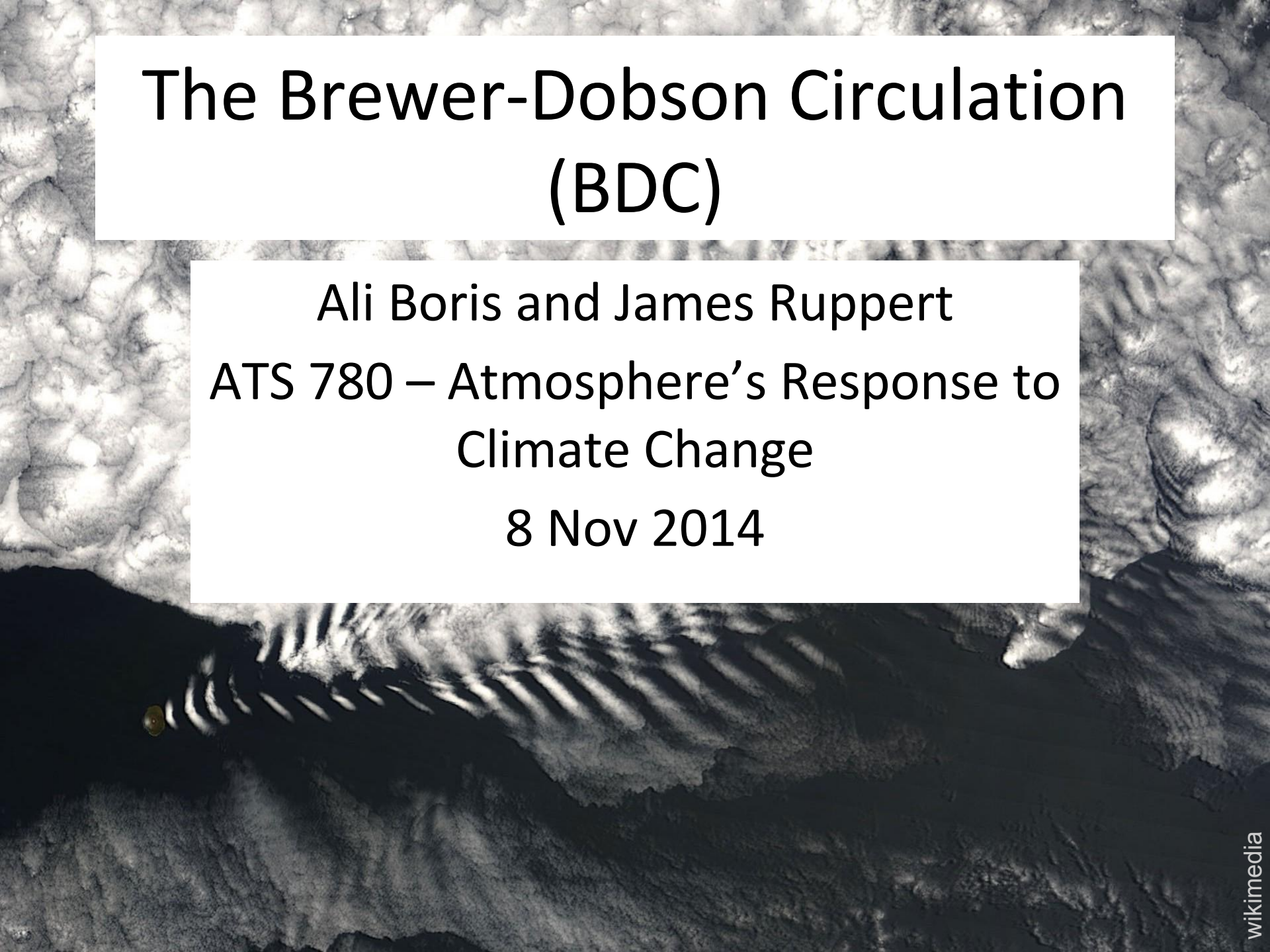
The Brewer-Dobson Circulation (BDC)

Ali Boris and James Ruppert

ATS 780 – Atmosphere's Response to Climate Change

8 Nov 2014



wikimedia

The Brewer-Dobson Circulation

- Thomas Birner comes up as the 2nd result when you search for the BDC in google: http://birner.atmos.colostate.edu/bdc.html
- He provides a summary of the political–historical context for the BDC's discovery
- Alan Brewer was a postdoc of Gordon Dobson, and was assigned to investigate contrails (1940s)
  - Wartime motivation (WWII)

The Brewer-Dobson Circulation

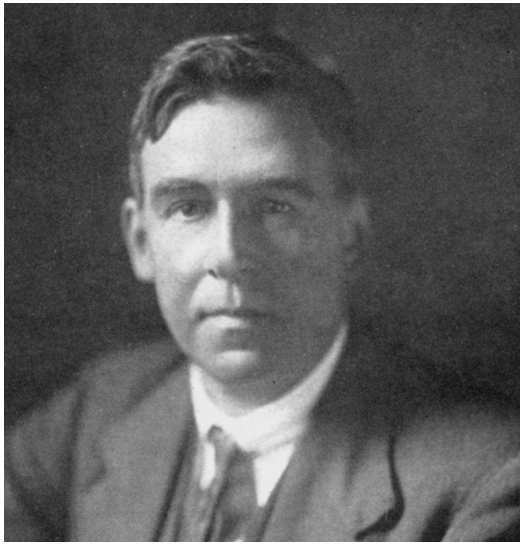
- Excellent historical overview by Jim Holton: http://www.atmosp.physics.utoronto.ca/SPARC/News15/15_Norton.html

Early Prevailing Principles and Assumptions

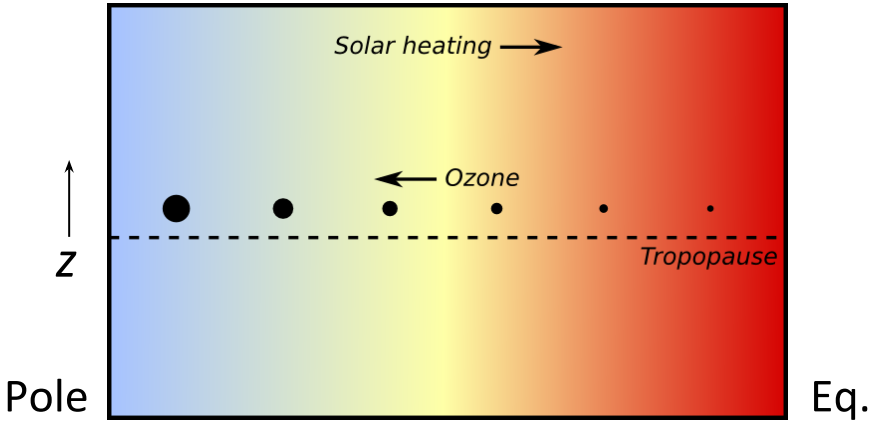
1. Large static stability in the stratosphere
2. Motionless stratosphere
   - Radiative equilibrium: incoming SW = outgoing LW
3. Ozone formation owes to UV radiation

Dobson et al. 1929

- Upon finding that ozone increases poleward in the lower stratosphere…
  - "...the present observations make it almost certain that UV radiation is not the chief cause of ozone formation"
  - "It is more in accordance with the observations to suppose that ozone is formed by some other cause and that the role of the sun is mainly to decompose that ozone"



Gordon Dobson

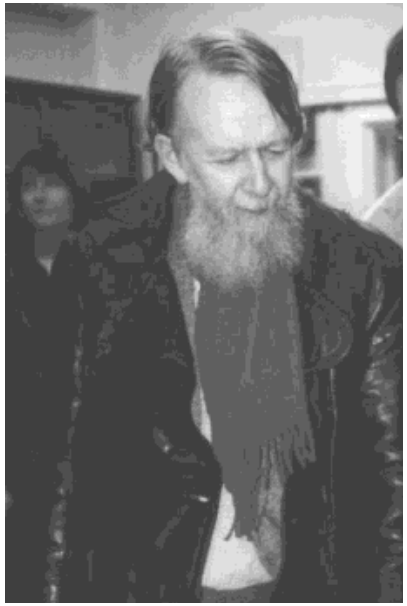


Dobson et al. 1929

- "The only way we can reconcile these observations, with the hypothesis that the ozone *is* formed by the action of sunlight, would be to suppose a <u>slow poleward drift in the highest atmosphere with a slow descent of air near the Pole</u>."
- "Such a current would carry ozone formed in the low latitudes to the Pole and concentrate it there."
- They disregard this, since the measurements to not provide the necessary insights as to ozone's vertical distribution
- …and because this would go against many strongly held notions of stratospheric dynamics

Brewer 1949

- *Evidence for a World Circulation Provided by the Measurements of Helium and Water Vapour*…
- If we take the motionless assumption, a given conservation equation (e.g., for water vapor) reduces to diffusion
- The predicament:
  - With diffusion working to moisten the lower stratosphere, "…how is the great dryness of the stratospheric air maintained?"

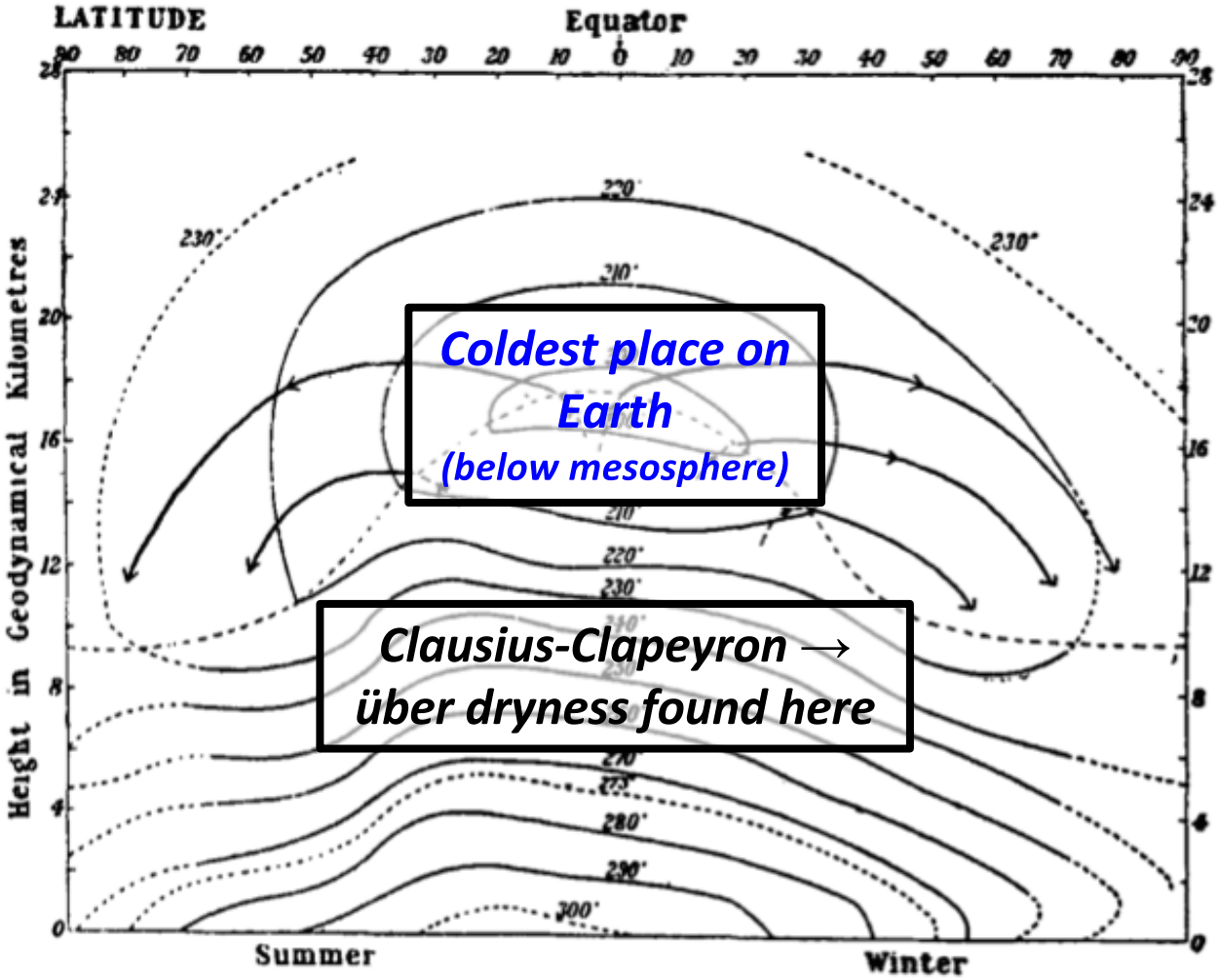


Alan Brewer

Brewer 1949

- “The observed distributions can be explained by the existence of a circulation in which air enters the stratosphere at the equator, where it is dried by condensation, travels in the stratosphere to polar regions, and sinks into the troposphere.”
- “The sinking will warm the air unless it is cooled by radiation…at the equator the ascending air must be subject to heating by radiation.”
- (All of this is speculative)

Brewer 1949



Isotherms over the Globe

FIG. 5. A supply of dry air is maintained by a slow mean circulation from the equatorial tropopause.

