The Response of the Tropospheric Circulation to Water Vapor-Like Forcings in the Stratosphere

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Summary

A dry general circulation model is used to examine the response of the tropospheric circulation to thermal forcings that mimic changes in stratospheric water vapor (SWV). It is shown that

- stratospheric cooling associated with SWV produces a poleward shift and acceleration of the jet and expansion and weakening of the Hadley cell;
- this response is almost entirely driven by cooling located in the extratropical lower stratosphere;
- when cooling is limited to the tropical stratosphere, it generates a much weaker and qualitatively opposite response;
- these circulation changes arise independently of any changes in tropopause height.

These results suggest a potentially significant contribution of SWV to future changes in the tropospheric circulation.

1. Motivation

Earlier studies have shown that changes in stratospheric water vapor (SWV) have a strong effect on global temperatures. In this study, we address the other half of SWV's climate impact: How do changes in SWV affect the tropospheric circulation? As a first step, we consider the response of an idealized dry model to temperature perturbations that mimic the effects of SWV.

2. Method

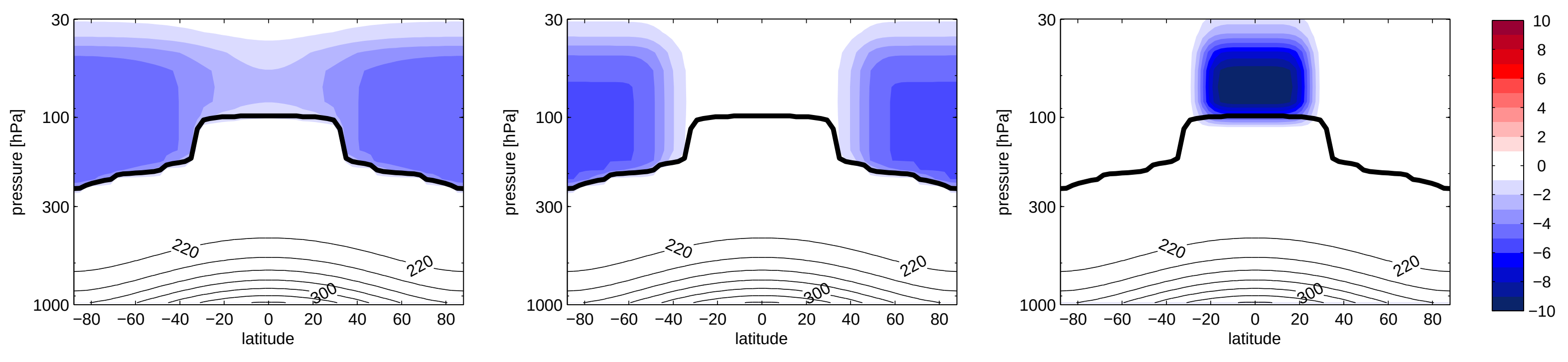
We impose a number of thermal forcings, consisting of perturbations of the model's radiative equilibrium temperature. The amplitude of each perturbation is controlled primarily by the parameter, δT, and additional parameters control its latitudinal and vertical structure. (See Appendix for additional details.)

- The **LS** ("lower stratosphere") forcing (e.g. Fig. 1a) mimics the temperature response due to a uniform 5 ppmv increase in SWV, with strong cooling in the extratropical lower stratosphere, and weaker cooling in the tropics and higher altitudes (Forster and Shine, 2002).
- The **ELS** forcing (e.g. Fig. 1e) isolates the extratropical portion of the LS forcing.
- The **TLS** forcing (e.g. Fig. 1i) isolates the tropical portion of the LS forcing.

