Abrupt Circulation Responses to Tropical Upper Tropospheric Warming in a Relatively Simple Stratospheric-Resolving AGCM

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Introduction

Current climate models predict that there will be a substantial warming by the end of the 21st century, accompanied by significant changes in the general circulation of the whole atmosphere, if GHG emissions are not abated. Most climate forecasts suggest a continuation or gentle acceleration of current warming trends. However, we have learned from the Earth's climate record, that climate change in the past has sometimes been more erratic and abrupt (e.g., Alley 2007). Integrations with highly truncated climate models, so-called Earth Systems Models of Intermediate Complexity (EMICs, Claussen et al. 2002), have demonstrated cases where the climate's sensitivity to external forcing changes suddenly.

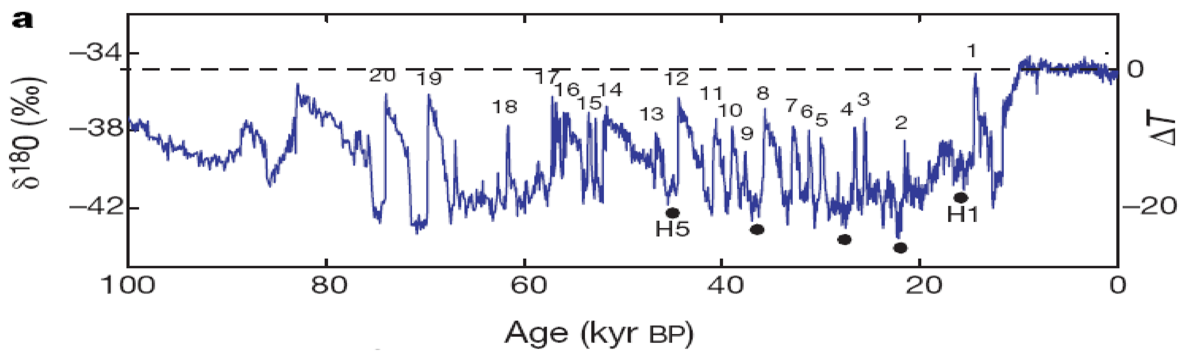

Fig. 0 Abrupt climate changes in Greenland ice-core data (Record of $\delta^{18}O$), adapted from Ganopolski and Rahmstorf (2001).

Such regime transitions have not been observed in most comprehensive climate models (e.g., the IPCC AR4 models).

- Regime behavior in EMICs is influenced by their severe truncation
- Comprehensive models have been overly constrained

We ask the following questions:

- Is abrupt climate change possible in well resolved dynamical models?
- Can nonlinear atmospheric dynamics alone produce abrupt change?

Methodology

We approximate the primary impact of anthropogenic climate forcing in an idealized AGCM, following Butler et al. 2010. Our simple AGCM: - Idealized physics
- numerical resolution is comparable to comprehensive GCMs

Our idealized Atmospheric GCM has a reasonable climate with realistic stratosphere-troposphere coupling:

- Dry dynamical core (primitive equations on the sphere)
- Tropospheric forcing as in Held-Suarez (1994) but in January; Stratospheric forcing as in Polvani & Kushner (2002)
- Wavenumber 2 topography (Gerber and Polvani 2009); High model top (80 km)