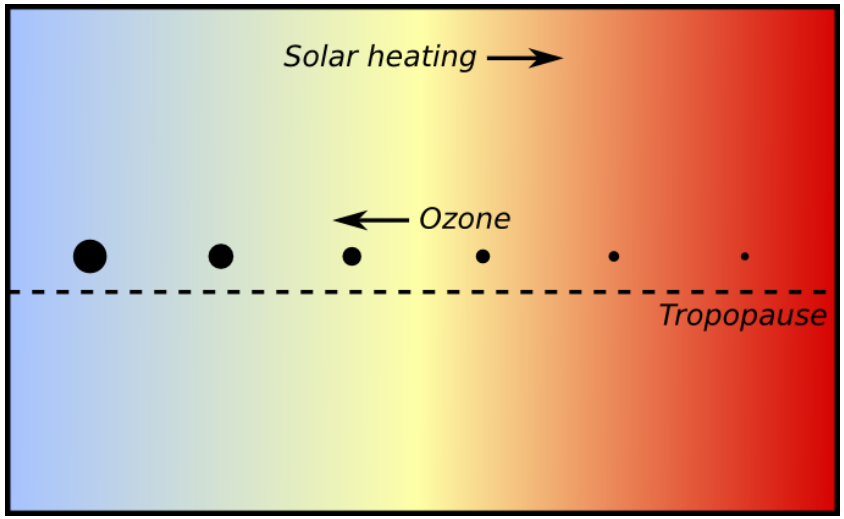
Brewer 1949

- Brewer calls for a radical paradigm shift in stratospheric dynamics:
  - Air is *not* motionless
  - Radiative cooling/warming must offset adiabatic warming/cooling, implying radiative *disequilibrium*
- Dynamical issue (angular momentum): “It should be noted that there is difficulty accounting for the smallness of westerly winds in the stratosphere.”

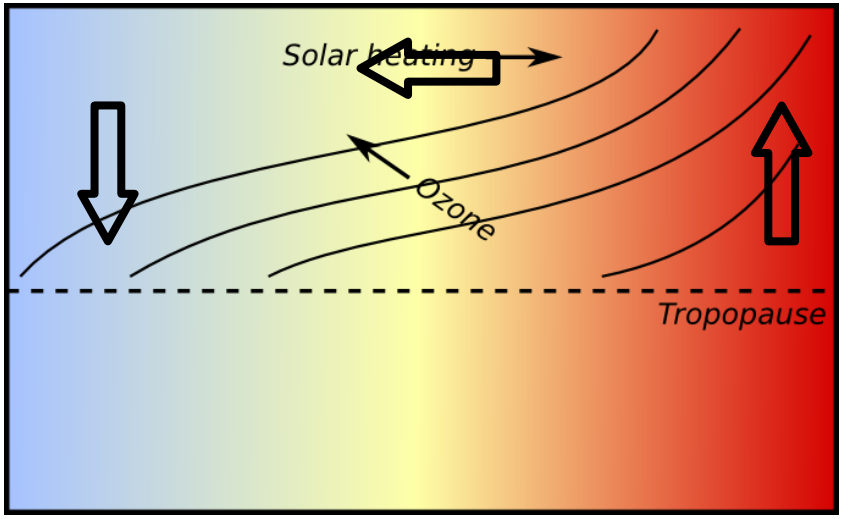
Dobson 1956

- Dobson finally comes around (27 years later) to his original supposition, guided by Brewer's innovations and new observations
  - Ozone maximizes in the tropical upper stratosphere, and is brought downward in the extratropics by subsidence

Dobson 1956



Early observations



New observations

Murgatroyd and Singleton 1959, 1961

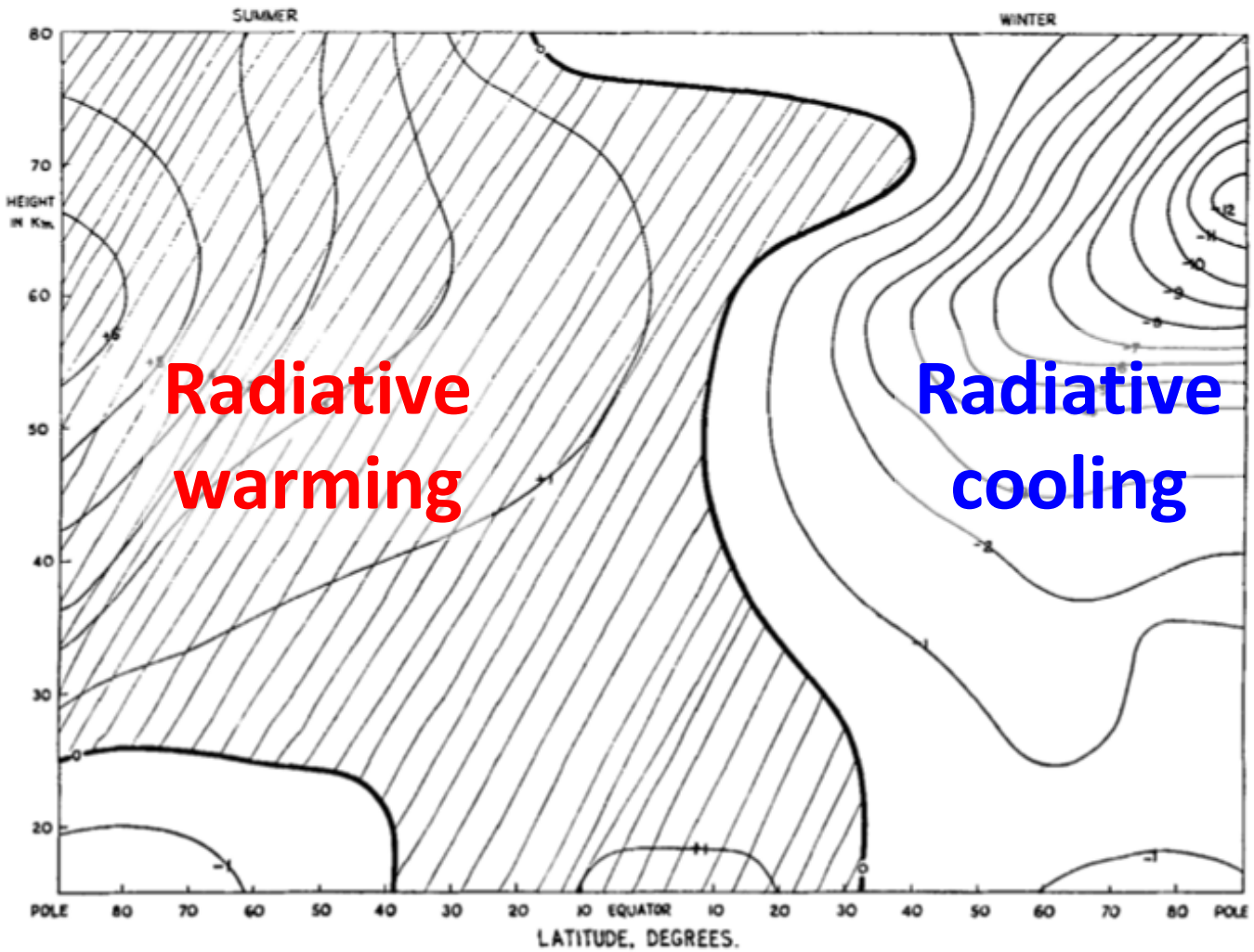
- "Significant deviations from radiative equilibrium exist at the poles, with heating at the summer pole and cooling at the winter pole"
- The circulation required to balance this radiative imbalance can be deduced:

$$\frac{\partial \overline{\theta}}{\partial t} + \frac{\overline{v}_d}{a}\frac{\partial \overline{\theta}}{\partial \phi} + \overline{w}_d \frac{\partial \overline{\theta}}{\partial z} = \overline{Q}$$

$$\frac{1}{a\cos\phi}\frac{\partial}{\partial \phi}(\overline{v}_d \cos\phi) + \rho_0^{-1}\frac{\partial}{\partial z}(\rho_0 \overline{w}_d) = 0,$$

Murgatroyd and Singleton 1961

Summer hem.

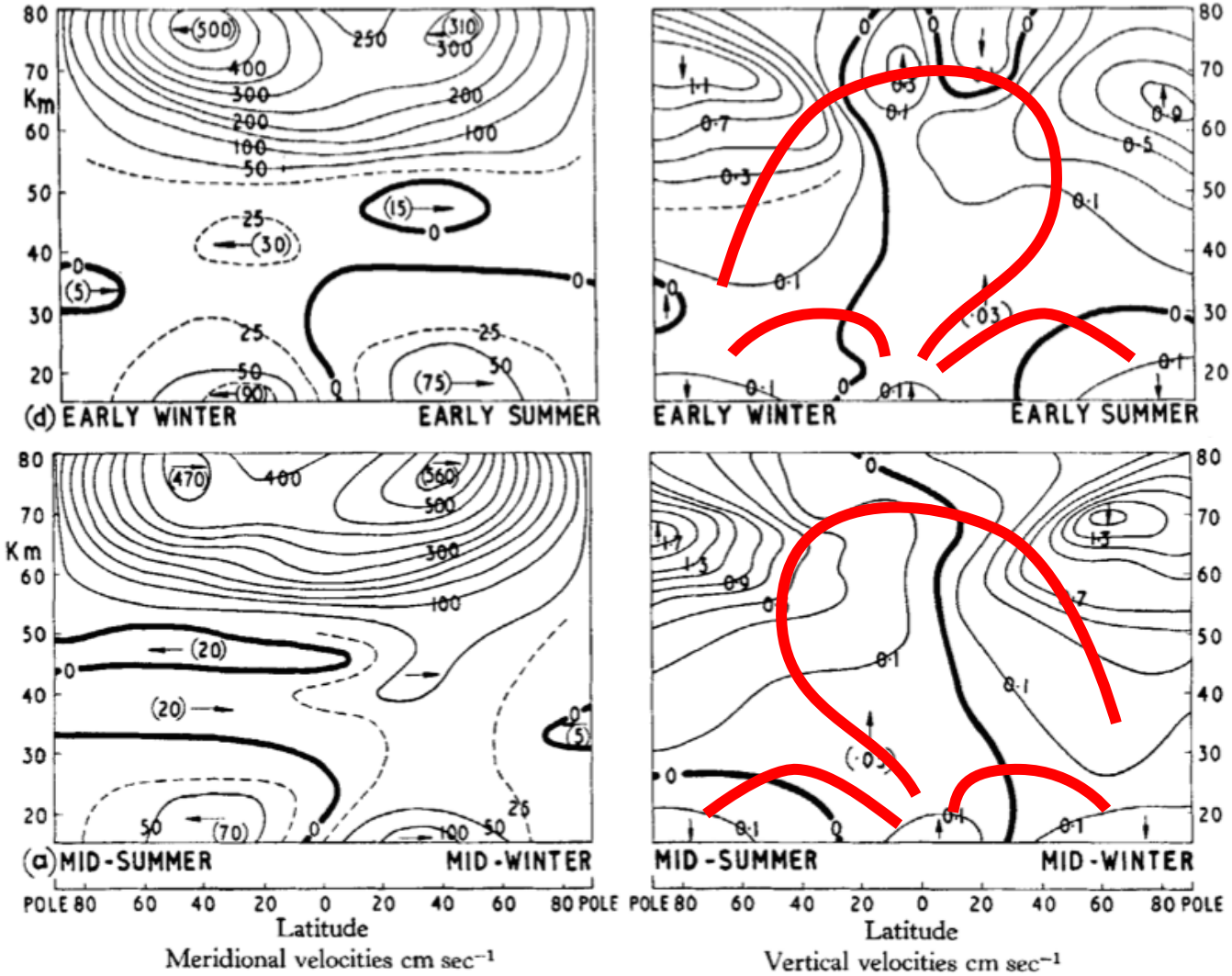


Winter hem.

