Certain and Uncertain Responses of the Atmosphere to Global Warming

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Toronto 2019

http://tiny.cc/Vallis

Vallis et al (2015), Quart. J. Roy Met Soc.
Hu and Vallis (2019), Submitted to QJRMS

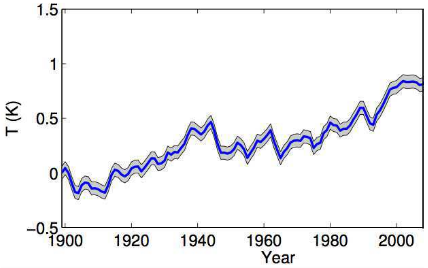
Note to Myself

Global warming...

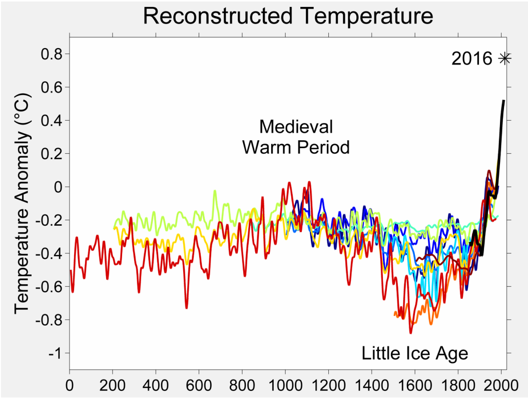
Just because a problem is important is not a reason for not studying it.

Global Warming

Observed-temperature record



Over last century, (NASA/HadCRUT)



Over 2000 years

What will be the effects of that warming on the circulation of the atmosphere?

Q. Is Global Warming – Natural Variability?

A. It is *required* to be skeptical.

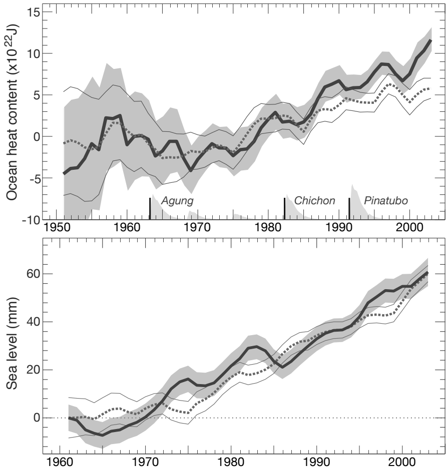
1. No known natural mechanism that is consistent with the observations.

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.

   There is no credible argument except that *the warming over the past 100 or so years is anthropogenic.*

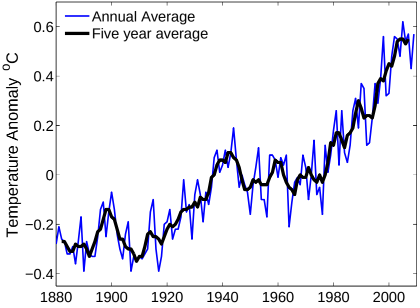
Ocean heat content in top 100 m and in top 700 m.



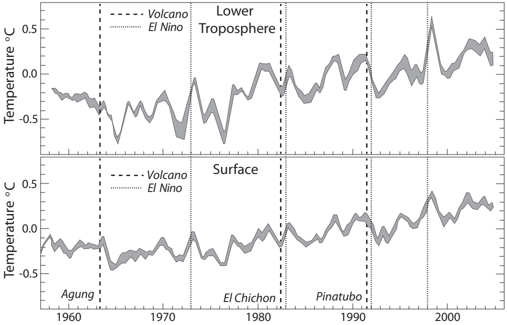
From Domingues et al (2009) via Vallis (2011).

20th Century Global Warming

Global average surface temperature, year-by-year and 5-year running mean:



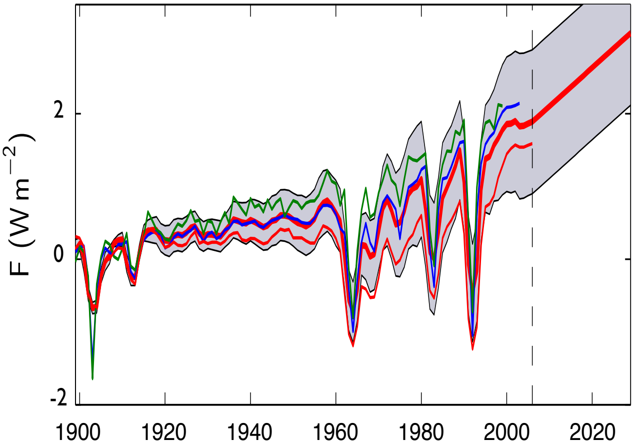
Last 50 years, including satellite measurements



Shows that the warming is not an ‘urban heat island’ effect.

What Forces Climate Change

Greenhouse gases (+ve), aerosols (-ve)



Padilla and Vallis 2011

Three different calculations of the total forcing:

(i) GISS calculation (original);

(ii) GFDL

(iii) Forster and Gregory (2008) (comprehensive).

Differences largely in aerosol formulation.

CO_2 contributes about 1.5 W/m^2 (COT doubling is about 3.5 W/m^2.)

Uncertainty of Forcing

Aerosols

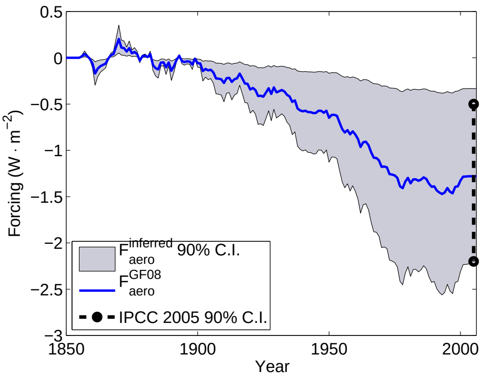
Difference in the forcings is mainly from aerosols.

We let

$$F(t) = F_{GHG} + \alpha F_{\text{aer}}(t)$$

where $F_{\text{aer}}(t)$. Aerosol uncertainty grows with time. We assume uncertainty proportional to aerosol levels.