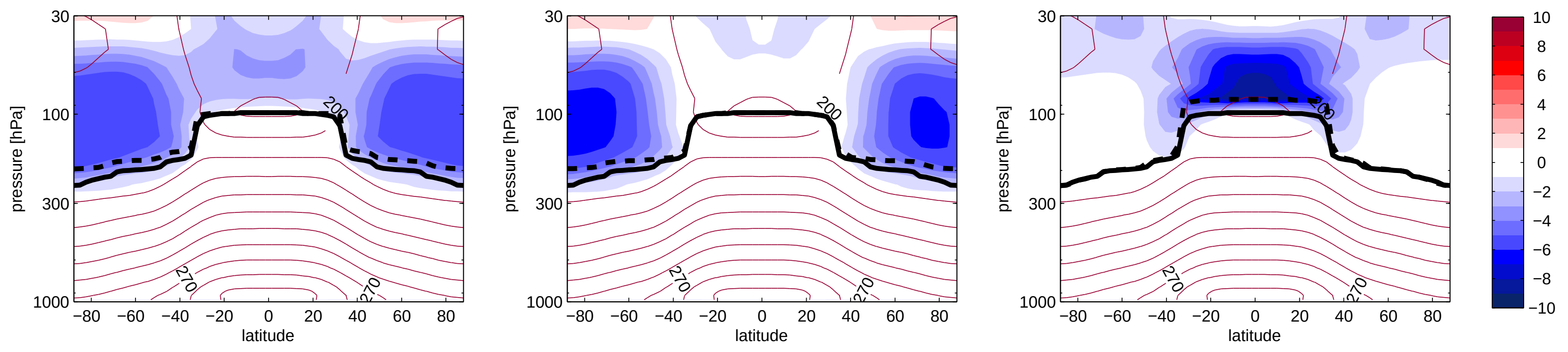
LS Forcing ($\delta T = -5$ K) (a) Thermal Forcing [K]

ELS Forcing ($\delta T = -5$ K) (e) Thermal Forcing [K]

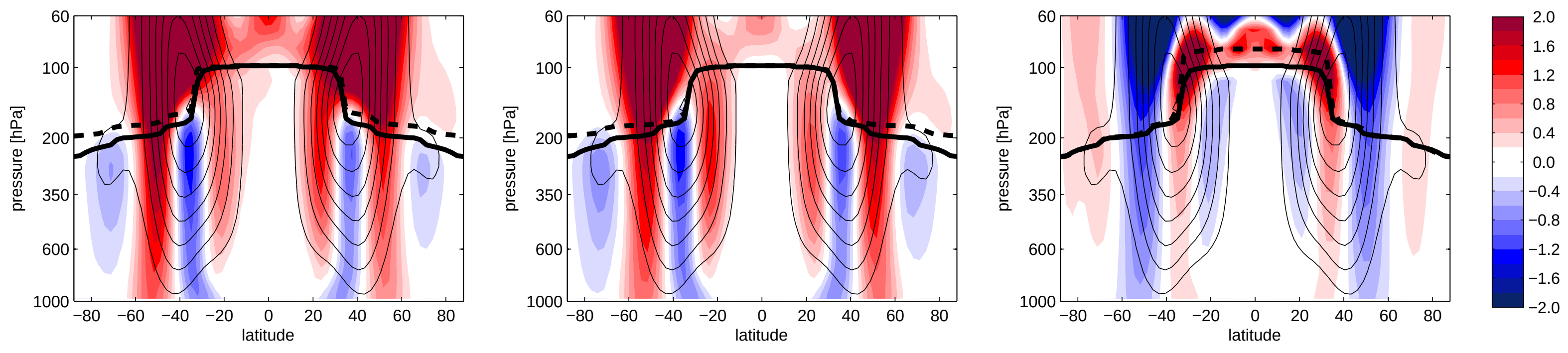
TLS Forcing ($\delta T = -10$ K) (i) Thermal Forcing [K]



(b) ΔT [K] (f) ΔT [K] (j) ΔT [K]



(c) Δu [m s^{-1}] (g) Δu [m s^{-1}] (k) Δu [m s^{-1}]



(d) $\Delta\Psi$ [10^9 kg s^{-1}] (h) $\Delta\Psi$ [10^9 kg s^{-1}] (l) $\Delta\Psi$ [10^9 kg s^{-1}]