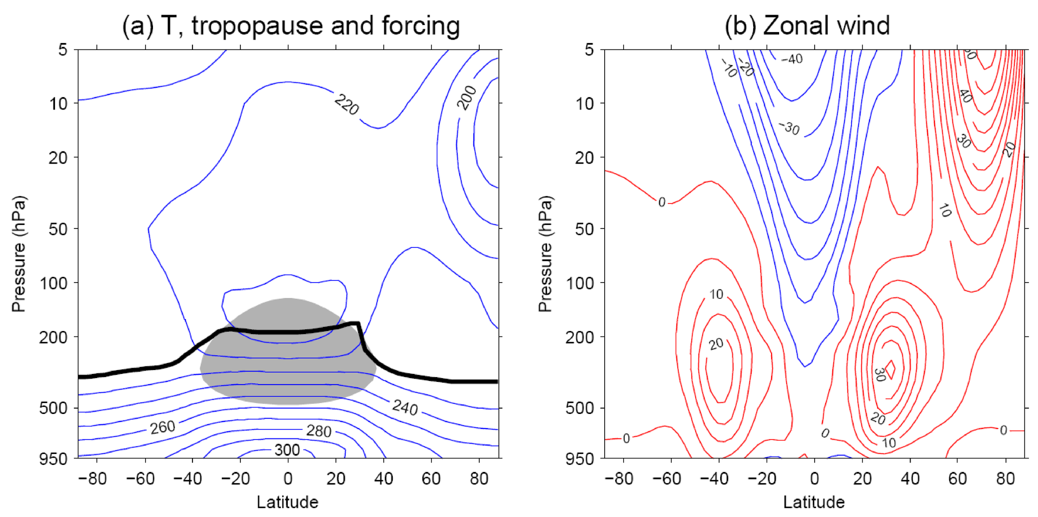

Fig. 1 Climatology of the reference integration (REF). (a) Temperature (CI=10K). Shaded: the imposed low latitude heating. Thick solid: the tropopause (lapse rate definition). (b) Zonal mean wind U (CI= 5 ms^{-1}).

We impose the heating forcing as in Butler et al. (2010) :

$$Heating = H_o \exp\left\{-\left[\frac{(Latitude)^2}{2\times 0.4^2}+\frac{(pressure-300hPa)^2}{2\times 0.3^2}\right]\right\}$$

H_0 is varied from -0.1-0.5 K/day. We use three different resolutions with a pseudo-spectral dynamical core: T42L40, T42L80 and T85L40, referred as T42, L80 and T85, respectively, in the figure legends below. All are integrated for 10,000 days. We also verify our results using finite volume dynamical core on a cubed-sphere grid.

Results

- The temperature response to heating is quantified using ΔTp, the change in the zonal mean tropical tropopause temperature, averaged over (25ºN, 25ºS) at 190 hPa, relative to the reference integration REF.
- ΔTp is linear with respect to the heating amplitude H_0. We use this linearity to relate circulation changes to tropical warming (ΔTp).
- The zonal mean response to tropical warming in two cases: weak and strong warming.

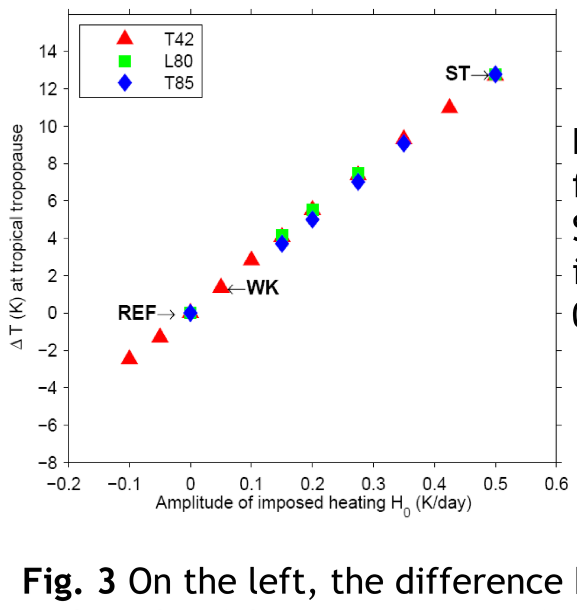

Fig. 2 ΔTp versus thermal forcing amplitude H_0. WK and ST denote the two T42 integrations with H0 = 0.05 and 0.5 K/day, respectively.