Aerosol forcing and uncertainty:



Padilla and Vallis 2011

Aerosols are uncertain and the latest CMIP6 models emphasize that uncertainty!

Equilibrium climate sensititivty (ECS) is equilibrium warming due to CO_2 doubling.

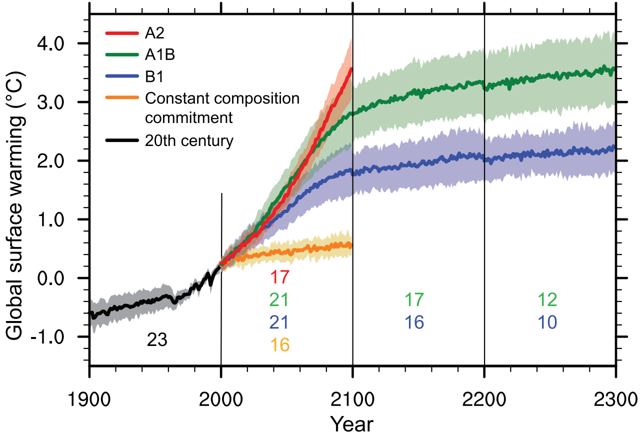
CMIP5 climate sensitivity $\sim 3\,\text{K}$

CMIP6 climate sensitivity $\sim 5\,\text{K}$ (tentative, results not in.)

The uncertainty of the *eventual* temperature rise in global warming due to CO_2 doubling has diminished only a little over the past several decades...

Performance of models over 20'th century was very good. Models are reasonably accurate at hindcasting in part because of *tuning and cancellation of error....*

(Aside: Is there an irreducible limit to the accuracy of our climate forecasts?)



(Old IPCC results. Current ones similar.)

Today's Thesis

Changes that involve thermodynamics and radiation are, in fact, '*robust*'.
Changes that involve dynamics (fluids, motion, etc) 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, and the response is 'certain'.

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

Two practical measures:

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

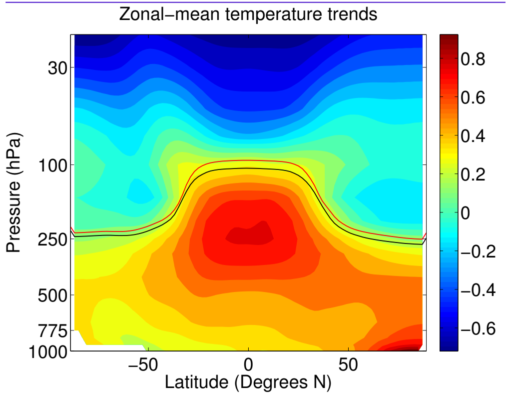
Illustrate with two examples

(i) The vertical structure of the atmosphere.
   - The height and temperature of the tropopause; stratospheric cooling.

(ii) The latitudinal structure of the circulation.
   - Expansion of the Hadley Cell
   - Shifts of the westerlies.

Downscaling is useless if the large-scale circulation is incorrect.
Regional climate change is a problem in global circulation.

Warming as Function of Latitude and Height

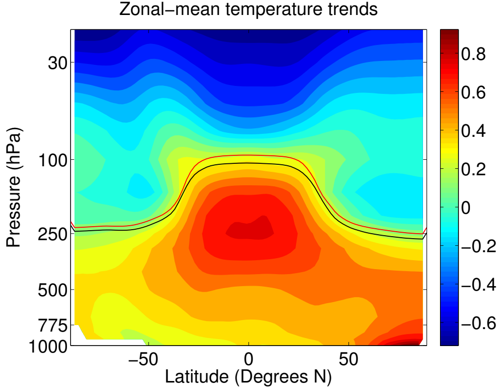


- Upper stratospheric cooling.
- Increase height of tropopause
- Surface polar amplification.
- Extra warming aloft in tropics

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

$$\Gamma \equiv -\frac{\mathrm{d}T}{\mathrm{d}z} = \frac{g}{c_p}\frac{1 + L_c q_s/(R_d T)}{1 + L_c^2 q_s/(c_p R_v T^2)}.$$

Warming as Function of Latitude and Height



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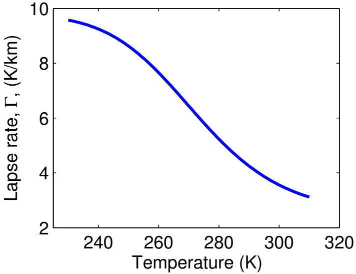
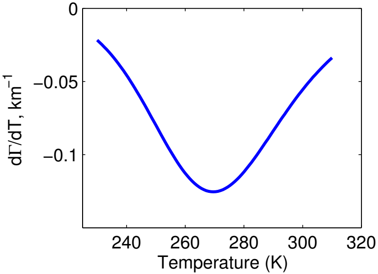
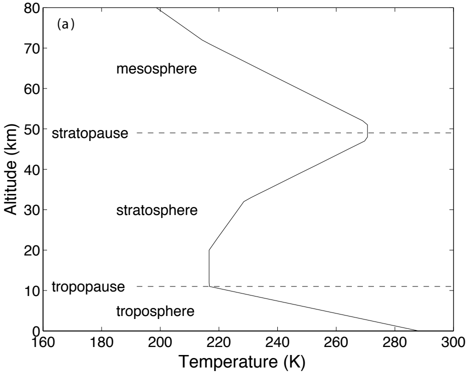
Lapse rate and its rate of change with temperature:



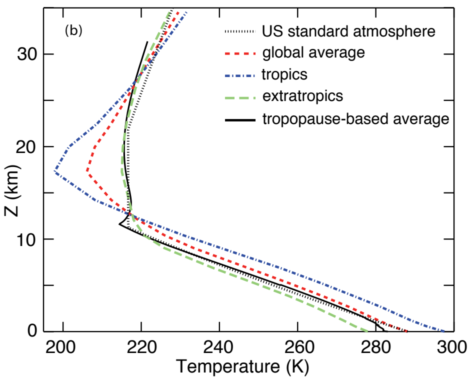


Troposphere, Stratosphere, Tropopause

'US standard atmosphere'