Figure 1. Radiative heating and cooling °K day^{-1}. Regions of heating are shaded.

Murgatroyd and Singleton 1961

v
O(m/s)



w
O(cm/s)

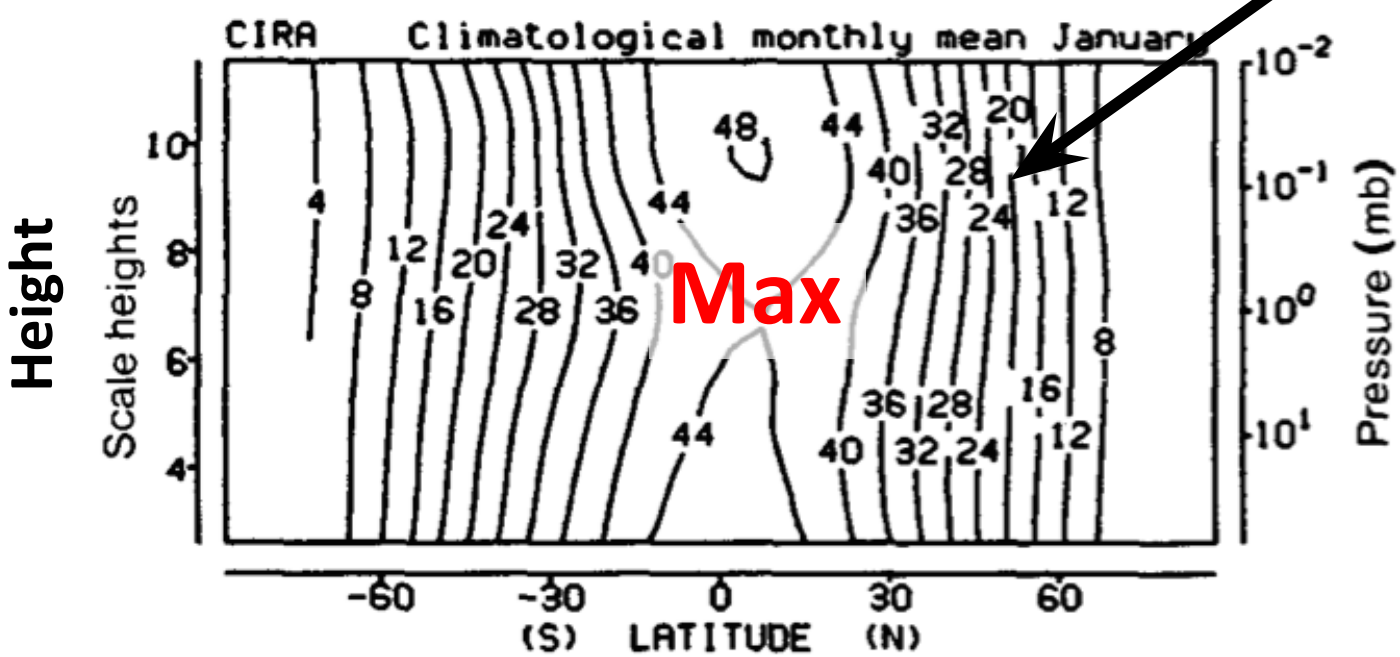
Murgatroyd and Singleton 1961

- The angular momentum issue…
  - "A poleward-moving particle would be expected to acquire a large westerly component…"
  - "This non-conservation of angular momentum implies the existence of <u>eddy processes</u> which are likely to be of importance to the heat and momentum balance."

Murgatroyd and Singleton 1961

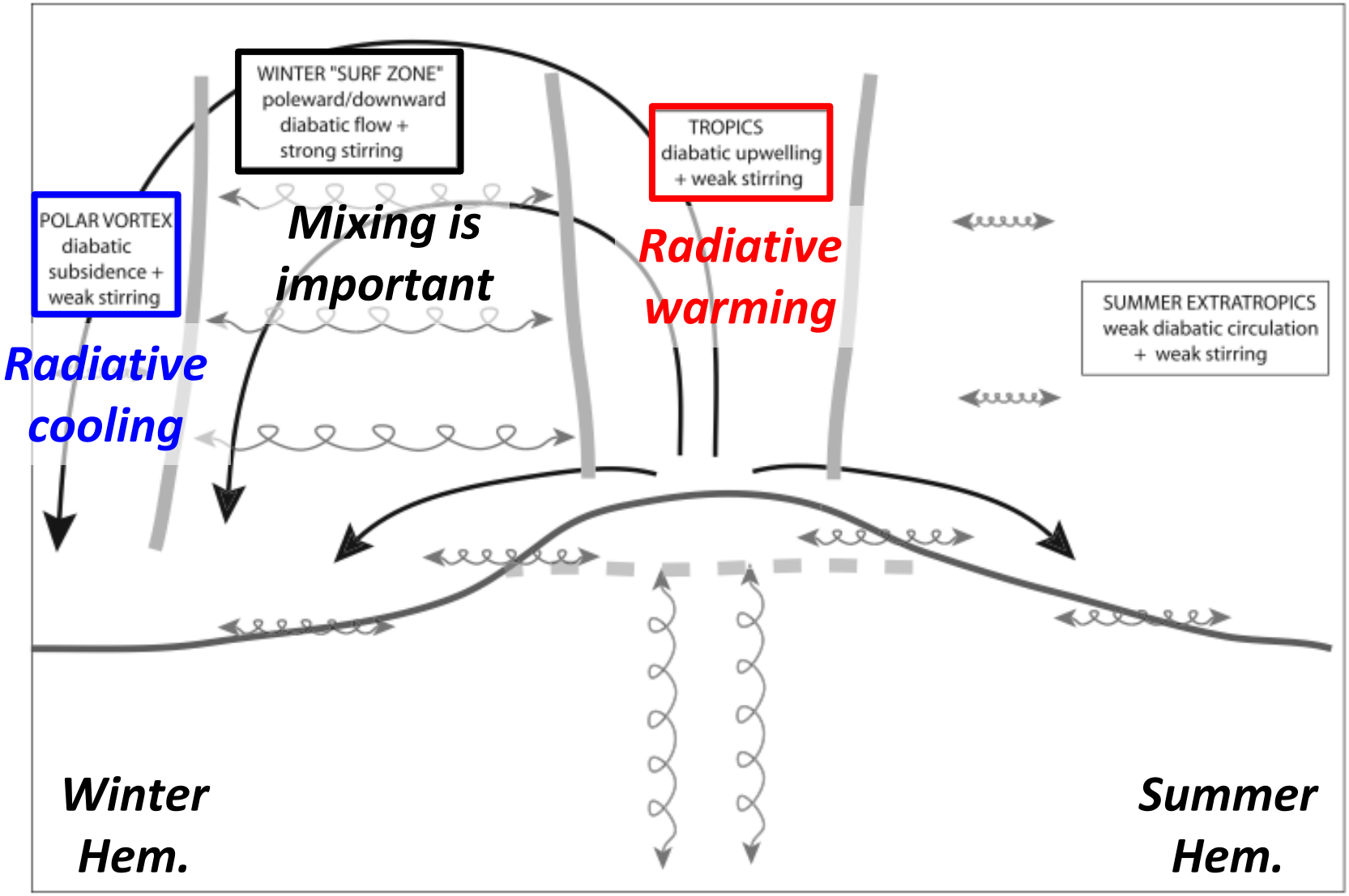
$$\bar{m} = a\cos\phi\left(\bar{u} + a\Omega\cos\phi\right)$$

How does air crossing this gradient conserve momentum?



S Pole **N Pole**

From Haynes et al. 1991



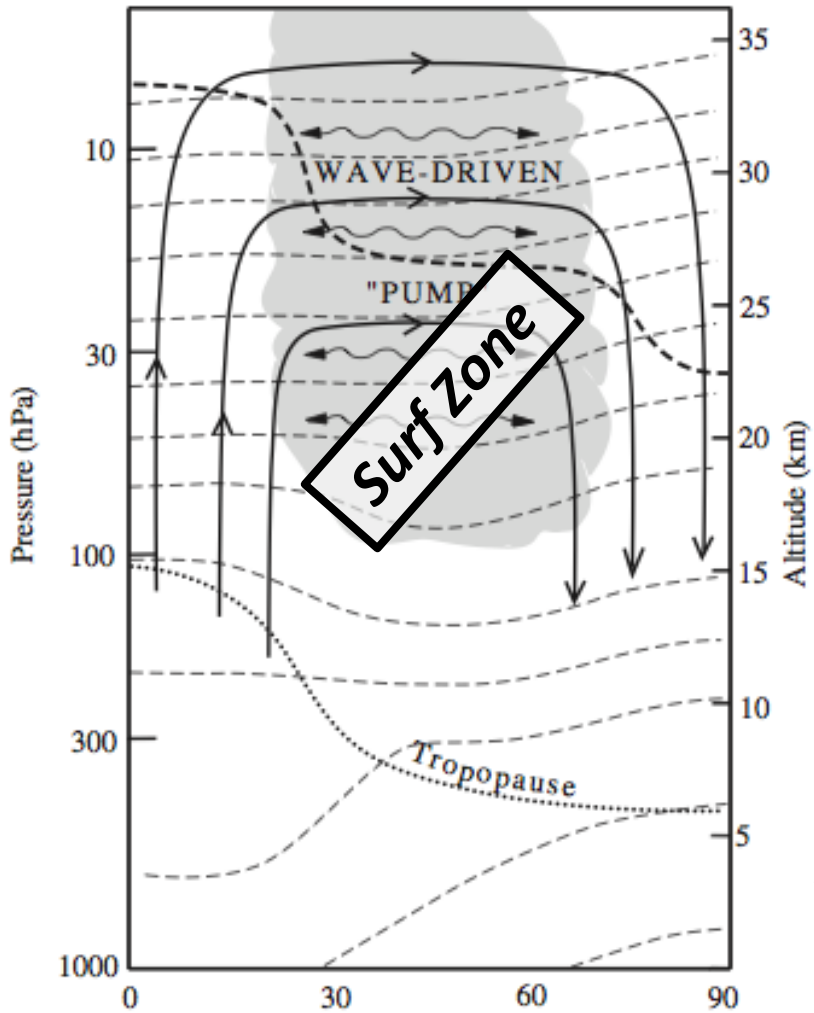
Tropics

From Plumb 2007

Eddy-mean Flow Interaction

- Key jargon:
  - “Extratropical pump,” “Rossby wave pump,” “gyroscopic pump,” etc. etc.
  - “Downward control” (Haynes et al. 1991)
- These all refer to:
  - Rossby and gravity waves transfer momentum between their source regions and where they break (dissipate), acting as a (eddy-driven) force to the mean flow

