Response of the Structure of the Atmosphere to Global Warming

What is robust, what is delicate?

Geoffrey K. Vallis

University of Exeter

J. Kidston, C. Cairns, P. Zurita-Gotor

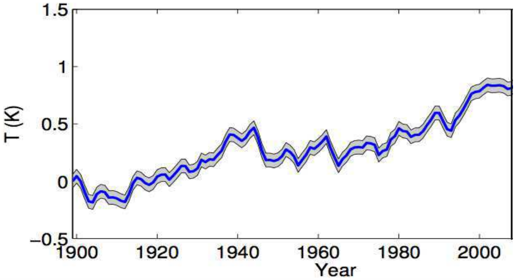
May, 2015

Note to Myself

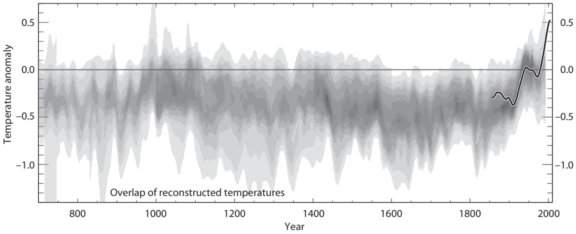
Just because a problem is important is not a reason for not studying it.

Global Warming

Over last century
(NASA/HadCRUT)



Over last millennium
(Mann et al)



What will be the effects of that warming?

Thesis

Changes that involve thermodynamics and radiation are `robust'.

Changes that involve dynamics are less certain and possibly less robust.

Robust: If you know the parameters and the forcing you can calculate the response reasonably well. No sensitive dependence on parameters.

Thesis

Changes that involve thermodynamics and radiation are `robust'.

Changes that involve dynamics are less certain and possibly less robust.

Robust: If you know the parameters and the forcing you can calculate the response reasonably well. No sensitive dependence on parameters.

Two practical measures:

- Consistency of response of a variety of models.
- An underlying physical mechanism that is not structurally unstable.

Today, our interests are twofold

1. The vertical structure of the atmosphere.
   - The height of the tropopause and stratospheric cooling.
2. The latitudinal structure of the circulation.
   - Expansion of the Hadley Cell
   - Shifts of the westerlies.

Q. How do we know global warming is not just natural variability?

1. No known natural mechanism that is consistent with the observations.

2. In particular, record of ocean heat content. Ocean is not giving up heat to the atmosphere.

   Rather, the ocean is warming **because** it is taking up heat *from* the atmosphere.

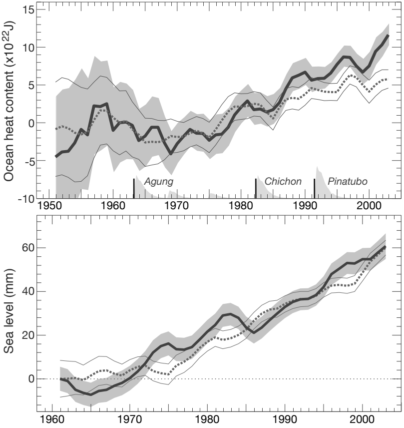
Q. How do we know global warming is not just natural variability?

1. No known natural mechanism that is consistent with the observations.

2. In particular, record of ocean heat content. Ocean is not giving up heat to the atmosphere.

   Rather, the ocean is warming **because** it is taking up heat *from* the atmosphere.

Ocean heat content in top 100 m and in top 700 m.

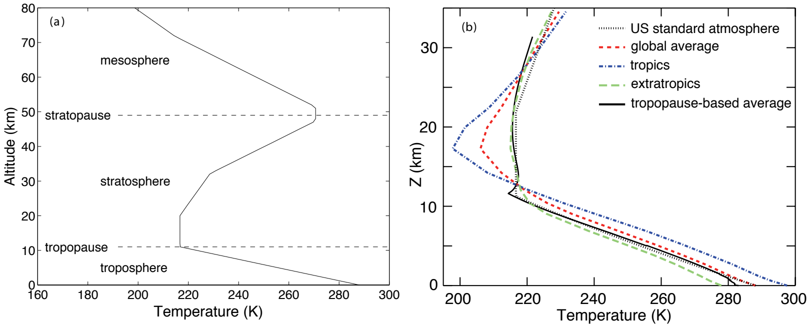


From Domingues et al (2009) via Vallis (2011).

Troposphere, Stratosphere and Tropopause Height

`US standard atmosphere'

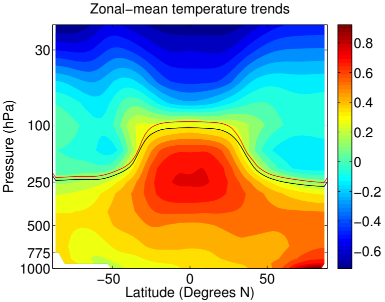
Observed profiles.