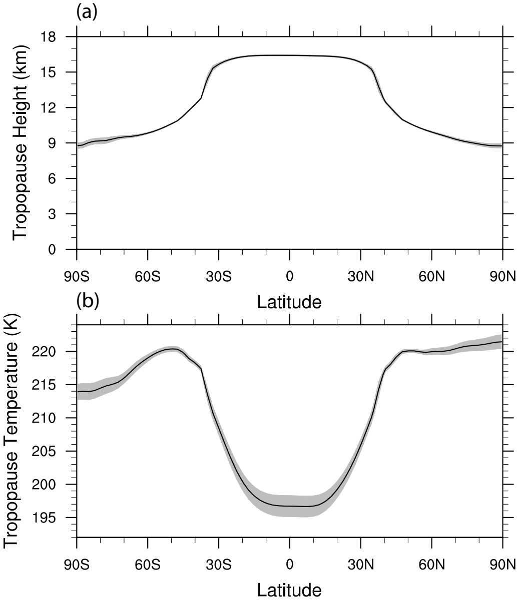
Observed profiles.



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

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

Tropopause Height and Temperature



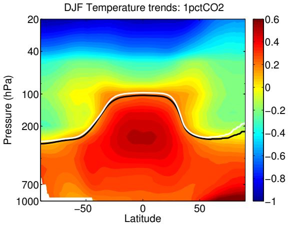
1. Tropical tropopause is higher.

2. Tropical tropopause is cooler.

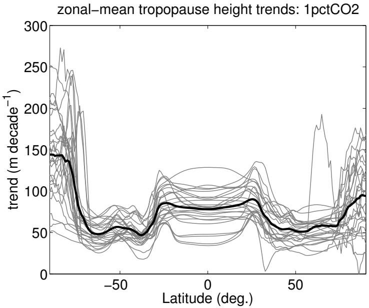
NCEP2 re-analysis.

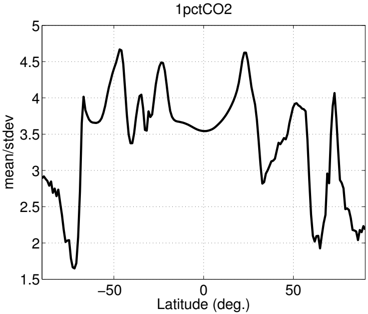
Temperature and Tropopause Height Changes

From CMIP5



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





Radiative Equilibrium

IR radiative transfer (Schwarzschild) equations:

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

where $\tau = \tau(z)$ is optical depth, U is upwards irradiance, D is downwards irradiance.

If grey $B = \sigma T^4$.

Boundary conditions at top: U = Incoming solar radiation, $D = 0$

Radiative equilibrium:

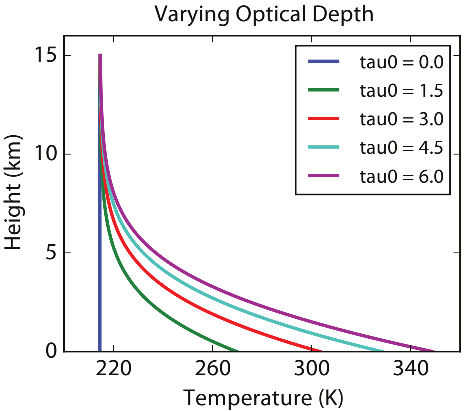
$$D = \frac{\tau}{2} OLR, \qquad U = \left(1 + \frac{\tau}{2}\right) OLR, \qquad B = \frac{1+\tau}{2} OLR$$

and if $\tau \ll 1$ (e.g., stratosphere)

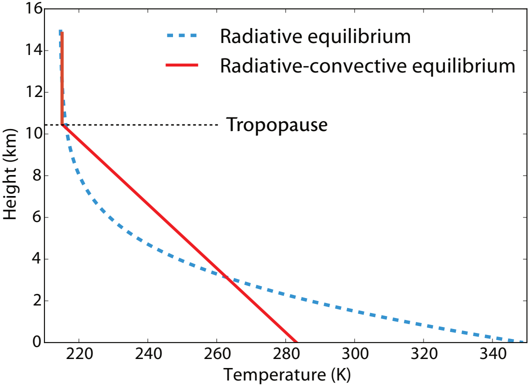
$$D = 0, \qquad U = OLR = 2B, \qquad B = \sigma T^4 = OLR/2.$$

In optically thin limit, stratosphere is isothermal,

$$OLR = 2\sigma T_{strat}^4.$$



Creation of a Tropopause



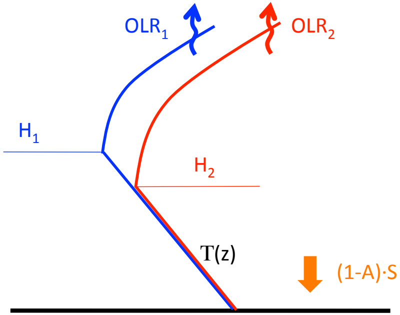
- Assume 'dynamics' operates to a finite height, and with a specified lapse rate.
- Solve the radiative transfer equations, and demand overall radiative balance, allowing tropospheric height to adjust.
  (i) Outgoing IR at top of atmosphere equals incoming solar
  (ii) Upward IR at surface $= \sigma T_g^4$
- Obtain numerical solution exactly, or analytic solution approximately.

Similar to an equal area construction.