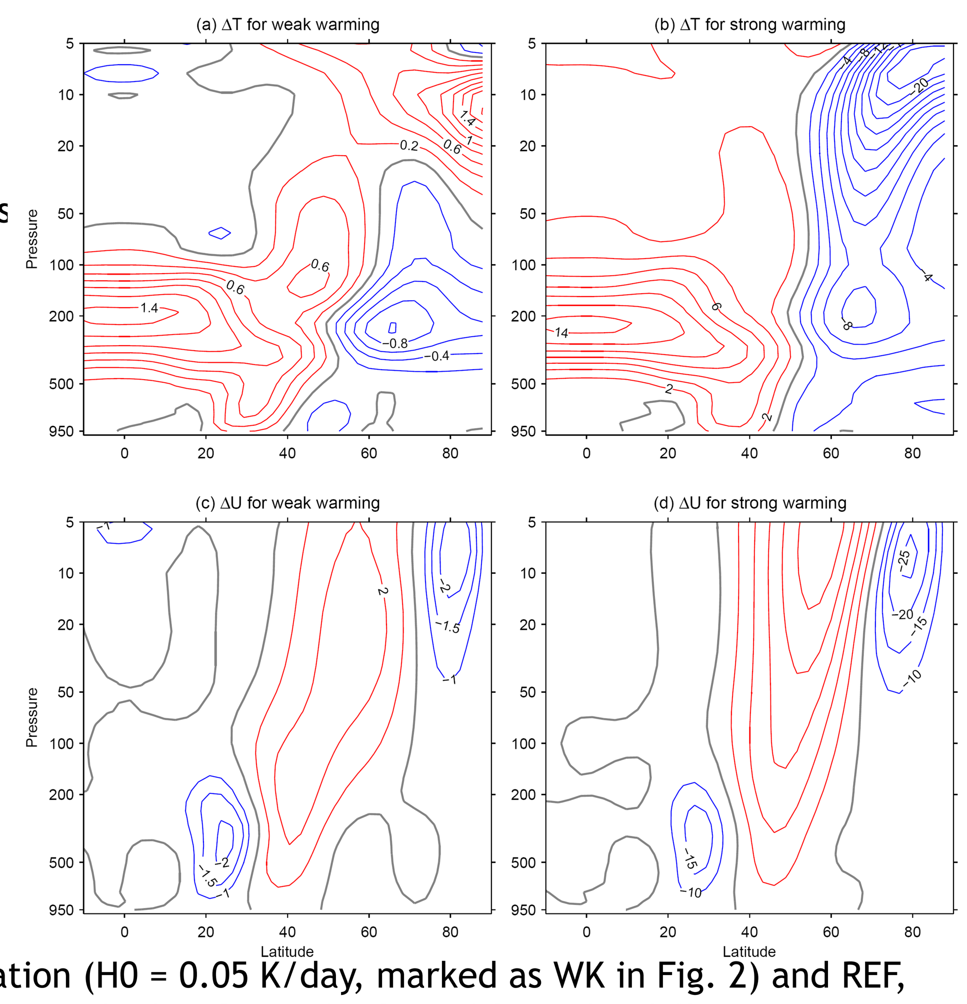

Fig. 3 On the left, the difference between a weak warming integration (H0 = 0.05 K/day, marked as WK in Fig. 2) and REF, and on the right, a strong warming integration (with H0 = 0.5 K/day, marked as ST in Fig. 2) and REF. The difference in zonal mean temperature (contour every 0.2 K for WK, and 2 K for ST) and zonal mean zonal wind are contoured in the top and bottom panels respectively. The contour intervals in ST-REF are 10 times of that in WK-REF. The gray lines denote zero values.

- Near surface jet: abrupt 10^0 shift when ΔTp >= 5 K
- Upper tropospheric jet shifts poleward smoothly
- Trends in wind strength exhibit a marked shift at the tipping point
- Polar jet expands equatorward and strengthens; its trends change abruptly