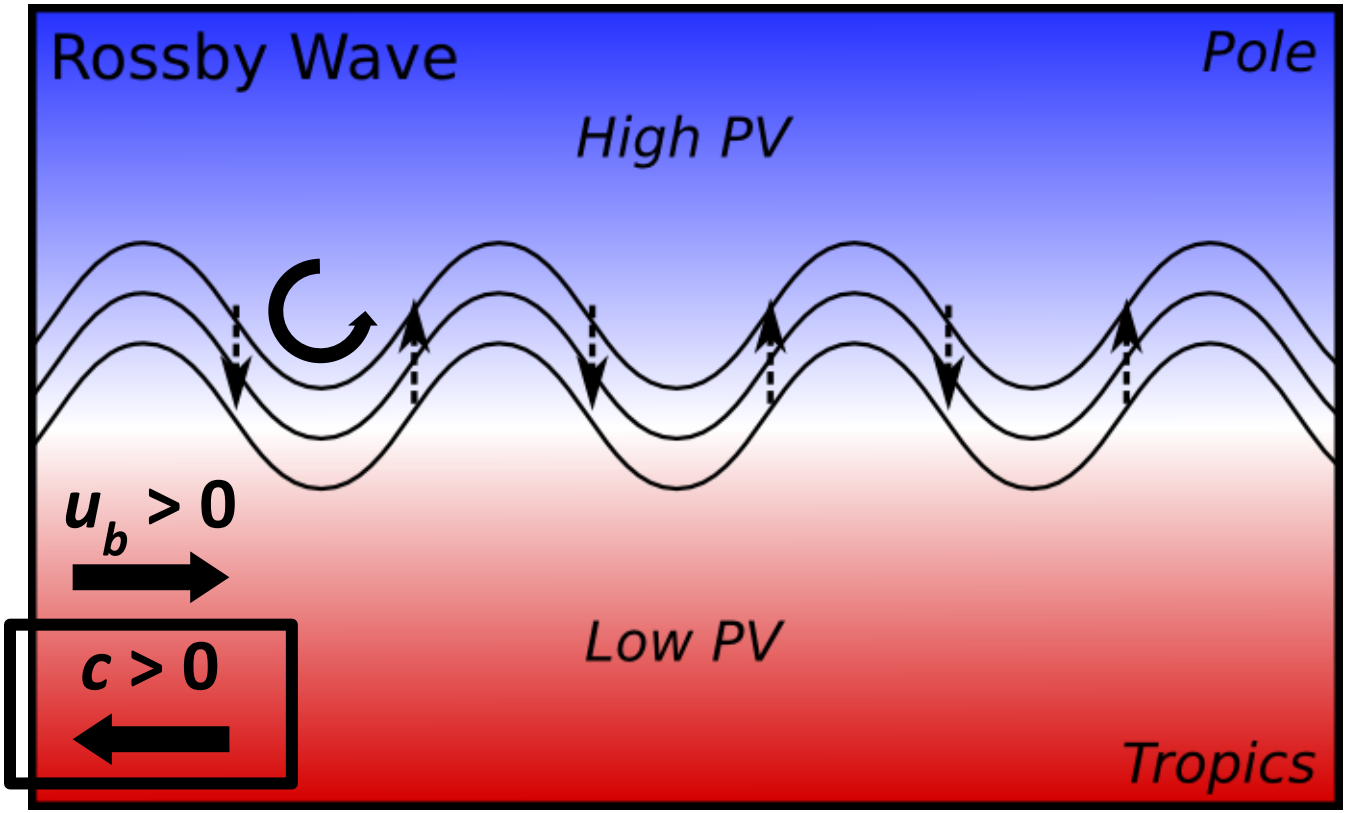
“Wave-driven Pump”



Equator **Winter Pole**

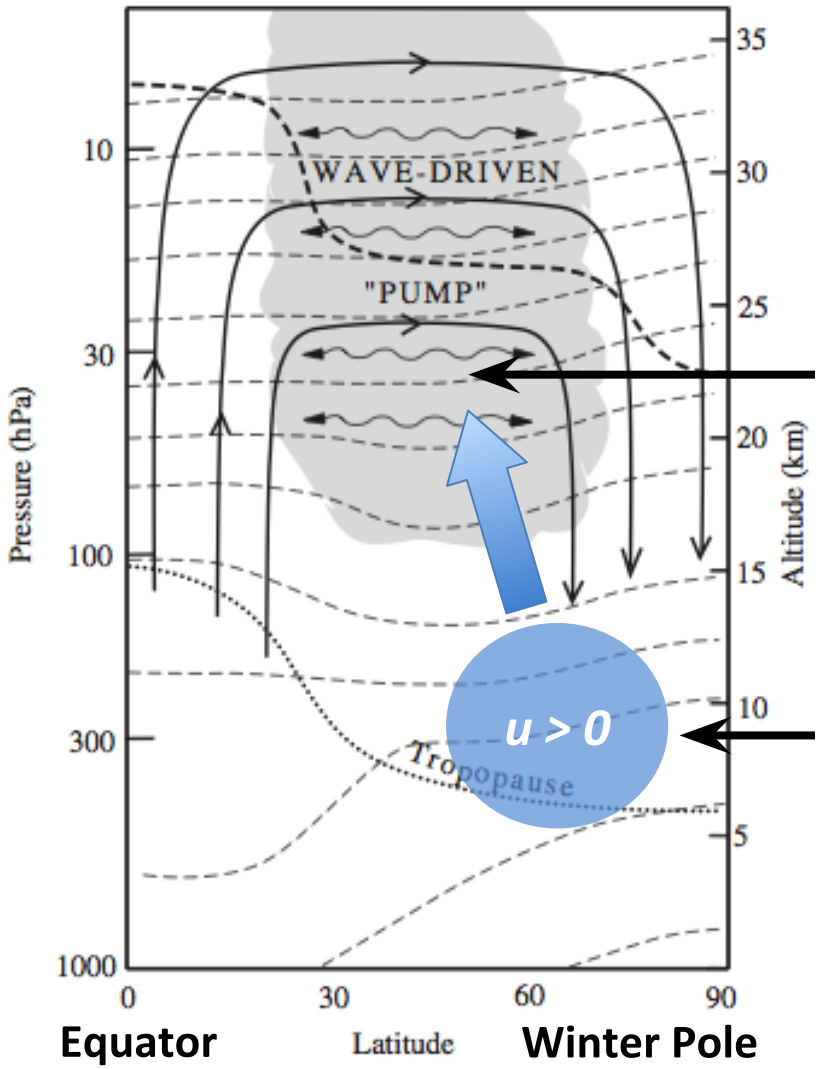
From Holton’s textbook

“Wave-driven Pump”



Easterly phase speed represents the momentum taken from the jet, which is carried with the wave

"Wave-driven Pump"



Surf zone:
Easterly momentum is deposited, causing poleward flow (Coriolis torque)

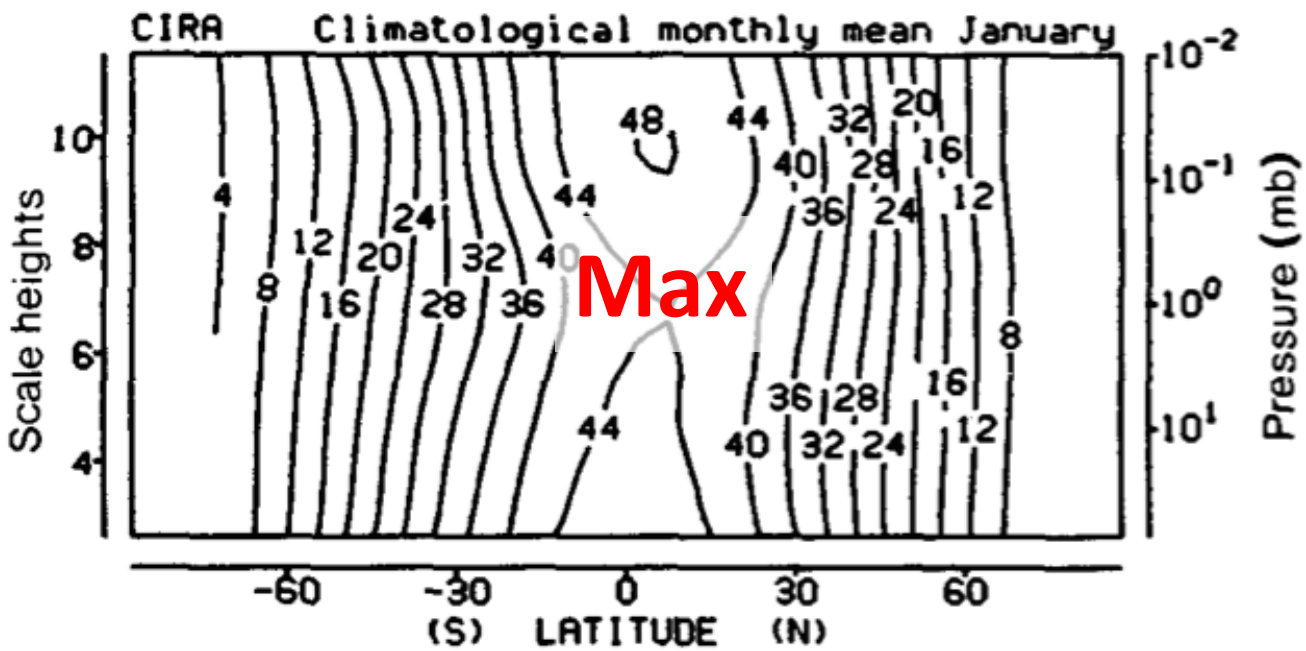
Wave origin –
Rossby waves take up easterly momentum

- Poleward motion facilitated by the deposit of *negative westerly momentum*
- Up- and down-branches cause adiabatic cooling/warming, breaking radiative equilibrium

Angular Momentum is Conserved!

$$\bar{m} = a\cos\phi\left(\bar{u} + a\Omega\cos\phi\right)$$

- Negative angular momentum is taken from the jet during wave genesis, rides the waves, and is deposited in the surf zone causing parcels to drift poleward



From Haynes et al. 1991

The Transformed Eulerian Mean (TEM) System

- Zonally averaged system
- *G* represents the total *zonal force* resulting from eddy activity (wave breaking)

Zonal momentum

$$\partial \overline{u}/\partial t - f_0 \overline{v}^* = \rho_0^{-1} \nabla \bullet \mathbf{F} + \overline{X} \equiv \overline{G}$$

Thermo

$$\partial \overline{T}/$$

$$, t)]$$

$$- f_0 \overline{v}^* = \overline{G}$$

$$N^2 H R^{-1} \overline{w}^* = -\alpha_r \left[\overline{T} - \overline{T}_r (y, z, t)\right]$$

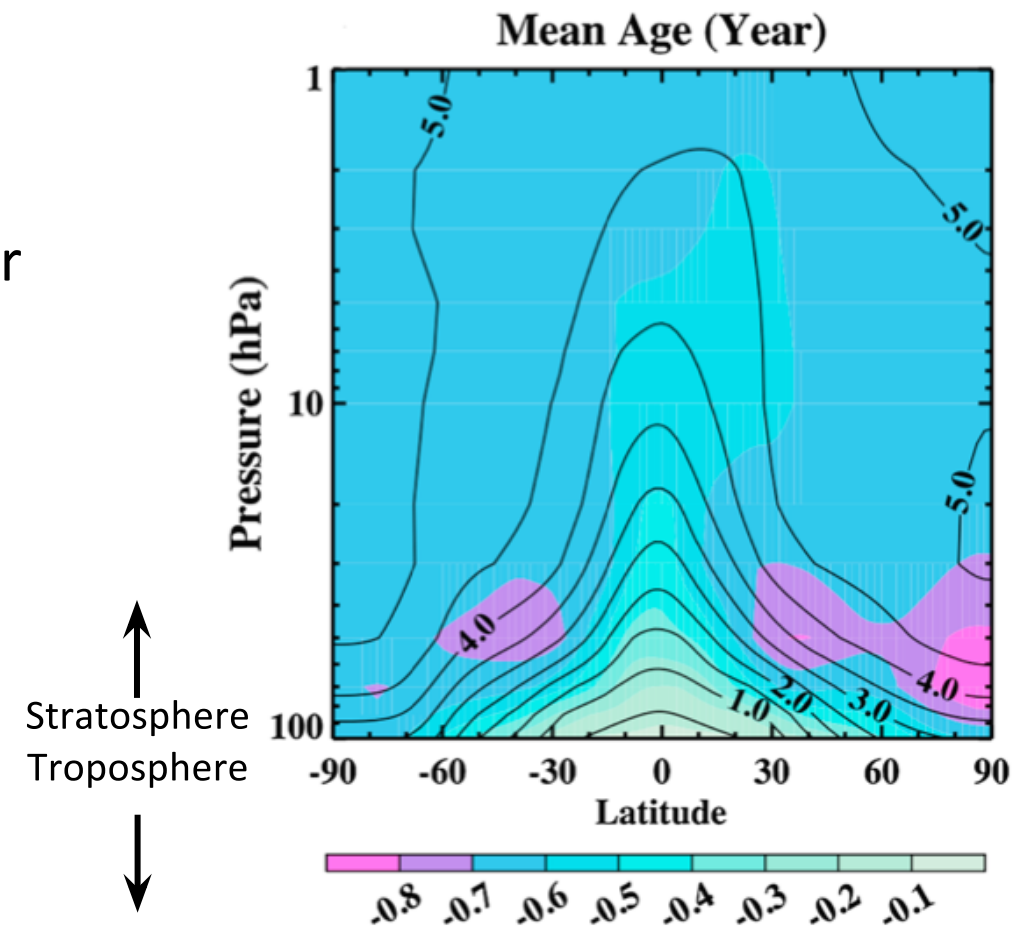
Continuity

TWB

$$f_0 \partial \overline{u}/\partial z + R H^{-1} \partial \overline{T}/\partial y = 0$$