Tropopause Height

Radiative Balance

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



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

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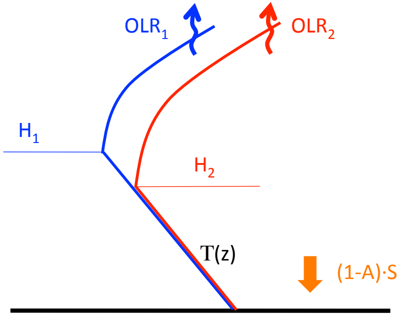

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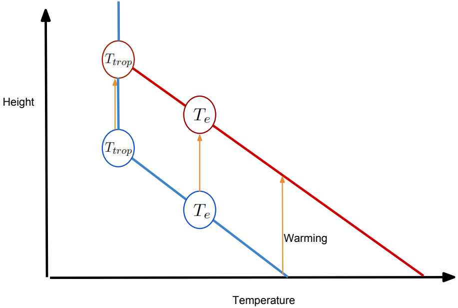
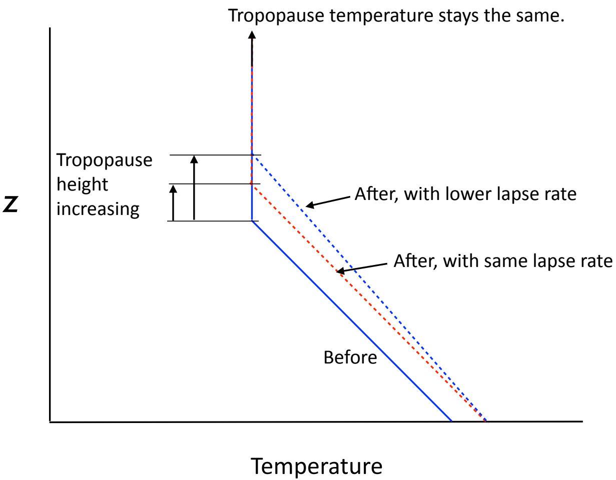


Tropopause height increases with increased COT.

Lapse Rate and Temperature Effects



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

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H_T is the tropopause height.

ΔT is the increase in tropospheric temperature.

Γ is in the lapse rate.

$\Delta\Gamma$ the change in the lapse rate.

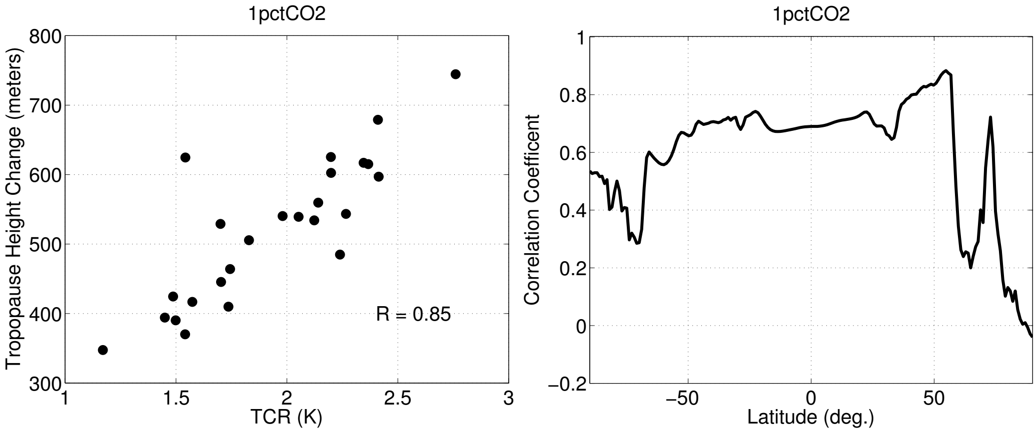
Both effects are comparable.

Predict about 300 m increase per degree Celsius:

$\Delta H_T = 300\,\Delta T$

CMIP5, results

Tropopause height vs Climate Sensitivity



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

Every model change in tropopause height is about 300 m per degree!
(Implications for commercial air flights.)

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:

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

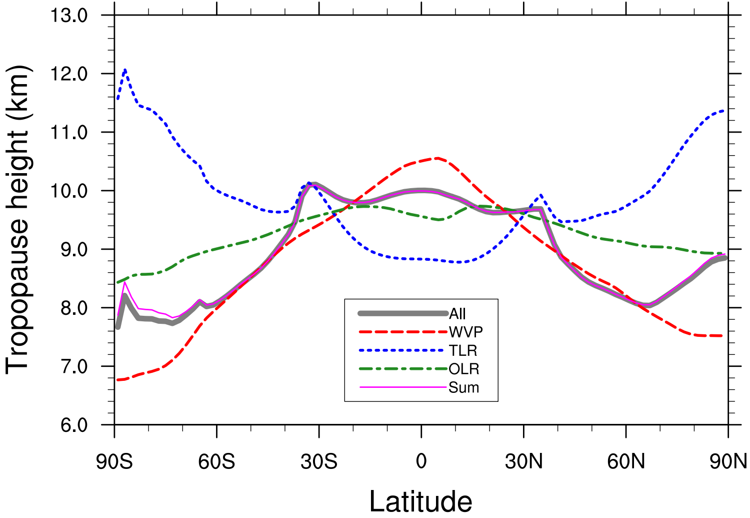
Must adjust H_T so that the equations satisfy the boundary conditions. After some algebra...

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

where τ_s is surface optical depth, H_a is the scale height of the main absorber and $C = \log 2$.

Theoretical Prediction of Tropopause Height

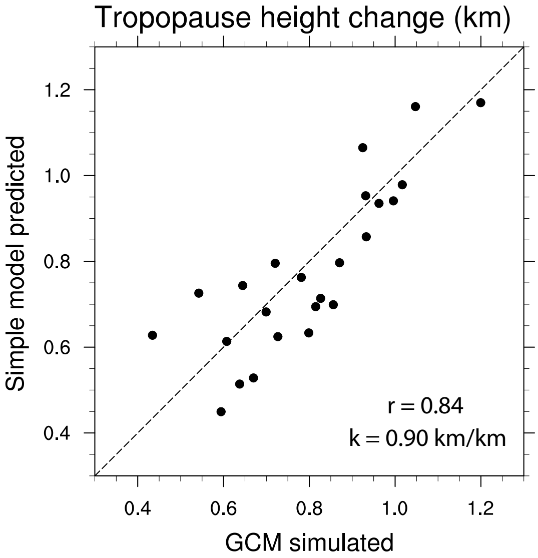
Does the theory reproduced the observed tropopause height? Semi-quantitatively, yes.