Troposphere: A region of fast dynamics in which the stratification is set dynamically.

Stratosphere: The region above that in which stratification is set radiatively

Warming as function of latitude and height

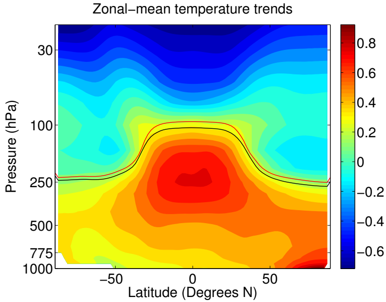


1. Upper stratospheric cooling.
2. Increase height of tropopause
3. Surface polar amplification.
4. Extra warming aloft in tropics

Moist adiabatic lapse rate (critical lapse rate for convection for saturated air)

$$-\frac{\mathrm{d}T}{\mathrm{d}z} \approx \frac{g}{c_p}\frac{1 + L_c q_s/(RT)}{1 + L_c^2 q_s/(c_p R T^2)}.$$

Warming as function of latitude and height

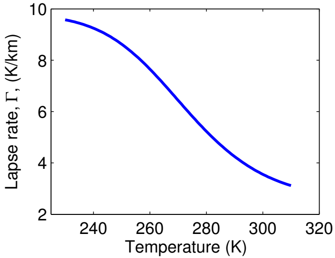


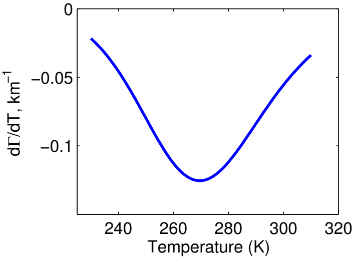
1. Upper stratospheric cooling.
2. Increase height of tropopause
3. Surface polar amplification.
4. Extra warming aloft in tropics

Moist adiabatic lapse rate (critical lapse rate for convection for saturated air)

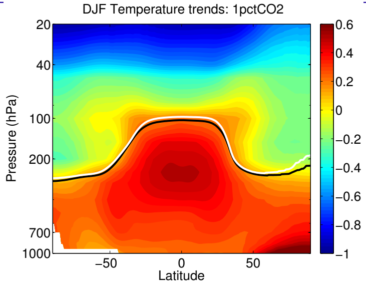
$$-\frac{dT}{dz} \approx \frac{g}{c_p}\frac{1 + L_c q_s/(RT)}{1 + L_c^2 q_s/(c_p R T^2)}.$$

Lapse rate and its rate of change with temperature:

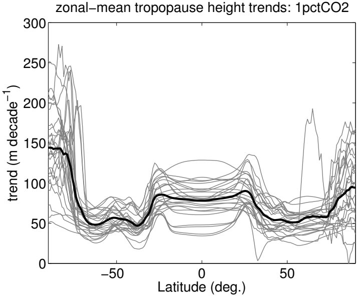


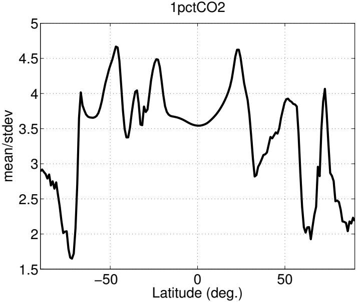


Model (CMIP5) predicted Temperature and tropopause height changes



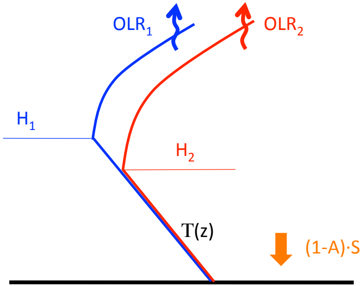
Increase in tropopause height is common across models. The change in height is greater than the model standard deviation, especially in low latitudes.





Tropopause Height

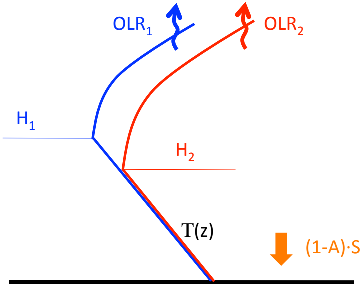
- → Incoming solar radiation = outgoing IR
- → Stratosphere in radiative equilibrium
- → Uniform tropospheric stratification
- → Outgoing IR radiation can be written as a function of tropopause temperature only.