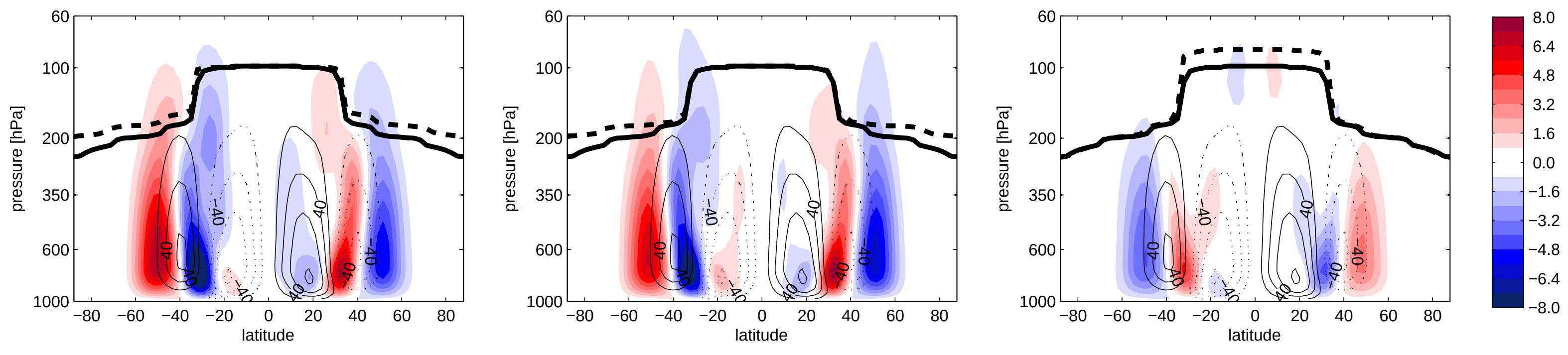


Figure 1: *Color shading: the response to the specific forcings, as indicated at the top of each column. Thin black contours: the climatology of the control integration. Solid, thick black contour: the tropopause of the control integration. Dotted, thick, black contour: the tropopause in the perturbed integration. Contour intervals are 10 K for