But the tropical tropopause is too low.

Changes in Tropopause Height, Global Warming

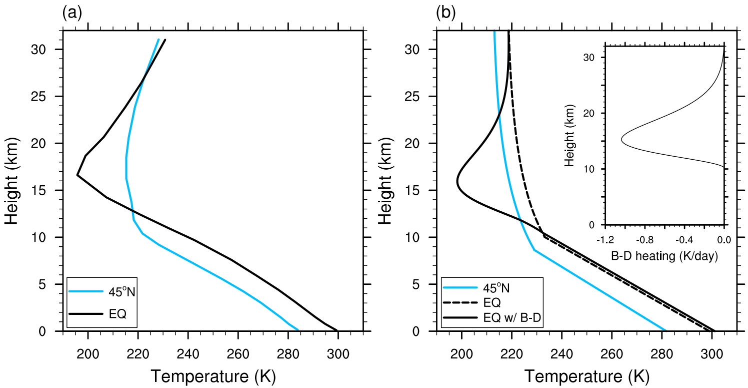
Semi-analytic Theory vs GCM



Theory vs comprehensive numerical model

Effects of the Stratosphere

Add a cooling to the stratosphere:

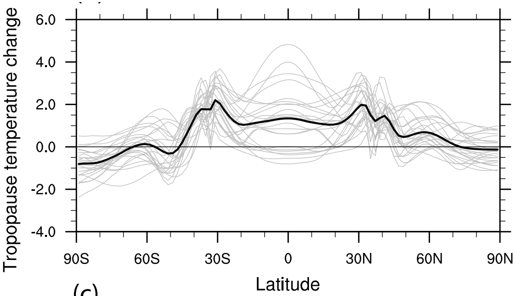


Observations

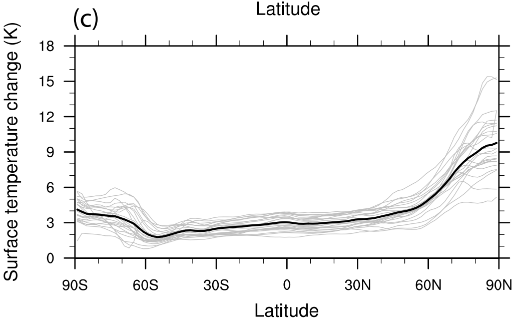
Theory

Tropopause Temperature

Constant in a gray atmosphere



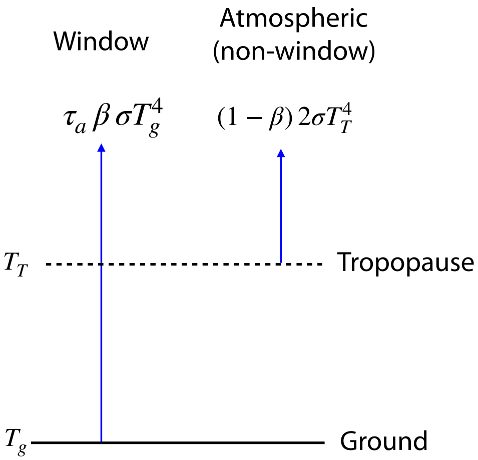
Tropopause temperature change



Surface temperature change

Tropopause temperature change is small but not zero

Non-Gray Effects of Radiative Transfer



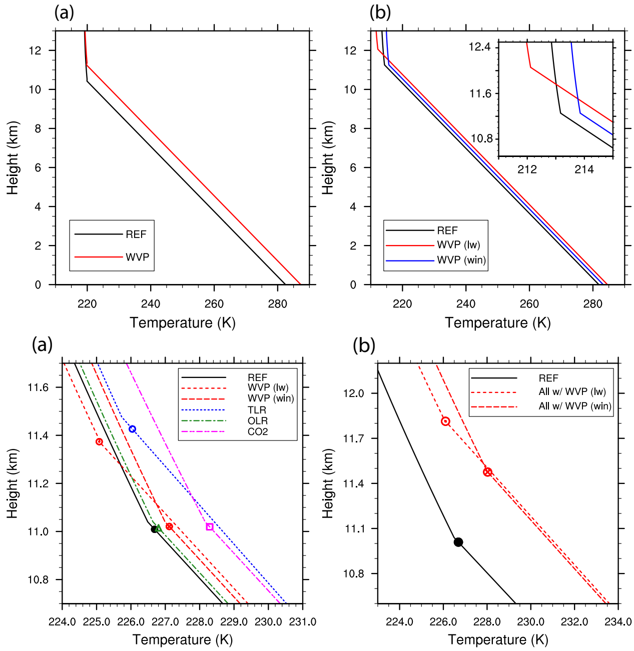
Total OLR remains constant with global warming.

$$\tau_a \beta \sigma T_g^4 + (1-\beta)\, 2\sigma T_T^4 = \text{OLR}$$

If τ_a diminishes sufficiently (i.e., the window closes) because of increase greenhouse gases then T_T must increase!

(Needs a detailed calculation to be quantitative.)

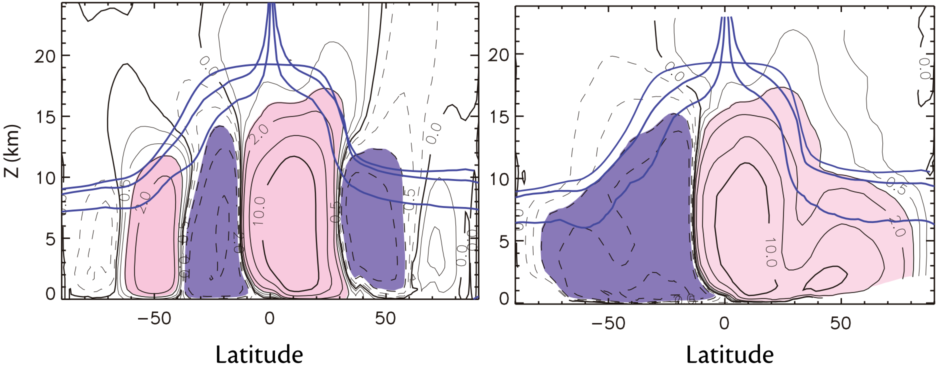
A Windowed Calculation



Temperature increase with non-windowed (left) and windowed (right) increase in greenhouse gases.