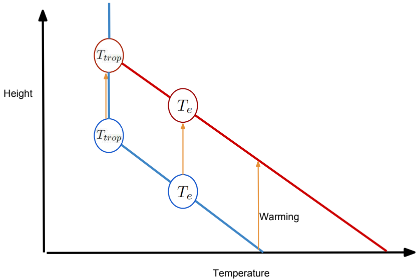
Only one choice of $H(T)$ gives the correct OLR.

Tropopause Height

- → Incoming solar radiation = outgoing IR
- → Stratosphere in radiative equilibrium
- → Uniform tropospheric stratification
- → Outgoing IR radiation can be written as a function of tropopause temperature only.



Only one choice of $H(T)$ gives the correct OLR.



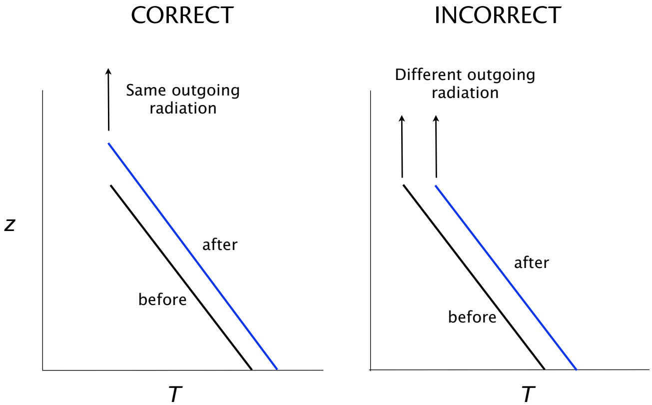
Tropopause height increases with increased COT.

Height of the tropopause (c.f., Thuburn and Craig; Santer)

Even as we add greenhouse gases, the OLR is *fixed* independently of optical depth.

In the troposphere: $T = T_s - \Gamma z, \qquad z \leq H_T$

Change in trop. height: $\Delta H_T = \dfrac{\Delta T}{\Gamma}$



Tropopause Height

with Gray Radiation and a `Thin' Stratosphere

$$\frac{\partial U}{\partial \tau} = U - B \qquad \frac{\partial D}{\partial \tau} = B - D,$$

where $\tau = \tau(z)$, U is upwards irradiance, D is downwards irradiance and $B = \sigma T^4$.

$$\frac{\partial}{\partial \tau}(U - D) = U + D - 2B, \qquad \frac{\partial}{\partial \tau}(U + D) = U - D$$

Stratosphere in longwave radiative equilibrium:

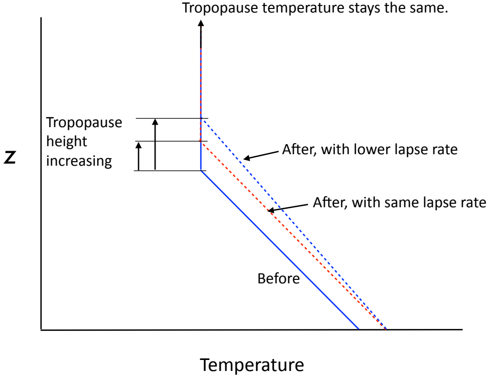
$$D = \frac{\tau}{2} OLR, \qquad U = \left(1 + \frac{\tau}{2}\right) OLR, \qquad B = \frac{1 + \tau}{2} OLR.$$

and if $\tau \ll 1$

$$D = 0, \qquad U = OLR = 2B, \qquad B = OLR/2.$$

Stratosphere is isothermal. Tropopause temperature fixed by OLR.

Lapse rate and temperature effects



$$\Delta H_T = \frac{\Delta T}{\Gamma} - \frac{H_T \Delta \Gamma}{\Gamma}$$

T_T is the tropopause temperature, ΔT is the increase in temperature at a given height in the troposphere
$\Delta \Gamma$ the change in the lapse rate.

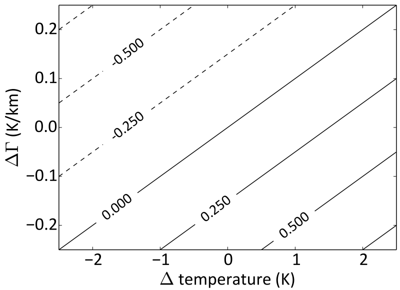
That is:

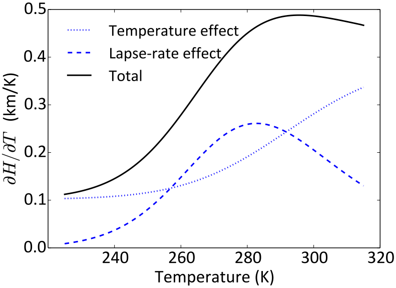
$$\frac{\partial H_T}{\partial T} = \frac{1}{\Gamma} - \frac{H_T}{\Gamma}\frac{\partial \Gamma}{\partial T}$$

Change in tropopause height with change in temperature and lapse rate.