temperature (top row), 5 m s^{-1} for zonal wind (middle row) with contours below 5 m s^{-1} omitted, and 20 × 10^9 kg s^{-1} for the meridional mass streamfunction (bottom row), with negative contours dashed and zero contour omitted.*

3. Results

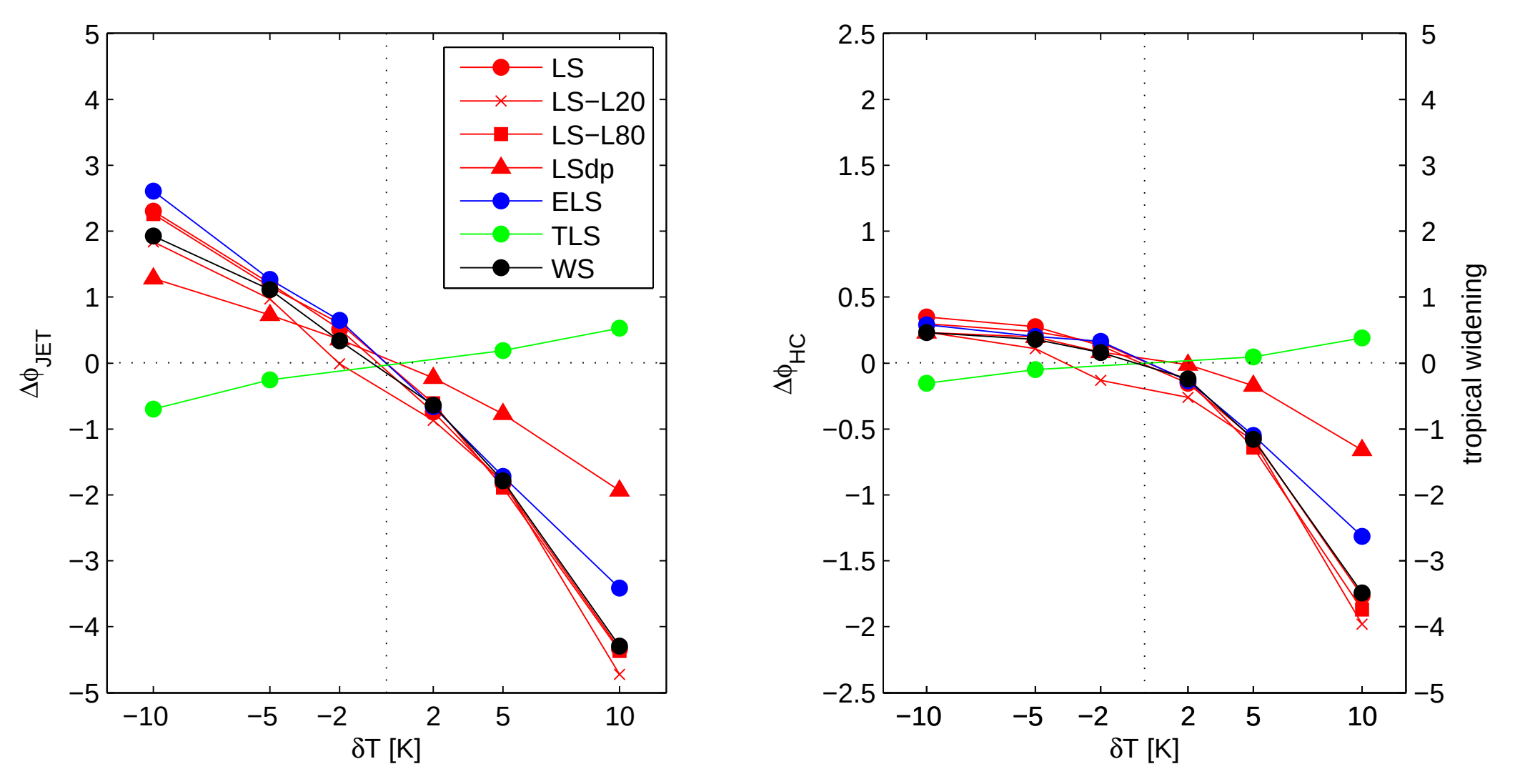
For the **LS** forcing (Fig. 1 left column, Fig. 2 red circles) stratospheric cooling ($\delta T < 0$) causes