Climate Change: Age of Air

- Climatology:
  - Stratospheric air is youngest in the lower tropics, and oldest near the poles
- Climate change:
  - Air gets younger everywhere, roughly proportional to its climatology age



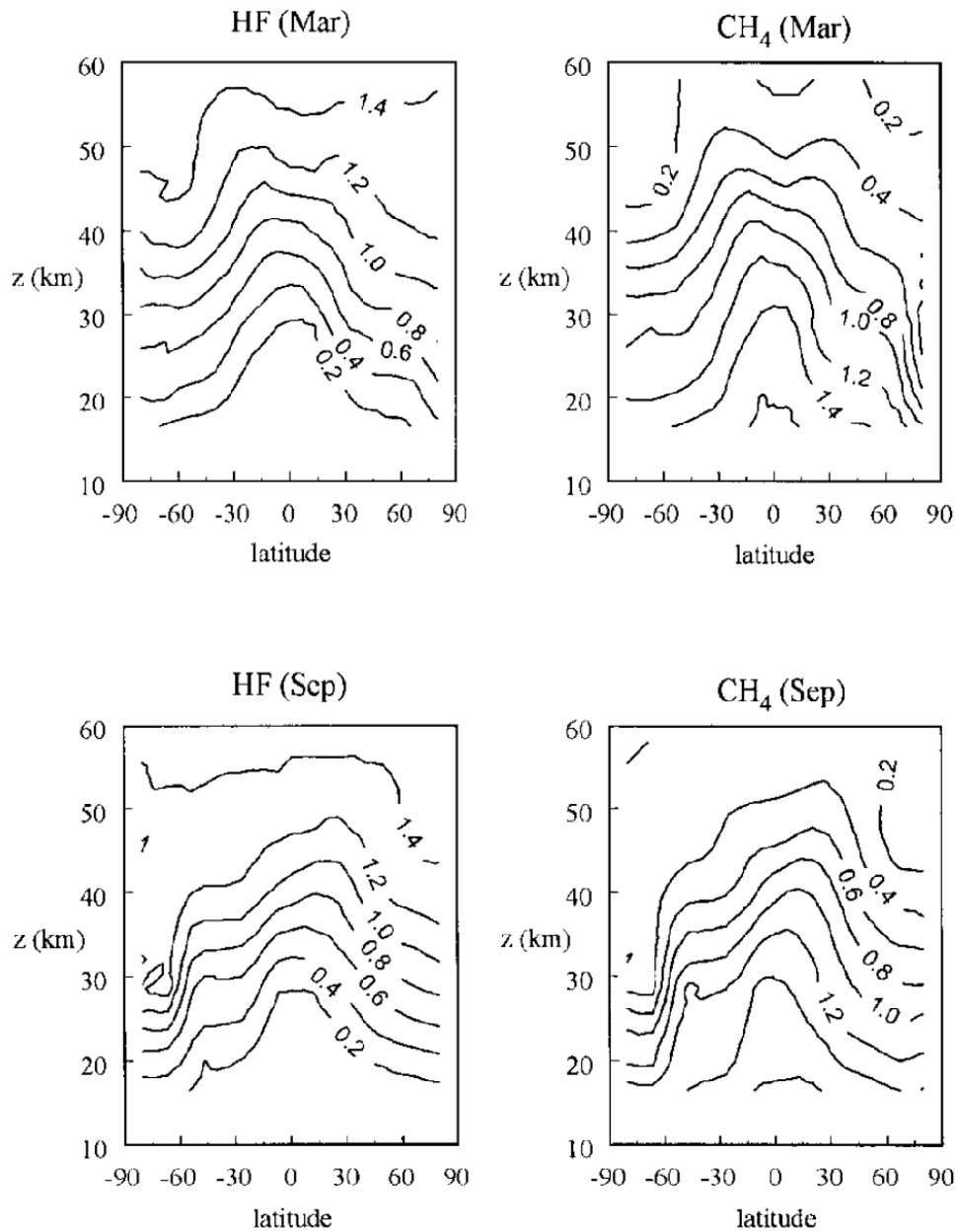
Why do we care about all this??

Chemistry!

In figures, stratospheric and tropospheric chemicals have almost the same distribution!

→Changes to the BDC will affect chemistry

…which affects heating, which affects *dynamics*…

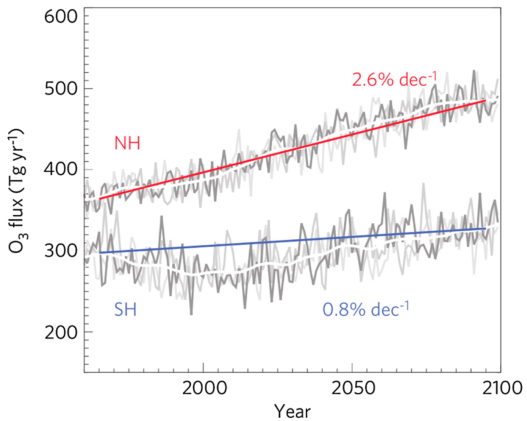


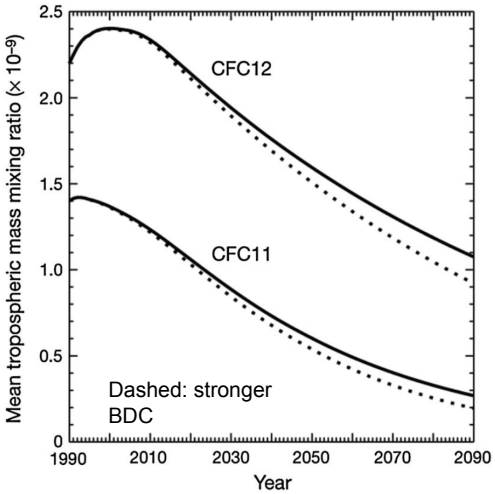
Plumb, 2002

(ppbv; from satellite)

Findings: Ozone and the BDC

Hegglin & Shepherd, 2009:
more tropospheric ozone





Butchart et al., 2006 *Reviews of Geophys.*

Less O_3 at tropics, mid-lats

BDC speeds, slowing more O_3 depletion (a little):

Faster BDC → Younger air → Loss of catalysts → +Lifetime of O_3

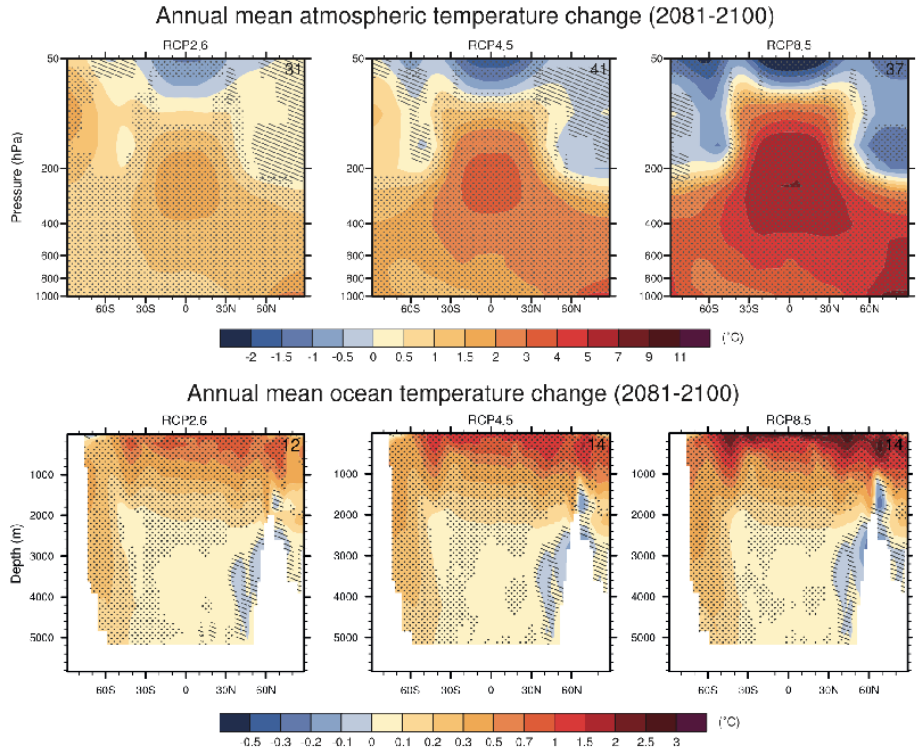
BDC strengthens, cleaning the upper troposphere (how much?):

Stronger BDC → More strat-trop exchange → More O_3 intrusions → Eliminates hydrocarbons

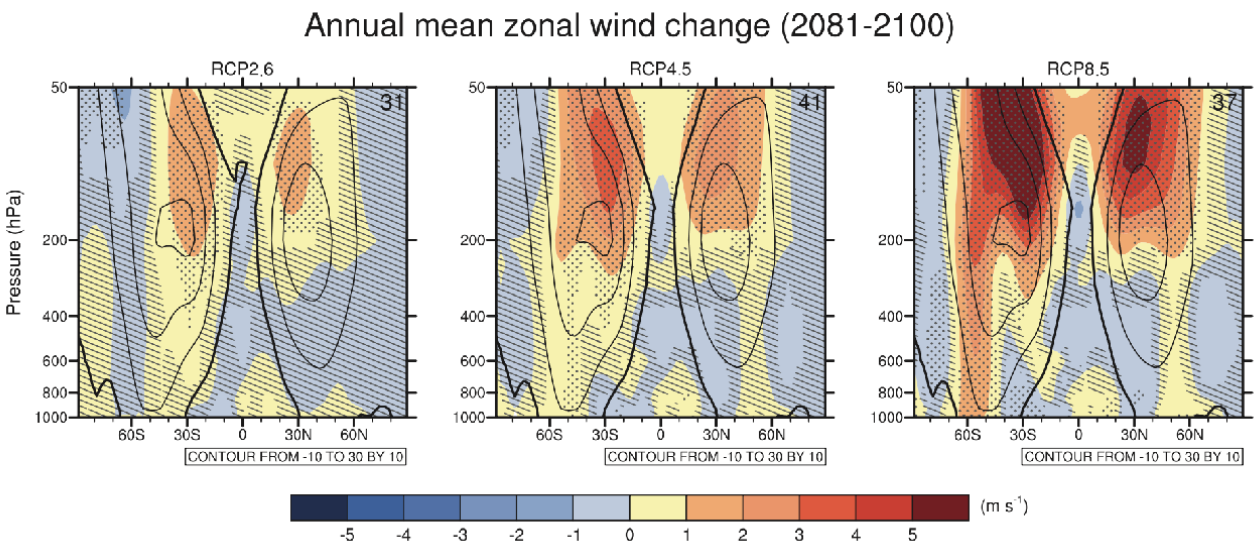
But ozone recovery counteracts BDC changes:

More O_3 → Polar strat. warming → Lesser meridional T gradient → Slowed BDC

General Trends as the Climate Changes (Refresher)



IPCC AR5 Fig. 12.12



IPCC AR5 Fig. 12.19

Figure 12.19 | Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble average of zonal and annual mean wind change (2081–2100 minus 1986–2005) for, from left to right, Representative Concentration Pathway 2.6 (RCP2.6), 4.5 and 8.5. Black contours represent the multi-model average for the 1986–2005 base period. Hatching indicates regions where the multi-model mean change is less than one standard deviation of internal variability. Stippling indicates regions where the multi-model mean change is greater than two standard deviations of internal variability and where at least 90% of models agree on the sign of change (see Box 12.1).