Theoretical predictions of tropopause height

Increase in tropopause height with change in lapse rate and with temperature.





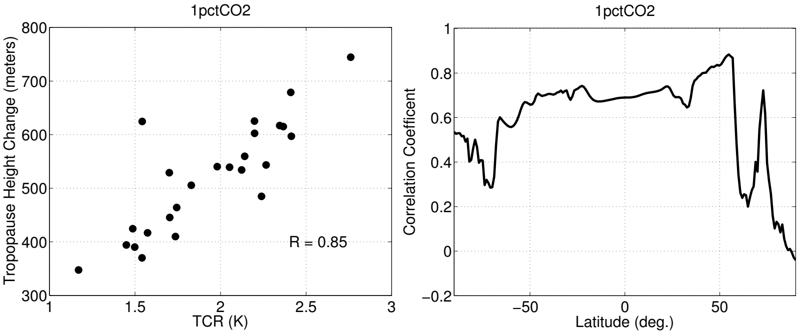
$$\frac{\partial H_T}{\partial T} = \frac{1}{\Gamma} - \frac{H_T}{\Gamma}\frac{\partial \Gamma}{\partial T}$$

$$\text{`Temperature effect'} = \frac{1}{\Gamma}$$

$$\text{`Lapse rate effect'} = -\frac{H_T}{\Gamma}\frac{\partial \Gamma}{\partial T}$$

$$\Delta H_T = \frac{\Delta T}{\Gamma} - \frac{H_T \Delta \Gamma}{\Gamma}$$

CMIP5, results



Change in tropopause height is correlated to the climate sensitivity, both locally and in the mean.

Analytic Expression for Tropopause Height

$$-\frac{\mathrm{d}U}{\mathrm{d}\tau} = B - U, \qquad \frac{\mathrm{d}D}{\mathrm{d}\tau} = B - D.$$

Suppose that lapse rate, Γ, is *given* up to a height H_T, above which the atmosphere is in radiative equilibrium.

Formal solution:

$$D(\tau') = \mathrm{e}^{-\tau'}\left[D(0) - \int_0^{\tau'} B(\tau)\mathrm{e}^{\tau}\,\mathrm{d}\tau\right], \qquad U(0) = U(\tau')\mathrm{e}^{-\tau'} + \int_0^{\tau'} B(\tau)\mathrm{e}^{-\tau}\,\mathrm{d}\tau$$

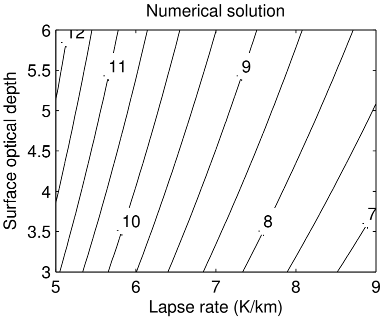
But, these expressions *don't give the right answer for outgoing radiation* for an arbitrary τ'.

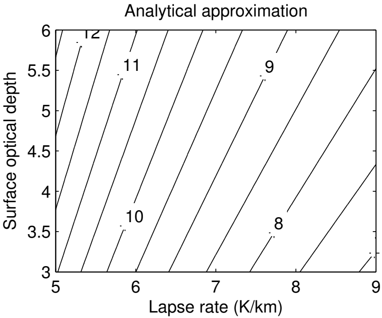
Must adjust H_T so that the equations satisfy the boundary conditions.

$$H_T = \frac{1}{16\Gamma}\left(CT_T + \sqrt{C^2 T_T^2 + 32\Gamma\tau_s H_a T_T}\right).$$

where H_a is the scale height of the main absorber and $C = \log 2$.

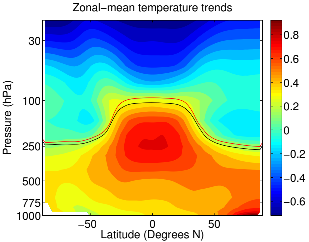
Numerical and Analytic Comparison





Stratospheric Cooling

Also robust, but dependent on the presence of ozone!



Basic Mechanism:

- A balance between solar heating and longwave cooling.
- If emissivity (optical depth) increases, a lower temperature will suffice to provide the needed cooling.

Algebra:

In a semi-grey atmosphere one may show...

$$3\sigma T^3 \frac{\partial T}{\partial z} \approx -\frac{\tau}{2H_a} I + \frac{1}{2\tau} Q$$

- The robustness of the effect does not depend on the detailed distribution of absorption bands of carbon dioxide or water vapor.
- Effect depends on there being (ozone) heating.