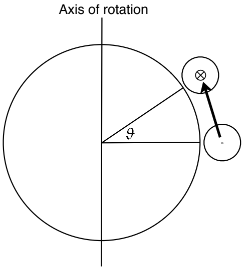
The Overturning Circulation

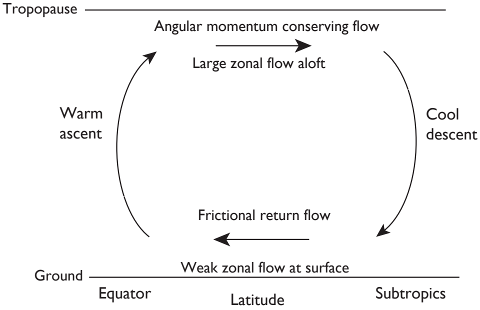
Hadley and Ferrel Cells



Hadley Cell, Axi-symmetric Theory

(E.K. Schneider, 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:

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

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)

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

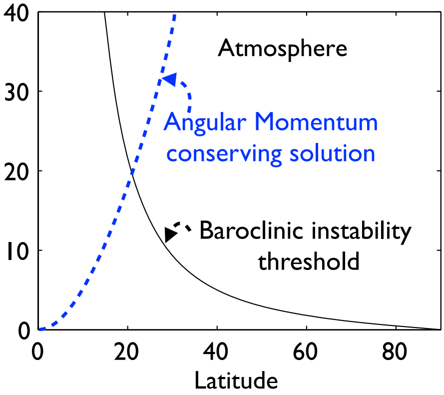
   - Increase in height of tropopause leads to Hadley Cell expansion.

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

   - Assumes other factors stay the same.

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

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)

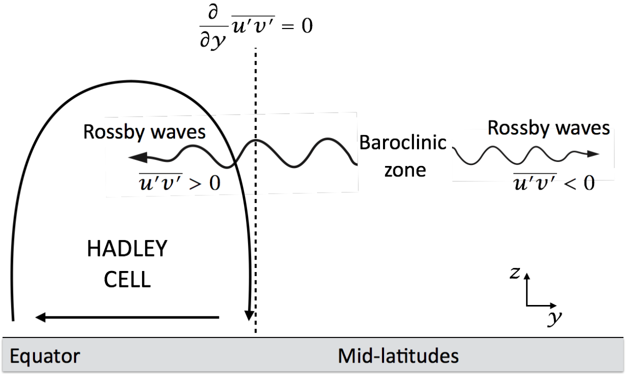
But note

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

$$(f+\zeta)\overline{v} = -\frac{\partial}{\partial y}\overline{u'v'} = \overline{v'\zeta'}$$

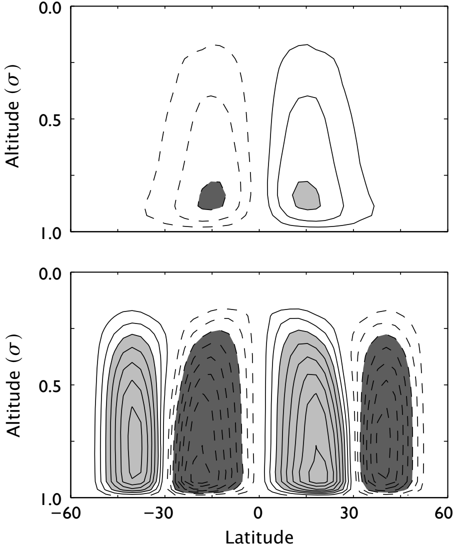


Hadley Cell termination not necessarily at the latitude of baroclinic instability onset.

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

Hadley Cell Width:

Numerical simulation, with and without eddies



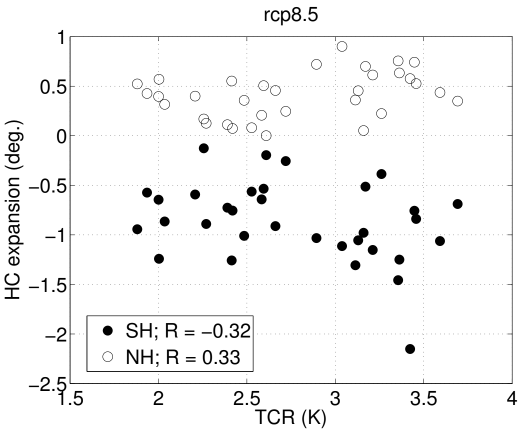
(a) Zonally symmetric simulation

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

Courtesy C. Walker

Expansion of the Hadley Cell

Scatter plot against temperature increase

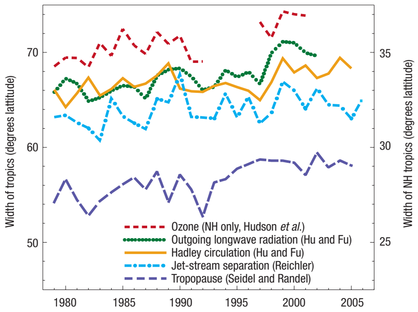


- Hadley cell expands in most models
- Significant scatter.
- Southern expansion is weakly correlated with Northern expansion
- Expansion is not correlated with degree of warming of a model.

