found a robust weakening and poleward expansion of the Hadley circulation in simulations of the 21st century climate taken from the A2 scenario of the IPCC AR4 project.

- In accord with the movement of the HC, the subtropical dry zones also expand poleward.

Conclusions

- Lu *et al.* found that extratropical tropopause height, which is a good proxy of the gross static stability, varies in concert with the width of the HC on both the interannual and longer time scales.

- The increase in the gross stability near the subtropics acts to suppress baroclinic instability, which is a critical factor controlling the limits of the outer boundaries of the HC.

- The extratropical stabilization inhibits the breakdown of the thermally driven cell, allowing it to reach higher latitudes, as a result the edges of the HC expand poleward.

Conclusions

- Fu *et al.* (2006) estimated the amount of latitudinal widening of the HC over the period 1979–2005 as 2º latitude. Over the same period the increase in global temperature was about 0.5º C, so that the widening of the HC amounts to 4º latitude per degree warming

- This is much greater than found in the AR4 A2 scenario simulations (0.6º latitude/K).

- Thus, the observed expansion of the Hadley circulation during the late 20th century may, to a large degree, be attributed to factors other than the GHG-induced global warming, such as ozone depletion and/or natural climate variability. It is also possible that the contribution from the GHG forcing may be larger than the ensemble mean suggests, given the large spread between the individual model simulations (Figure 3).

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