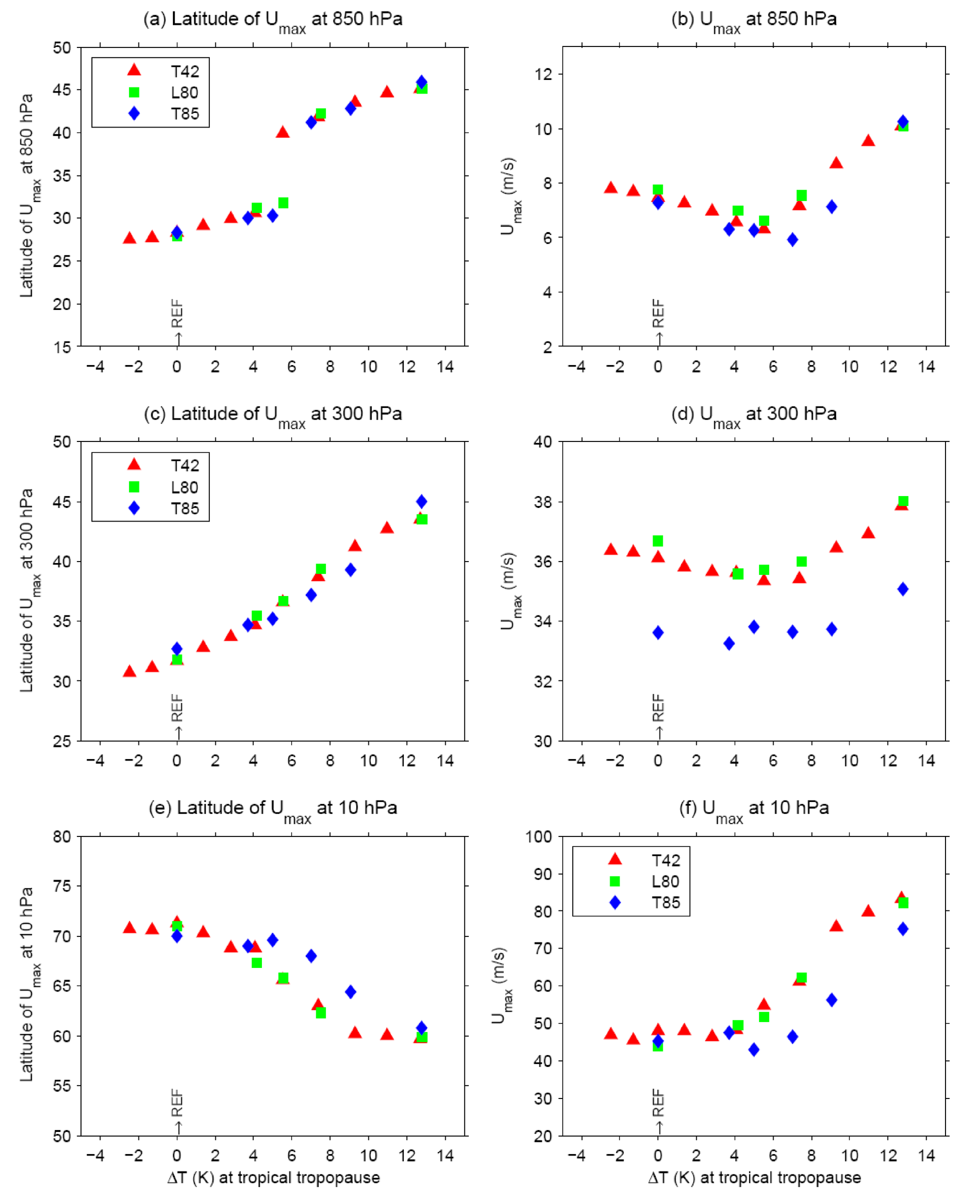

Fig. 4 Left, the latitude of the maximum zonal mean zonal winds Umax; Right: the amplitude of Umax, as a function the tropical warming (ΔTp).

- The abrupt circulation change can be viewed as shift in the frequency of flow regimes. This is illustrated by PDF of the latitude of maximum 850 hPa winds. Notice two regimens: the low and high latitude regimes - the mechanism behind the abrupt climate change - and the gradual shift of the regimes themselves - a reflection of a more linear shift in underlying climatology.

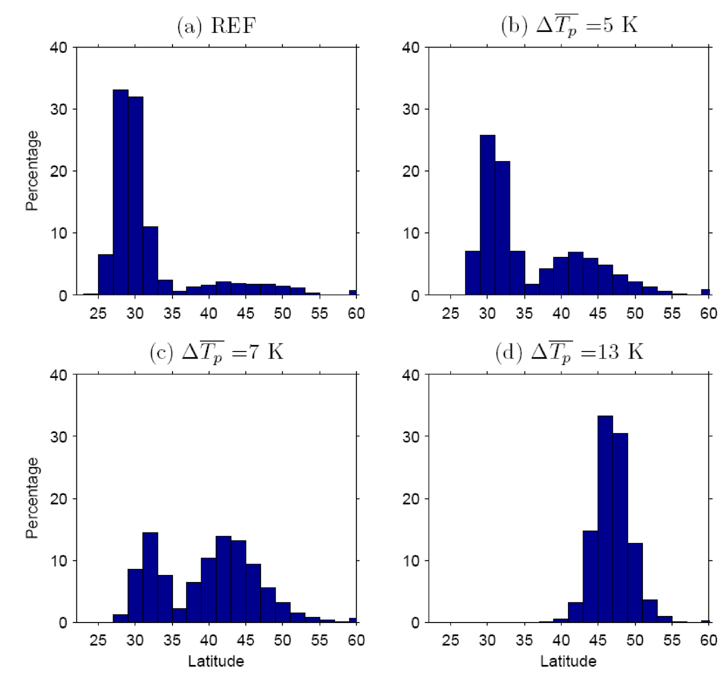

Fig. 5 Histograms based on the daily latitude of the maximum wind at 850 hPa for four T85 integrations with Tp = 0, 5, 8 and 13 K. The histograms have been normalized to show the probability of finding the instantaneous jet within each latitude band.

- As the stratospheric circulation is largely driven by wave-mean flow interactions, the regime shift is magnified there. For weak to moderate warming the Brewer-Dobson Circulation (BDC) increases moderately, in part driven by the rise of the tropopause and associated extension of the entire wave driven circulation upward. After the tipping point, the stratosphere-troposphere coupling collapses as wave activity which formerly entered the stratosphere is steered away.