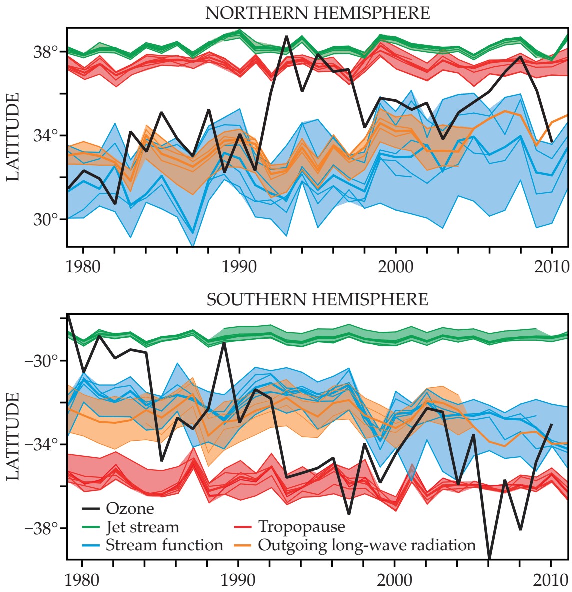
Observed expansion

Many estimates!

1. Vary significantly
2. Observations show much more expansion than models predict. (Natural variability?)



Seidel et al 2008



Birner et al

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,

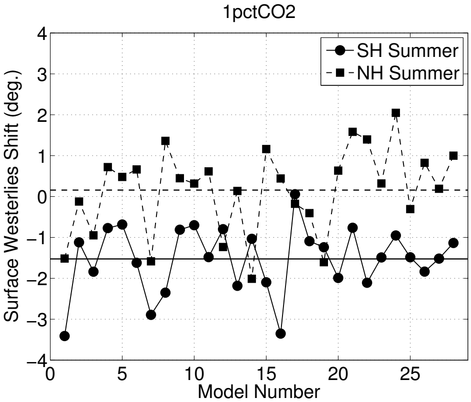
$$r\overline{u}_s \approx \int \frac{\partial \overline{u'v'}}{\partial y}\,\mathrm{d}z = \int \overline{v'q'}\,\mathrm{d}z$$

where r is a surface friction parameter.

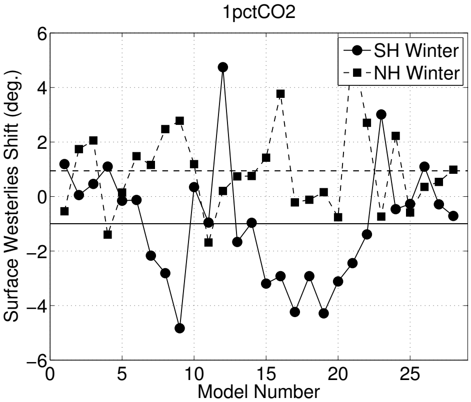
Shift of the Surface Westerlies

In model predictions of global warming.

Summer

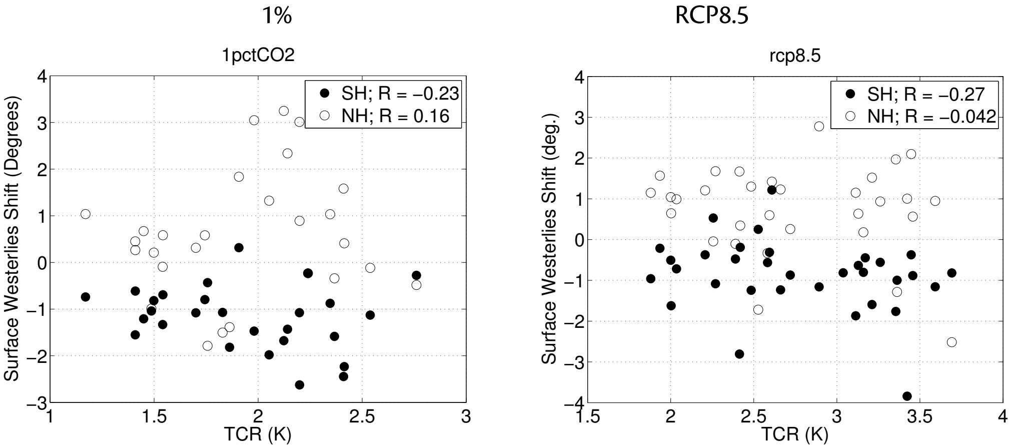


Winter



Shift of the surface westerlies

vs increase in temperature

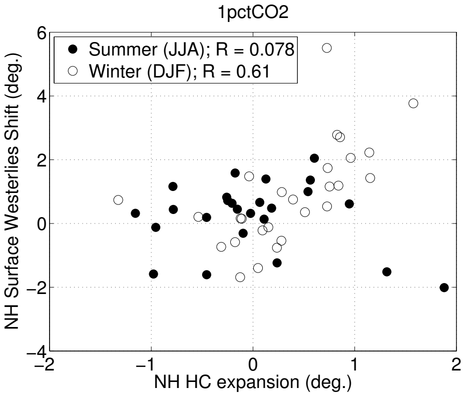


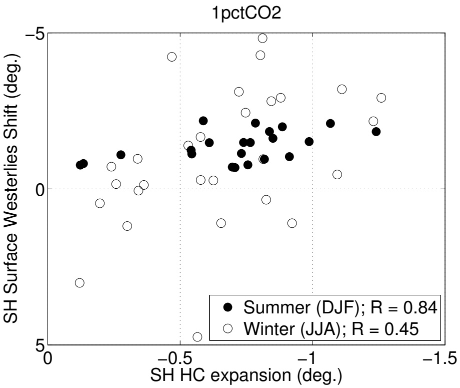
Lots of scatter!

Shift of Hadley Cell & Mid-latitude Westerlies

Are they correlated?