Stratosphere: warmer at the equator, colder at the poles and in the upper atmosphere

SSTs warmer, esp. the N pole

Jets stronger, esp. in the SH, moving upward

Mechanism of BDC *Change*

Warmer SSTs → Convective waves → More active wave breaking

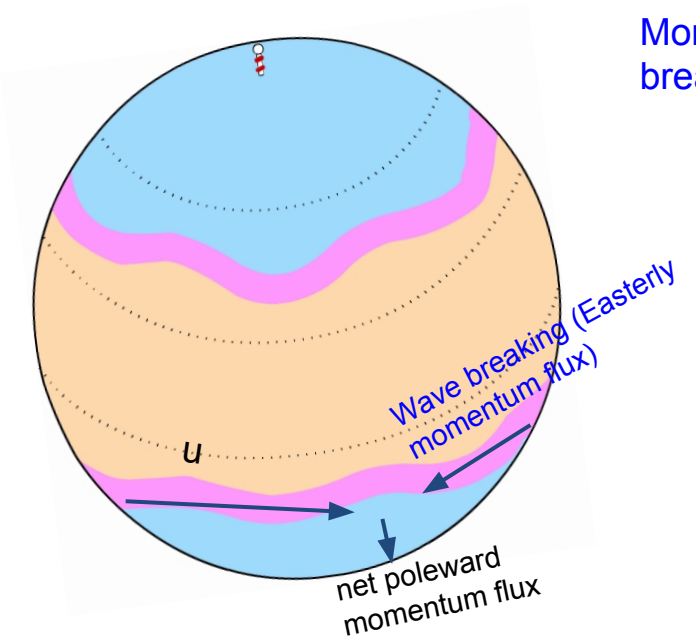
More of a meridional T gradient → More active wave breaking

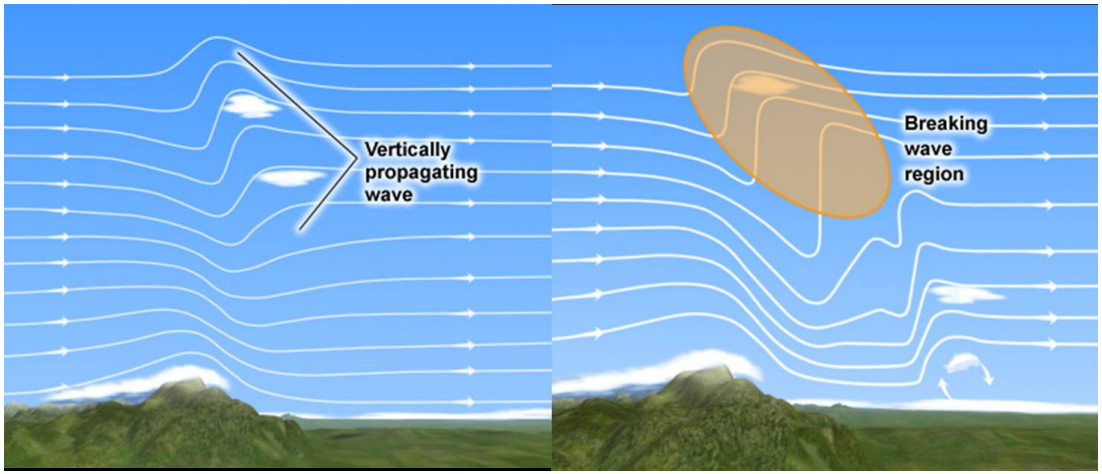
More active wave breaking → Stronger subtropical jets

More active wave breaking → More poleward deflection of momentum (pumping) → Strengthened BDC

Wave types:

- Gravity (parameterized)
- Planetary
- Synoptic





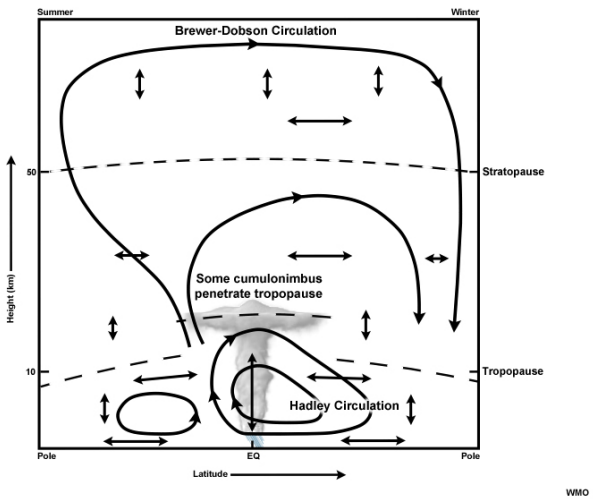
(Ozone recovery: less of a meridional T gradient --reverse)

Images: Wikimedia, Seoul National University

Overview of Climate Change Effects on Stratospheric Circulation

Main findings across the board (all from models):

- **Strengthening** of tropical upwelling, which would be accompanied by more down-welling in the extra-tropical (ET) regions
- Strongest in **lower stratosphere** of the **winter NH**
- Strength of change **depends on easterly momentum flux** from wave breaking



Points that differ between papers:

- Biggest Point: **What causes the change in momentum flux? (which wave types important, what's changing them)**
- Where are the "layers" of the BDC?
- Model changes: ensemble used, resolution in upper strat., ocean-atmosphere coupling
- Focus of paper ---seasonality, meridional upwelling width, type of waves (planetary in the troposphere, gravity in the stratosphere, excitation versus transmission)

Butchart *et al*., 2006

Garcia & Randel, 2008

Calvo & Garcia, 2009

Shepherd & McLandress, 2011

Lin & Fu, 2013

****Hardimann *et al*., 2013**

Palmeiro *et al*., 2014

Hardiman *et al.*, 2013:

Quarterly Journal of the Royal Meteorological Society Q. J. R. Meteorol. Soc. (2013) DOI:10.1002/qj.2258

RMetS
Royal Meteorological Society

The morphology of the Brewer–Dobson circulation and its response to climate change in CMIP5 simulations

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Questions:

- How does the width, strength of the tropical upwelling region change spatially, seasonally?
  - How do Rossby waves affect this?
  - How does ET down-welling respond?

Methods:

- Time periods:
  - Historical simulations (1960-2000), re-analyses (1989-2009)
  - CMIP5 2006-2100 - RCP 8.5 (extreme)
- Models: "High-top" only, one member from ensemble
- Diagnostic: Monthly mean residual vertical velocity

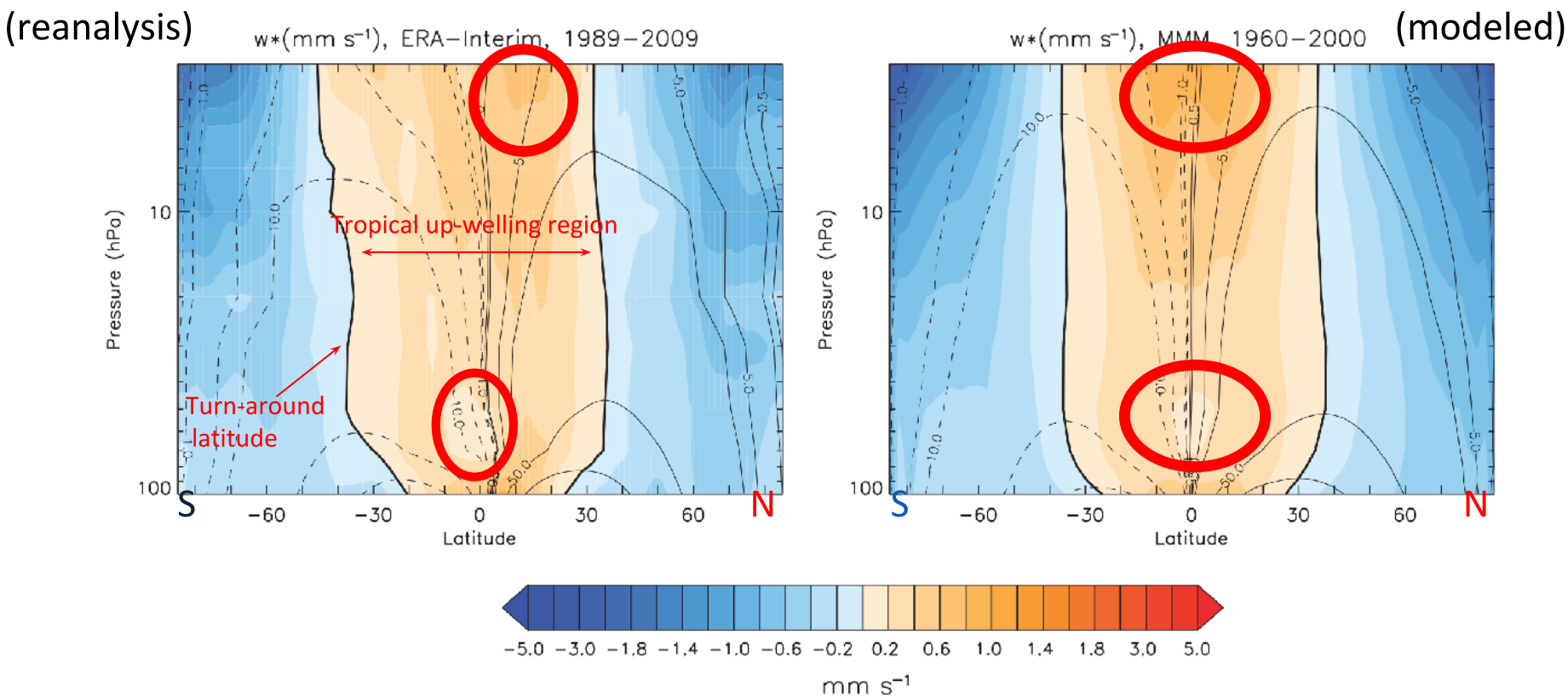


Figure 1. Annual mean residual vertical velocity, $\overline{w}^*$(mm s^{-1}), for ERA-Interim (1989–2009), and the CMIP5 models. Multi-model mean (MMM) values are shown, using historical simulations (1960–2000). The zero line is shown as a bold black contour. The stream function (kg m^{-1}s^{-1}) is shown in logarithmically spaced grey contours. Dashed contours represent negative values.