- poleward migration of the jets (Fig. 1c, Fig. 2a)
- acceleration of the jets (Fig. 2c)
- expansion of the Hadley cells and a poleward shift of the Ferrel cells (Fig. 1d, Fig. 2b)
- weakening of the Hadley circulation (Fig. 2d)
- **These responses are of the same order as those caused by well-mixed greenhouse gases (e.g. Johanson and Fu, 2009).**

Furthermore,

- For the **ELS** forcing (Fig. 1 middle column, Fig. 2 blue circles) the response is almost identical to that of LS.
- The **TLS** forcing (Fig. 1 right column, Fig. 2 green circles) shows a response qualitatively opposite to those of LS and ELS, but for lower δT, the response is very weak.
- **CONCLUSION: The circulation response is driven almost entirely by cooling in the extratropical lower stratosphere.**
- Note, if we shift the forcing function up to leave tropopause height unchanged (Fig. 2, red triangles) the response remains qualitatively almost identical.
- Note, if we change the vertical resolution (Fig. 2, red crosses and red squares) or impose uniform stratospheric cooling (black circles) the response is not substantially changed.

(a) Jet Latitude (b) Hadley Cell Width



(c) Jet Speed (d) Hadley Cell Strength

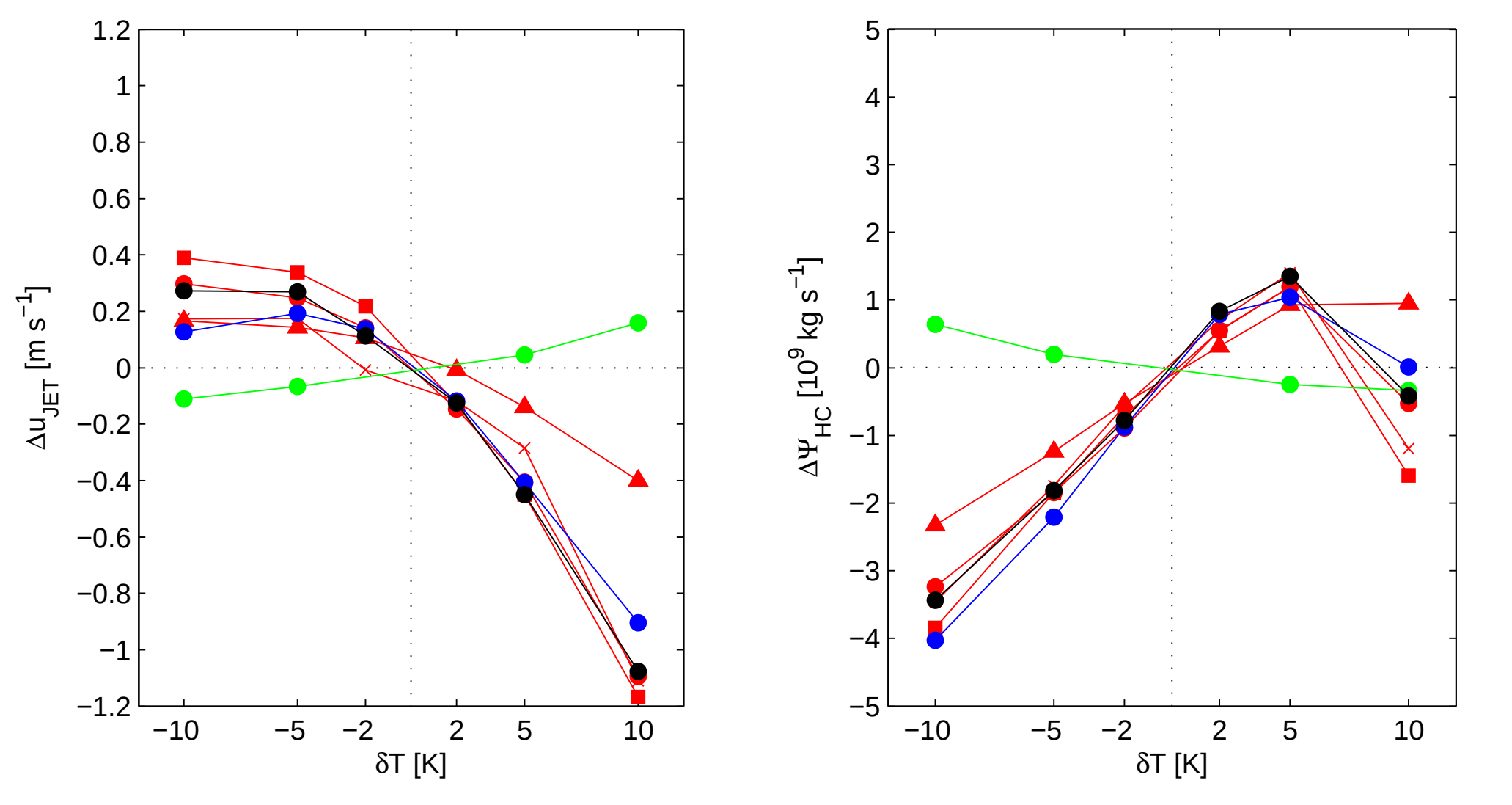


Figure 2: *Changes in circulation metrics as functions of δT. (a) The change in jet latitude, defined as the latitude of maximum zonal wind at the lowest model level. (b) The change in Hadley Cell width, measured using the zero crossings of Ψ at 500 hPa. The right-hand axis multiplies the Hadley Cell widening by two to obtain the total "tropical widening." (c) The change in jet speed, defined as the maximum in zonal wind at the lowest model level. (d) The change in Hadley Cell strength, defined as the maximum of Ψ within the Hadley Cell. Northern and southern hemisphere values are averaged together.*

Appendix: Model Details

- GFDL Flexible Modeling System, spectral dynamical core
- T42 horizontal resolution, 40 vertical levels, no topography
- idealized radiative-convective parameterizations from Schneider and Walker (2006)
- sponge layer top, Rayleigh damping at surface

Each integration lasts 10,000 days. To compute climatological fields, we discard the first 300 days as spin-up and time-average the rest. To recover the "response" of the model, we subtract the climatology of the control integration, in which $\delta T = 0$.

References

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