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

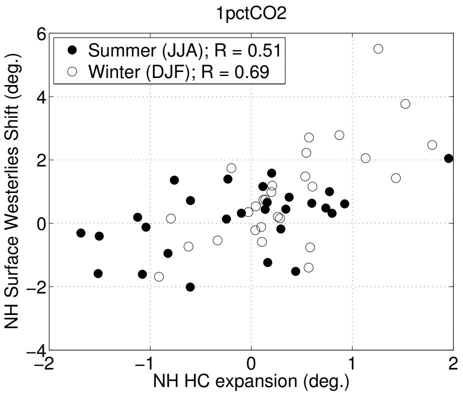


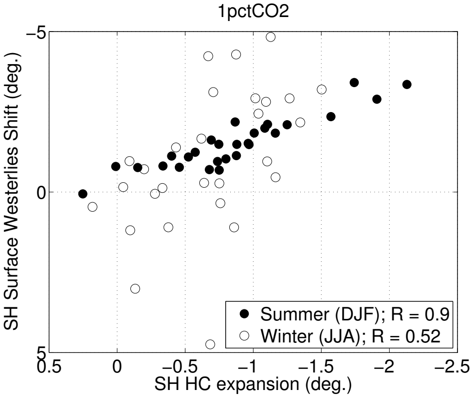


Shift of Hadley Cell & Mid-latitude Westerlies

Are they correlated?

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

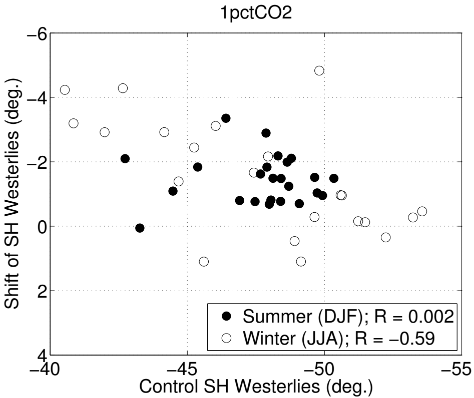


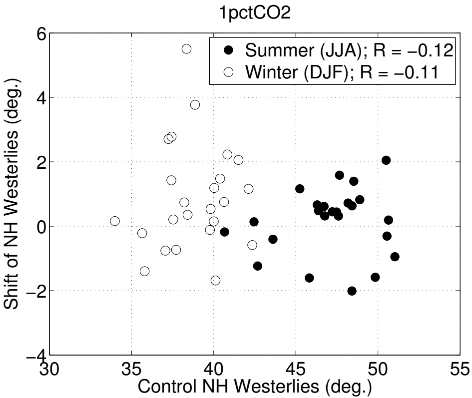


Surface Wind Changes

As a function of Current position

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

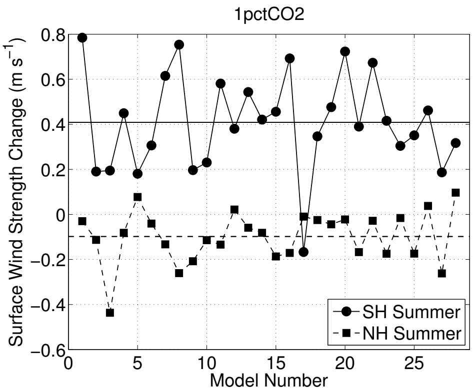




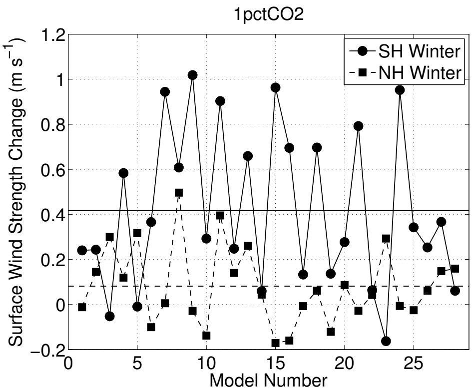
Change in Surface-Wind Strength

For each model

Summer



Winter



Dependent on season, hemisphere and the model itself!

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

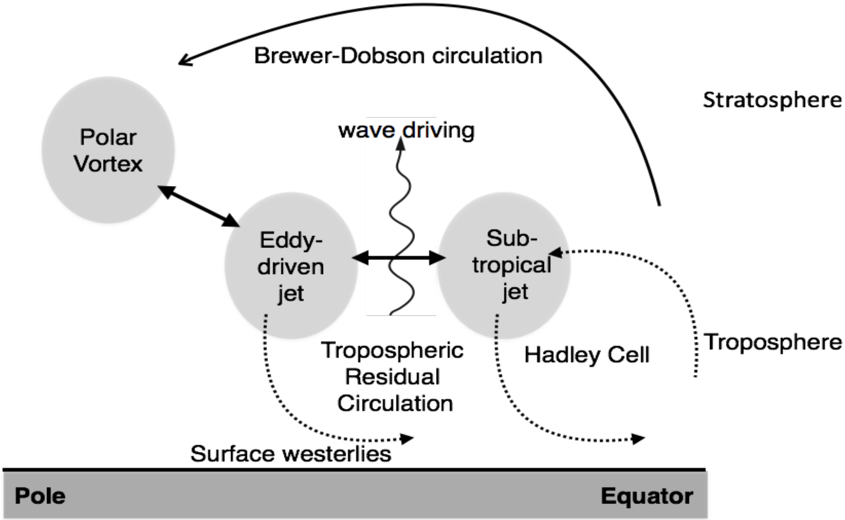
Possible Changes in Jet Position and Strength

due to...

1. Change in location of baroclinic zone because of changes in meridional temperature gradient.
2. Change in position of waves break
3. Stratospheric influences.
4. etc.

Factors influencing jets

A stratospheric influence?



Multiple interactions...

Conclusions

- Thermodynamic/radiative changes to atmosphere have uncertainties but are robust – at least we know the sign! Examples:
  - The warming itself and associated changes (e.g. sea ice loss).
  - Increase in height (and temperature) of the tropopause, and cooling of the stratosphere, have solid physical mechanisms *and* are reproduced by comprehensive models.
- Dynamical/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 – perhaps they are all correct.
  - Different mechanisms may dominate in different models.
- Consequence – changes in regional climate and weather are relatively uncertain. Poorly understood examples:
  - Remote consequences of sea ice loss.
  - Changes in precipitation over land, storm track changes, expansion of the deserts.

MUTIPLE INTERACTIONS WITHIN A SINGLE MODEL!