Stratospheric Cooling: A quantitative(ish) calculation

Assume $\tau(z) = \tau_0 \exp[-z/H]$ and that the stratosphere is in radiative equilibrium, with long-wave cooling balancing short wave heating, Q.

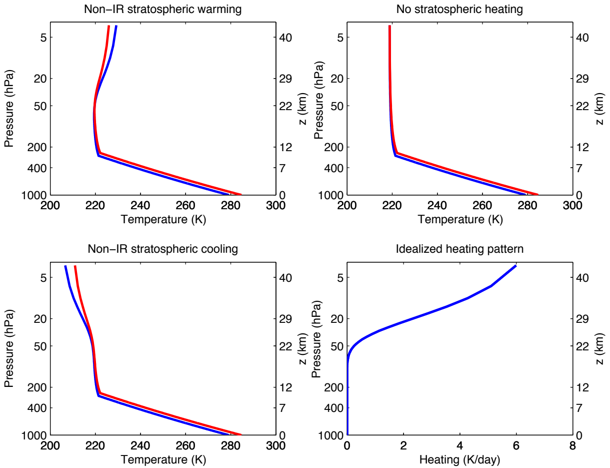
After manipulation we find:

$$\frac{\partial B}{\partial z} \approx -\frac{\tau}{2H_a} I + \frac{1}{2\tau} Q$$

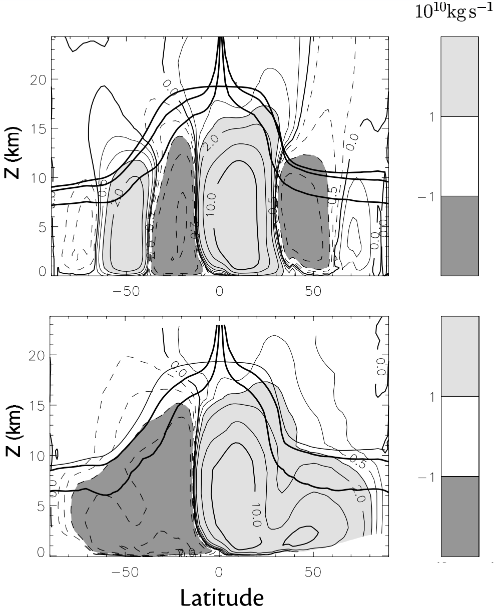
If τ increases the heating term diminishes, and the temperature increase with height falls.

Before: ---

After: ---

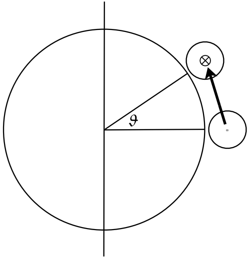


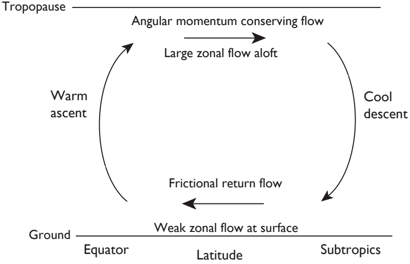
The Overturning Circulation: Hadley and Ferrel Cells



Hadley Cell, Axi-symmetric Theory

(Schneider and Lindzen, Held and Hou)





Assume flow is axi-symmetric.
Outflow is angular momentum conserving:

$$U = \Omega a \frac{\sin^2 \vartheta}{\cos \vartheta}$$

Temperature from thermal wind balance:

$$T = T(0) - \frac{T_0 \Omega^2 \vartheta^4}{2gHa^2}$$

Temperature falls rapidly with latitude.

Width of Hadley Cell is constrained by thermodynamics:
Air gets too cold and sinks.

Hadley Cell Width

1. Held--Hou theory (axi-symmetric)

$$\phi_H = \left(\frac{5\Delta\theta_h g H}{3a^2\Omega^2\theta_0} \right)^{1/2} \propto H^{1/2}.$$

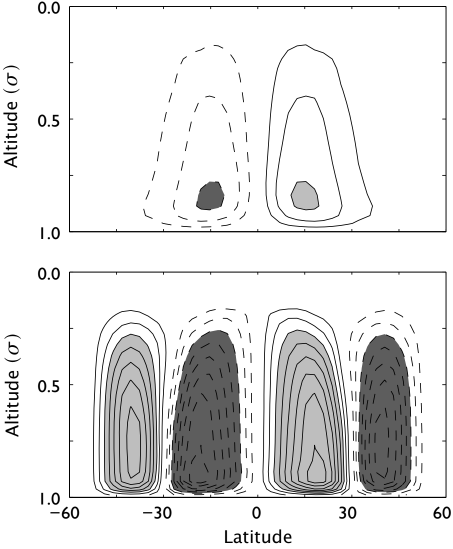
   - Increase in height of tropopause leads to Hadley Cell expansion.

$$\frac{\Delta\phi_H}{\phi_0} = \frac{\Delta H}{2H_0} = \frac{\Delta T}{2H_0 \partial T/\partial z} \sim \frac{1}{50} \text{ per}\,^\circ\text{C}$$

   - Assumes other factors stay the same.
   - The atmosphere is not Boussinesq.