Mean historical BDC

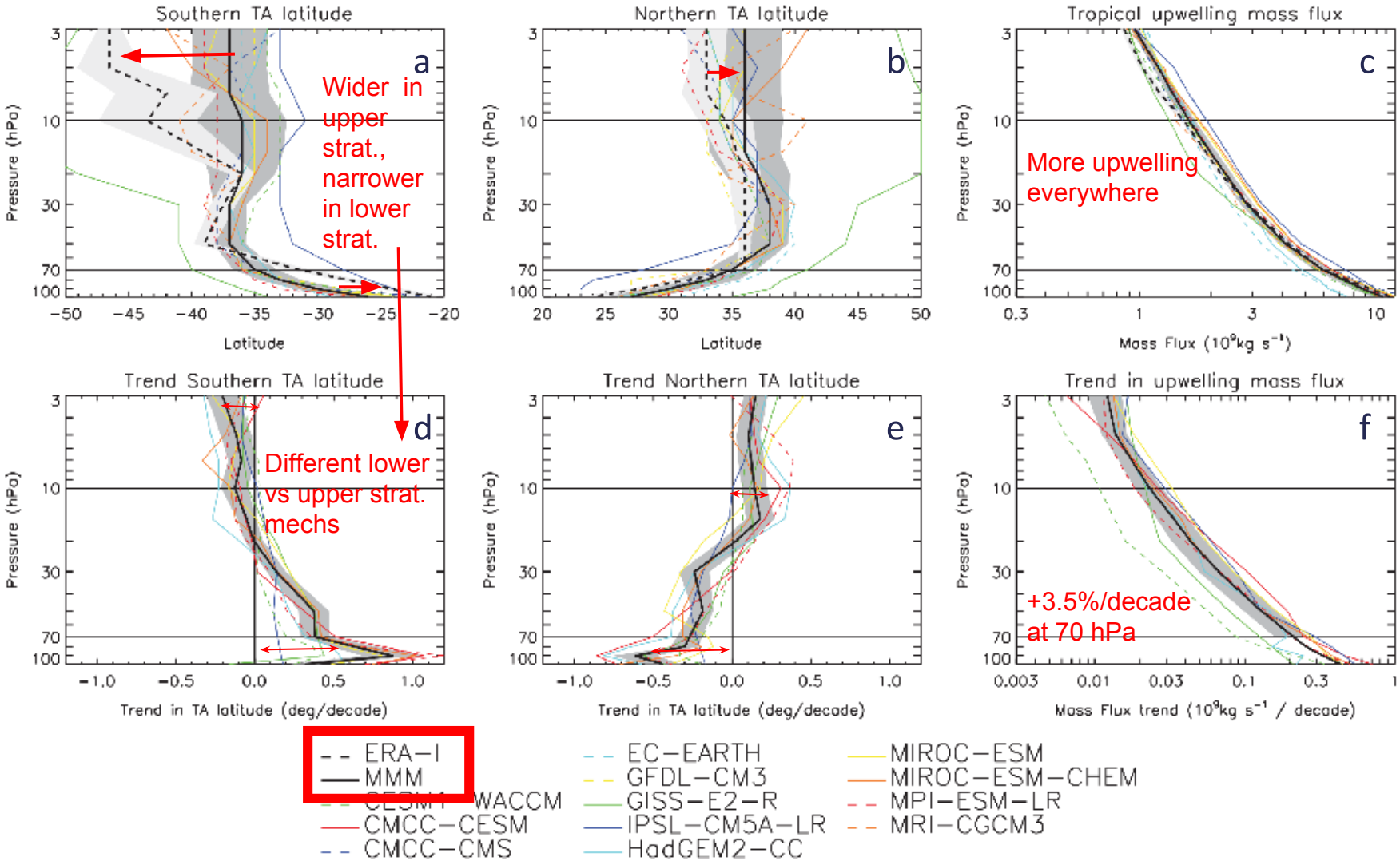


Figure 2. Upper panels: Turn-around latitudes calculated from annual mean $\overline{w}^*$(mm s^{-1}) climatologies for ERA-Interim (1989–2009) and models (1960–2000). Dashed black lines show the turn-around latitudes for ERA-Interim, with light grey shading showing the interannual standard deviation, scaled to represent a 95% confidence interval. Solid black lines show turn-around latitudes for the multi-model mean $\overline{w}^*$, with dark grey shading showing inter-model standard error, scaled to represent a 95% confidence interval. Individual model turn-around latitudes are shown by thin coloured lines, as specified in the key. Tropical upwelling is calculated for each year, as the mass upwelling between turn-around latitudes, and then averaged (1960–2000 for the models, and 1989–2009 for ERA-Interim). Lower panels: Trend in the turn-around latitudes and upwelling mass flux for the models, using a linear fit to years 2006–2099 from the RCP 8.5 scenario simulations, with dark grey shading showing inter-model standard error as above. Thin horizontal lines are shown at 70 and 10 hPa to aid comparison to previous studies. Note that, as discussed in detail by Hardiman *et al.* (2007), the turn-around latitudes of the mean $\overline{w}^*$, and their trends, are not equal to the mean of the individual model turn-around latitudes and their trends.

Upwelling Region Narrowing (Lower Strat.): Trends in Rossby Wave Patterns

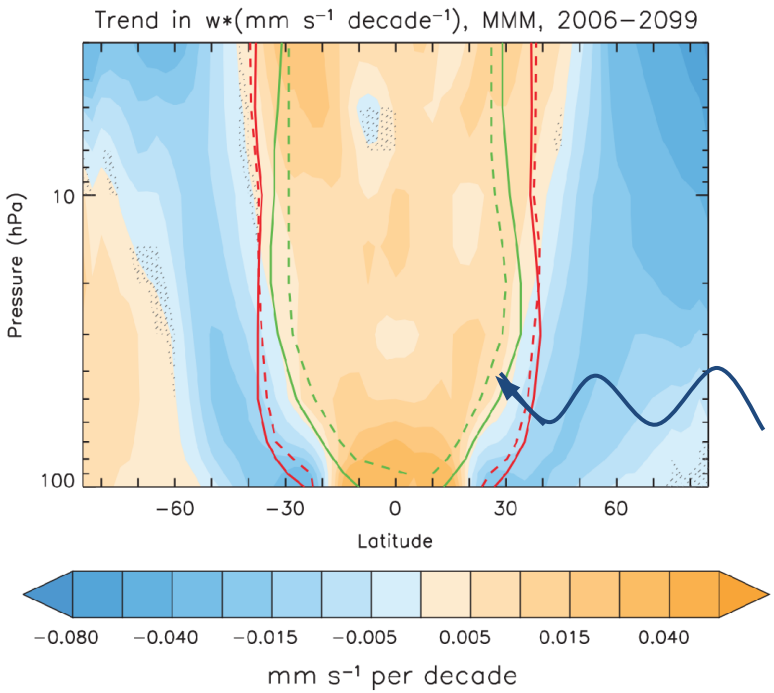
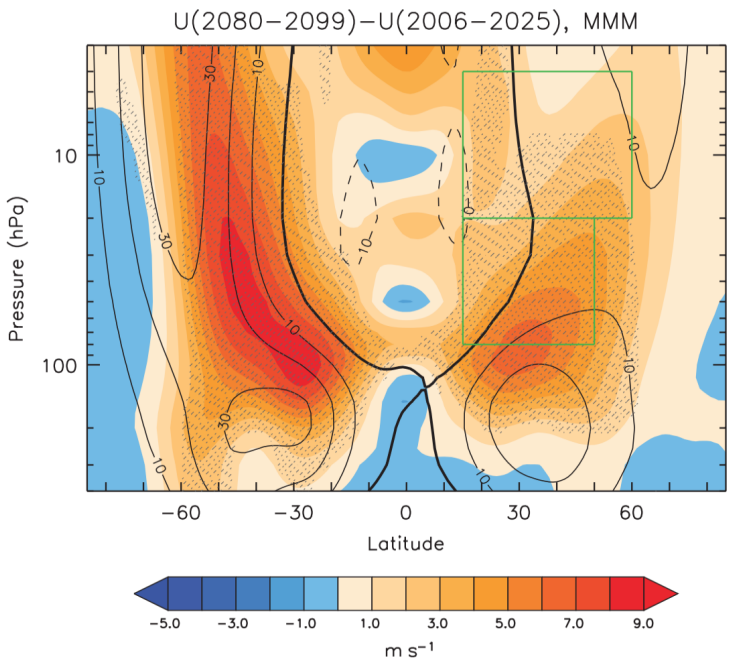


Figure 3. Contours show trend in $\overline{w}^*$(mm s^{-1}decade^{-1}) using a linear fit to years 2006–2099 from the RCP 8.5 scenario simulations. Red lines show the turn-around latitudes, with solid lines showing the mean position for the period 2006–2025, and dashed lines showing the mean position for the period 2080–2099. Green lines show the stationary wave critical lines, $\overline{u} = 0$, with solid lines showing positions where multi-annual mean $\overline{u}$(2006–2025) is zero, and dashed lines showing positions where multi-annual mean $\overline{u}$(2080–2099) is zero. Stippling shows regions where the trend is NOT significant at the 95% level.

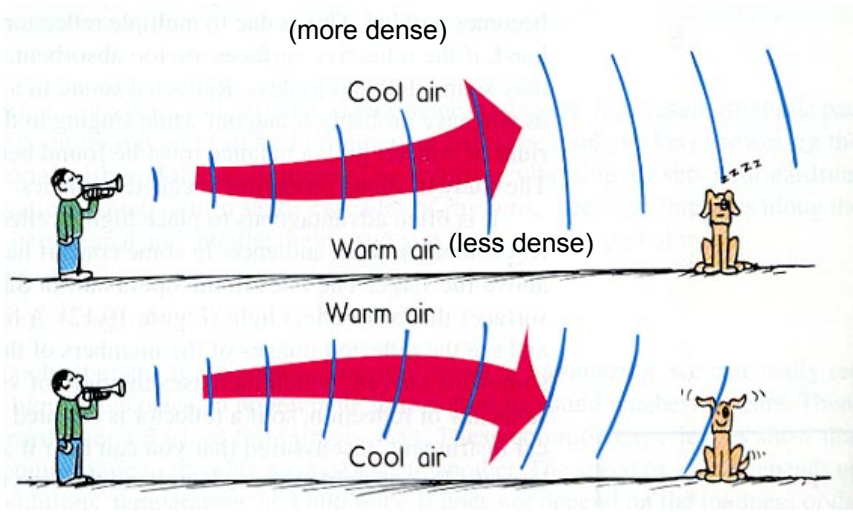
- Equator-ward movement of wave breaking location (green lines toward dashed)
  - Caused by jet stream changes
  - Allows waves (stationary Rossby waves) to propagate further into tropics (upwelling strengthened here)

Upwelling Region Widening (Upper Strat.): Trends in Rossby Wave Patterns



(This study doesn't show whether gravity waves are important --model limitations)

- <u>Weakened</u> equatorward refraction of planetary waves
  - Caused by jet stream changes (figure)
  - Waves cannot propagate as deeply into the tropics (upwelling not as strong here)



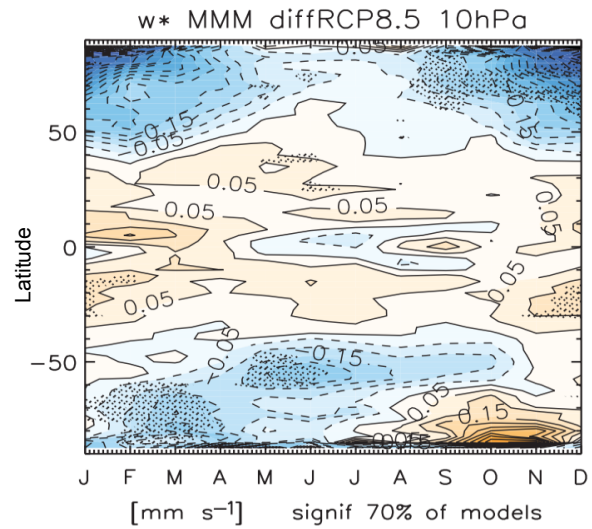
http://hendrix2.uoregon.edu/~imamura/102/images/refractionSound.jpg

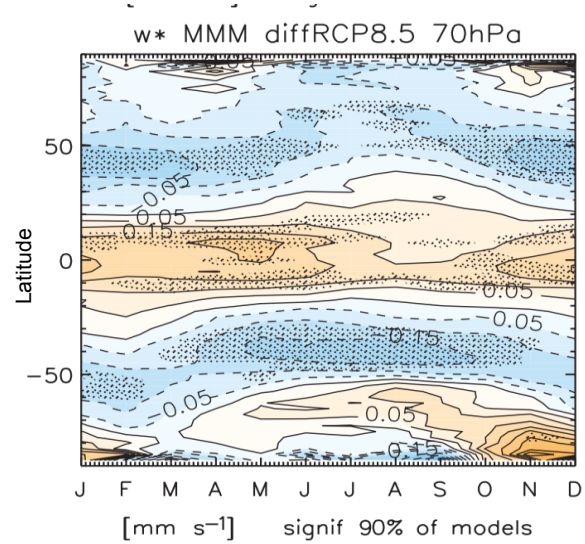
Downwelling Changes

More upwelling at the tropics means more downwelling at the extratropics ---which is observed (more of it in the winter).

- Lower stratosphere: increased downwelling is observed in the mid-latitudes (this means more strat.-to-trop. exchange of chemicals!)