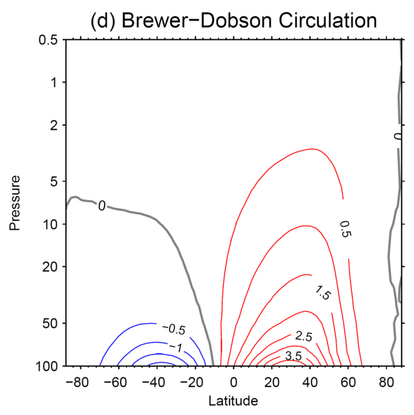

Fig. 6 BDC, or meridional mass transport through the stratosphere, quantified by the residual mean streamfunction Ψ* (CI =0.5× 10^9 Kg s^{-1}).

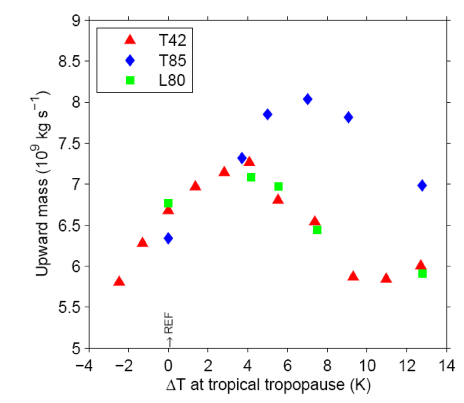

Fig. 7 The strength of the Brewer-Dobson Circulation as a function of tropical warming, quantified by the net upward mass flux at 100 hPa between the turn around latitudes in both hemispheres.

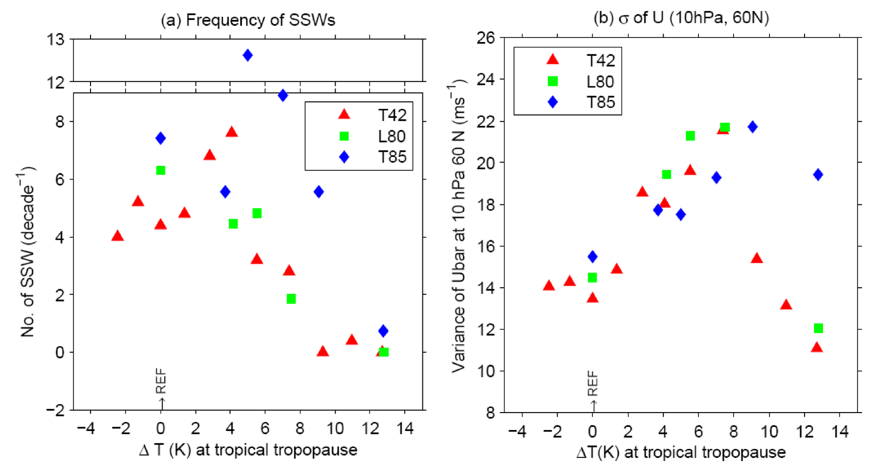

Fig. 8 The variability of polar vortex as a function of tropical warming. (a) The frequency of the Stratospheric Sudden Warming (SSW) events and (b) the standard deviation of zonal mean wind at 10 hPa and 60N. Different scales are used for two T85 integrations with dramatically more frequent SSWs.

Conclusions

Circulation responses can be highly nonlinear and abrupt.

- With weak to moderate warming, response is consistent IPCC predictions: subtropical and eddy driven jet displaces poleward, the BDC increases, etc.
- With strong warming, the model reaches a tipping point. The near surface jet jumps 10 degrees and coupling between the troposphere and stratosphere collapses: SSWs vanish, the BDC weakens, the polar vortex approach a Southern Hemisphere like state.
- Nonlinear dynamics alone can cause abrupt circulation shift, even if all forcings are varied smoothly.

Alley, R.B., 2007. *Ann. Rev. Earth and Planetary Sci.*, 35, 241-272.
Butler, A. H., D.W.J. Thompson, and R. Heikes, 2010. *J. Clim.*, 23, 3474-3496.
Claussen, M., et al., 2002. *Climate Dyn.*, 18, 567-586.
Ganopolski, A. and Rahmstorf, 2001. *Nature*, 409, 153-158.
Gerber, E. P. and LM Polvani, 2009. *J. Clim.*, 22, 1920-1933.
Held, I. M. and M. J. Suarez, 1994. *Bull. Amer. Meteor. Soc.*, 75, 1825-1830.
Polvani, L. M. and P. Kushner, 2002. *Geophys. Res. Lett.*, 29.