2. But baroclinic eddies are likely important. Hadley Cell extends until it feels the effect of baroclinic instabilities.

Hadley Cell Width: with and without eddies

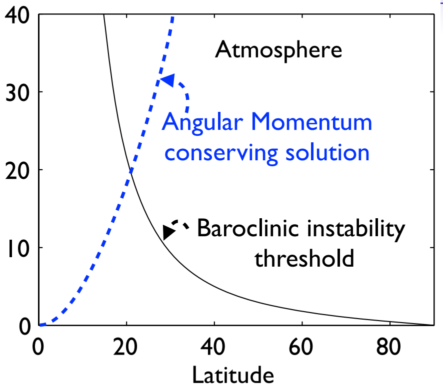


(a) Zonally symmetric simulation

(b) 3D simulation. Hadley cell is narrower and stronger.

Courtesy C. Walker (c.f., Walker & Schneider).

Hadley Cell Extent and Baroclinic Instability



Critical shear in two-layer model:

$$U_s = \frac{1}{4}\beta L_d^2 \quad \text{where} \quad L_d = \frac{NH}{f}$$

gives critical latitude:

$$\phi_c \approx \left(\frac{N^2 H^2}{\Omega^2 a^2}\right)^{1/4} = \left(\frac{g \Delta_v \theta\, H}{\theta_0 \Omega^2 a^2}\right)^{1/4}$$

Dependence on tropopause height and stratification.

Hadley Cell expands if:

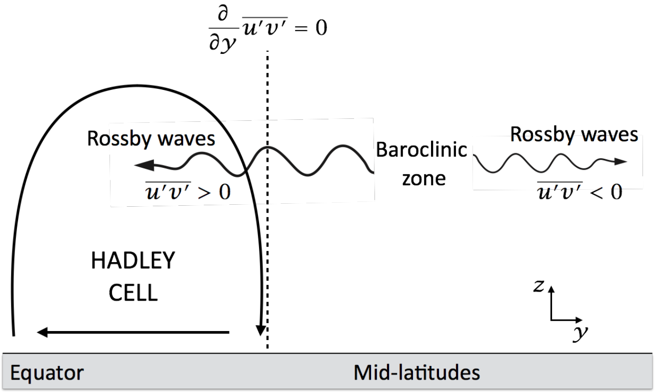
1. Tropopause height increases.
2. Stratification increases (which stabilizes the flow)

But note

The atmosphere is not a two-level model!

Other formulations are possible, but quantitative predictions will necessarily be uncertain.

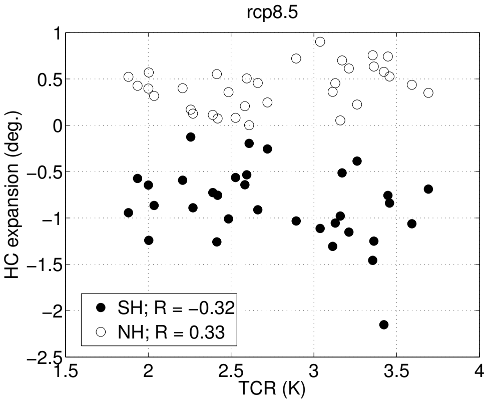
Rossby wave breaking and the Hadley Cell



The Hadley Cell terminates where Rossby wave breaking occurs, not at the latitude of baroclinic instability.

The real Hadley Cell is probably a combination of the above mechanisms. Different GCMs may have different combinations, and different scalings.

Expansion of the Hadley Cell



- Hadley cell expands in most models
- Significant scatter.
- Southern expansion is weakly correlated with Northern expansion
- Expansion is not correlated with degree of warming of a model.

The Mid-latitudes: A still harder problem?

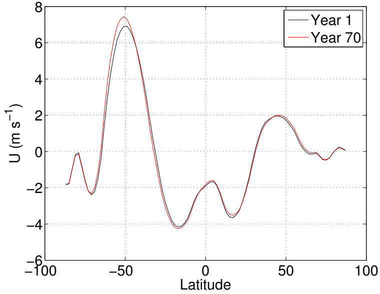
- The atmospheric mid-latitude circulation is a problem in weak turbulence (eddy--mean-flow interaction) and so a difficult problem.
- A small shift in the surface winds could have large effects on the climate in mid-latitudes.
- Surface winds approximately obey the eddy--mean-flow balance, in QG approximation and in the steady state,

$$r\overline{u}_s \approx \int \frac{\partial \overline{u'v'}}{\partial y}\,\mathrm{d}z = \int \overline{v'q'}\,\mathrm{d}z$$

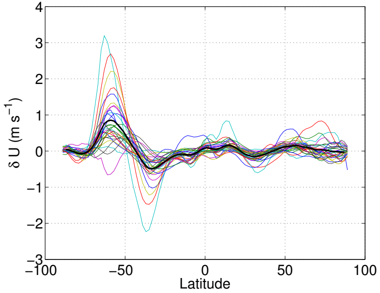
where r is a surface friction parameter.

Changes in Surface Winds

Ensemble mean surface wind



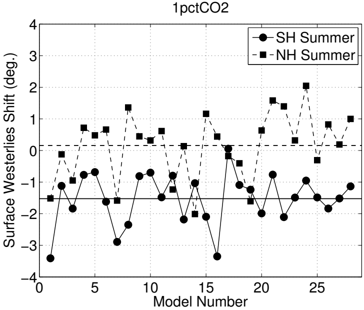
Changes in wind of individual models



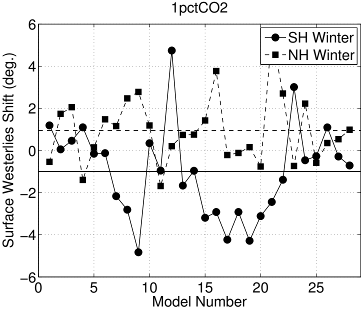
Small and inconsistent differences in general, larger in Southern Hemisphere

Shift of the surface westerlies

Summer



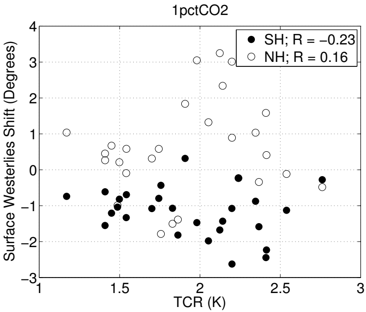
Winter



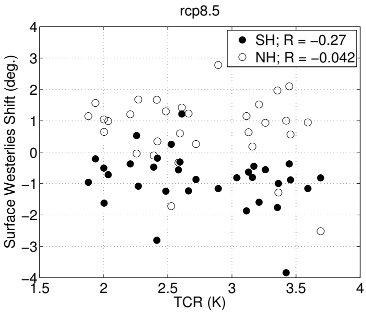
Shift of the surface westerlies

vs increase in temperature

1%



RCP8.5

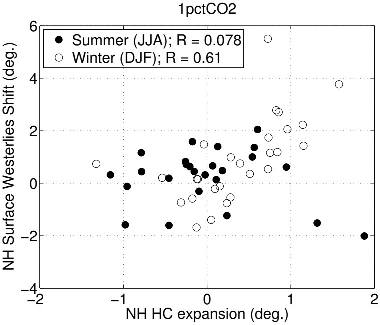


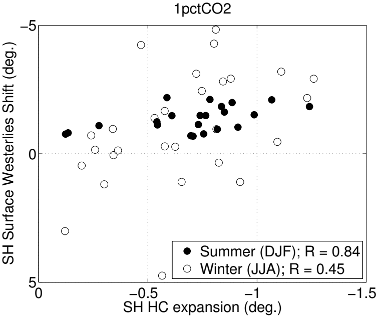
Lots of scatter!

Shift of Hadley Cell and the Mid-latitude Westerlies

Are they correlated?

Hadley Cell expansion vs shift of the westerlies, using an **overturning** measure

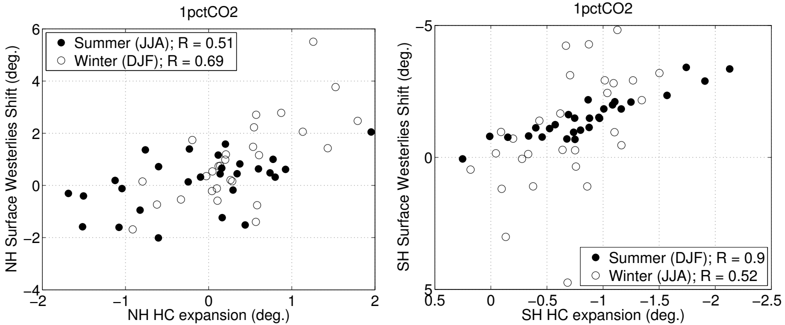




Shift of Hadley Cell and the Mid-latitude Westerlies

Are they correlated?

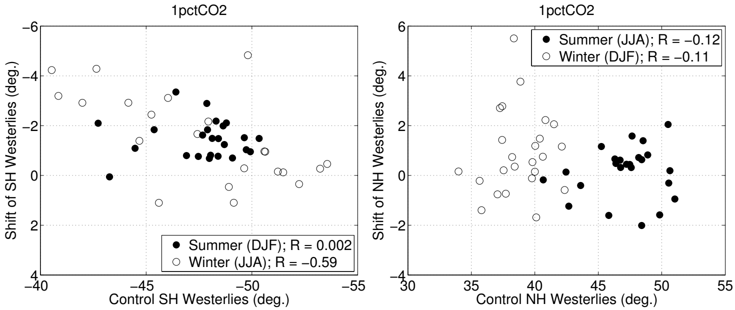
Hadley Cell expansion vs shift of the westerlies,
using a **surface wind** measure



Surface Wind Changes

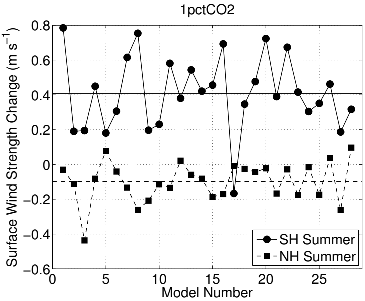
As a function of Current position

Scatter plot of latitude of surface westerlies vs shift in the future.

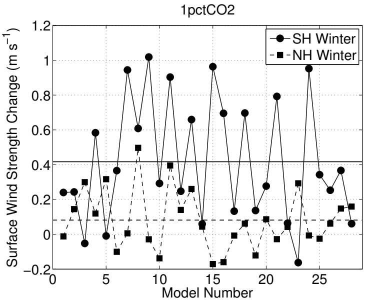


Surface Wind Strength

Summer



Winter

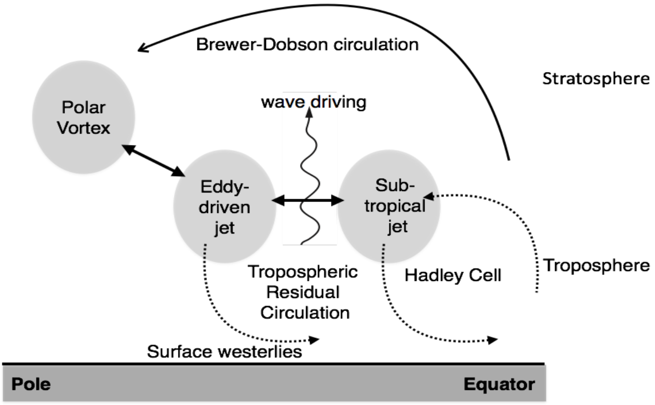


Dependent on season, hemisphere and the model itself!

Far more scatter in these results than in the warming itself.

Factors influencing jets

A stratospheric influence?



Conclusions

- Thermodynamic/radiative changes to atmosphere are robust:
  - Increase in height of the tropopause, and cooling of the stratosphere, have solid physical mechanisms *and* are reproduced by comprehensive models.
- Dynamical or circulation changes are less well understood.
  - Hadley cell expansion is a common feature, and the poleward shift of westerlies is also common, but scatter is very large.
  - Many proposed mechanisms (acting alone, not all can be correct).

Conclusions

- Thermodynamic/radiative changes to atmosphere are robust:
  - Increase in height of the tropopause, and cooling of the stratosphere, have solid physical mechanisms *and* are reproduced by comprehensive models.
- Dynamical or circulation changes are less well understood.
  - Hadley cell expansion is a common feature, and the poleward shift of westerlies is also common, but scatter is very large.
  - Many proposed mechanisms (acting alone, not all can be correct).

- To what extent are dynamical changes are predictable or knowable?
- Depends on interaction with subgridscale parameterizations (e.g., convection).

Conclusions

- Thermodynamic/radiative changes to atmosphere are robust:
  - Increase in height of the tropopause, and cooling of the stratosphere, have solid physical mechanisms *and* are reproduced by comprehensive models.
- Dynamical or circulation changes are less well understood.
  - Hadley cell expansion is a common feature, and the poleward shift of westerlies is also common, but scatter is very large.
  - Many proposed mechanisms (acting alone, not all can be correct).

- To what extent are dynamical changes are predictable or knowable?
- Depends on interaction with subgridscale parameterizations (e.g., convection).
- Entering a Golden Age for dynamicists! --- or at least we should be.