- Upper stratosphere: increased downwelling is observed at the poles





Lin & Fu, 2013:

JOURNAL OF GEOPHYSICAL RESEARCH: ATMOSPHERES, VOL. 118, 73–84, doi:10.1029/2012JD018813, 2013

Changes in various branches of the Brewer–Dobson circulation from an ensemble of chemistry climate models

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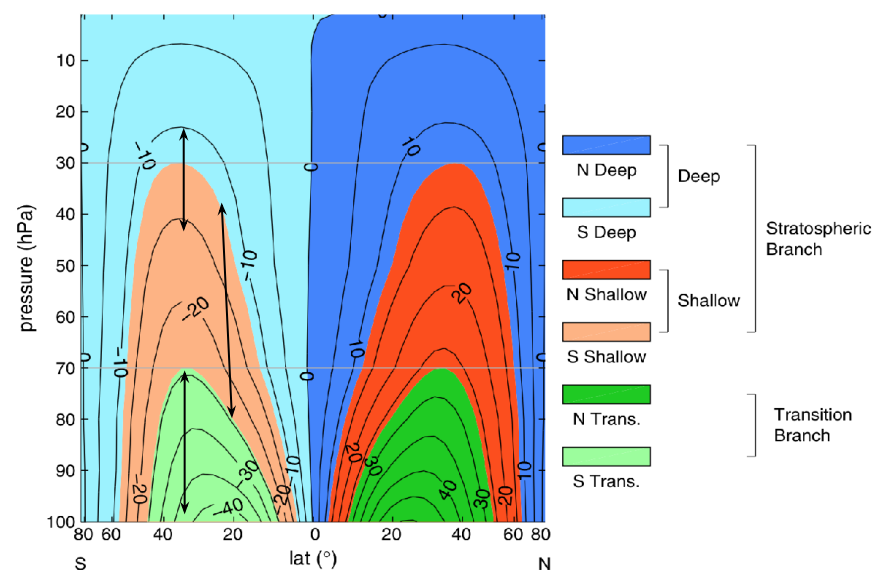
[1] We analyzed the changes of simulated Brewer–Dobson circulation (BDC) for 1960–2099 from 12 chemistry climate models participating the Chemistry-Climate Model Validation activity phase 2 (CCMVal-2). We decomposed the BDC into transition, shallow, and deep branches with vertical extent of 100–70, 70–30, and above 30 hPa, respectively. Models consistently simulate the acceleration in all three BDC branches over 140 years, but the acceleration rate of the deep branches is much smaller. The acceleration rate of the transition and shallow branches in general shows weak seasonal or hemispheric dependence and increases with time, consistent with the continuous and homogeneous increase of greenhouse gas concentrations. The trend magnitudes of shallow and transition branches differ from model to model, which are found to be associated with the simulated changes in subtropical jets and tropical upper tropospheric temperature. The acceleration of the deep branch is also a response to the increase of greenhouse gas concentrations but is modulated by the changes in ozone concentrations. The effect of ozone changes is particularly prominent in the southern deep branch during austral summer: almost all models simulated strong significant acceleration during the ozone depletion era, weak deceleration during the ozone recovery era

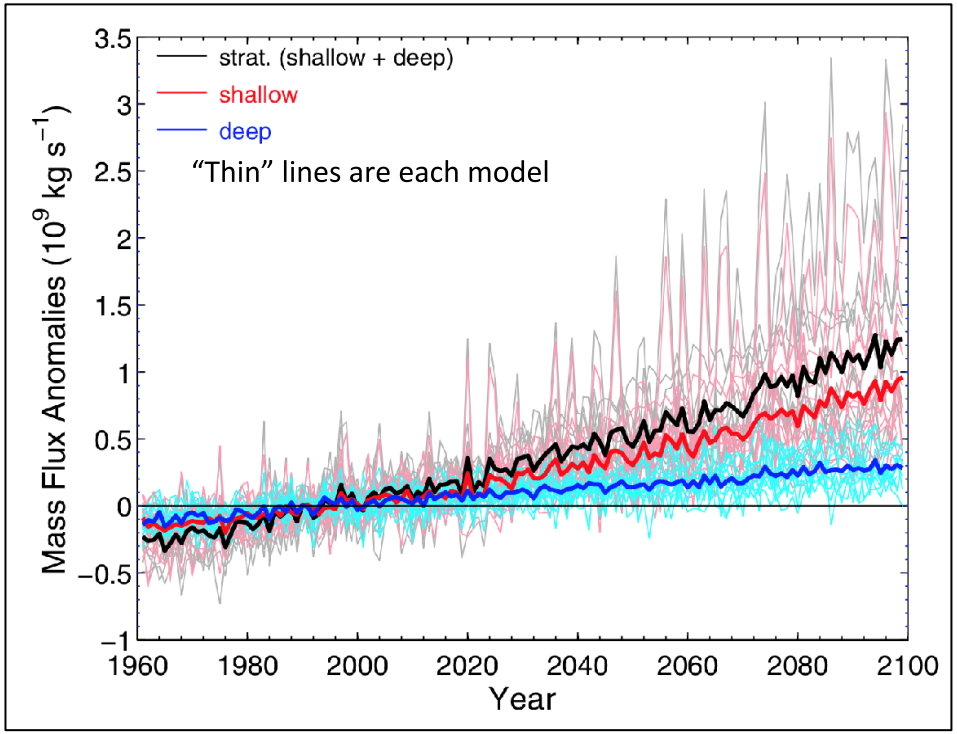
Question: What are the mean spatial and temporal structural changes in the BDC with time?

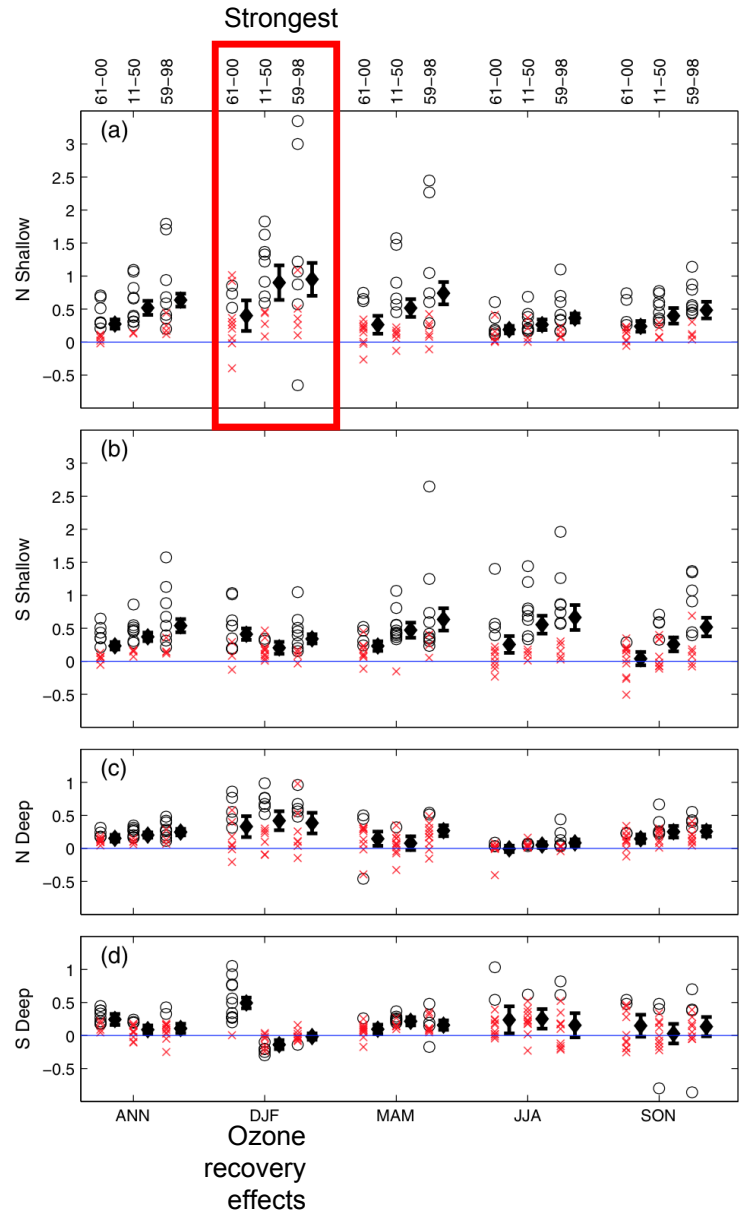
Methods:

- Time periods:
  - 1961-2009
  - CCMVal-2 2011-2050, 2059-2098
- Models: prescribed SSTs, sea ice, A1B (~RCP6)
- Diagnostic: “strength” of branch = (residual mass flux across layer)



Lin & Fu et al., 2013: Results





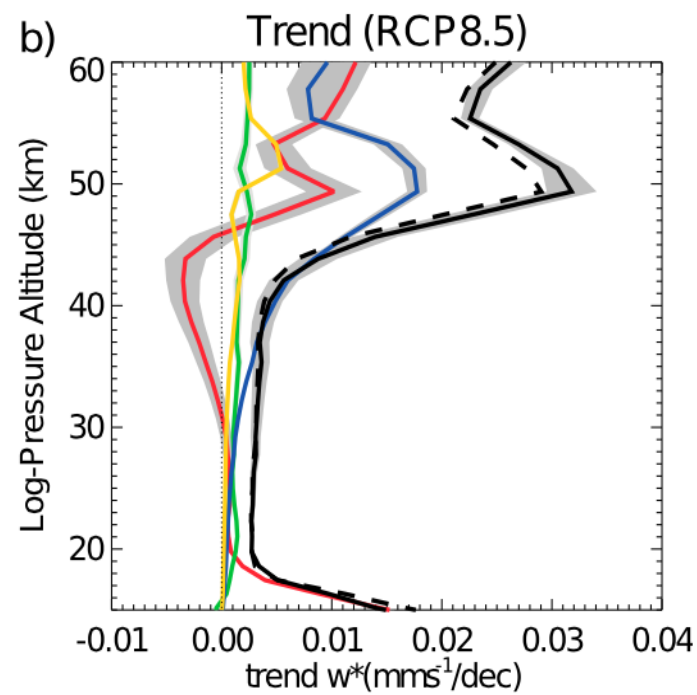
- Strongest at lower levels:
  - >30 hPa BDC +1.8% strengthening/decade 1960-2099
  - <30 hPa BDC + 3.0% strengthening/decade
- Winter, NH strongest change in BDC, absolute BDC strength (there's more landmass ---more eddies...)

Palmeiro *et al.*, 2014

Question: What effect do GWs have? (Maybe they're what's important?)

Answer:

- Past: Mainly non-gravity waves
- Future deep BDC: Non-gravity waves *and* frontal GWs, some convective GWs (only at the tropics)
- Future shallow BDC: Some orographic GWs



Methods:

- Time periods:
  - Historical (1960-2005)
  - RCP 2.6, 4.5, 8.5 Projections (2005-2100)
- Models: WACCM4 (ocean, land, sea ice)
- Diagnostic: TEM residual "upwelling" between the turnaround lat
  (individ. wave types)

How certain are we?

"In the upper atmosphere, a robust feature of projected stratosphere circulation change is that the [BDC] will *likely* strengthen in the 21st century…"
"The projected increase in troposphere-to-stratosphere mass exchange rate and stratospheric mixing associated with the strengthening of the [BDC] will *likely* result in a decrease in the mean age of air in the lower stratosphere."

----IPCC AR5 Ch. 12

Summary

What is the Brewer Dobson Circulation?

- Mean meridional overturning circulation in the stratosphere and mesosphere
- Wave-breaking forces northward drift of air parcels in the extratropics, and the up/down branches by mass continuity (*wave pump*, *downward control*)
- Upward/downward branches break radiative equilibrium → net radiative heat sources/sinks balance adiabatic cooling/warming

Changes in Stratospheric Circulation:

- We're still deciding what and where the branches of the BDC are
- BDC will strengthen, especially in the upper stratosphere, winter, Northern Hemisphere

- Caused by: Changes in wave-breaking by location, type, strength
  - Rossby waves -- planetary and synoptic important
  - Gravity waves *halfway* important
- This will likely cause:
  - Faster ozone hole recovery
  - More stratosphere-to-troposphere exchange:
    - Changes in O_3 in the troposphere (hydrocarbon oxidation)
    - More O_3 depletion at the mid-latitudes?

(End)

Changing BDC Papers: Methods

Lin & Fu:

- Time periods:
  - Historical (1961-2009) simulations
  - Historial ERA-Interim re-analyses (1961-2009)
  - Projections 2011-2050,2059-2098 (O_3 recovery and stable O_3, respectively) - CCMVal-2 (known over-est. polar vortex)
- Models: prescribed SSTs, sea ice, A1B (~RCP6)
- Diagnostic: "strength" of branch = (TEM residual mass flux across layer)

Hardiman

- Time periods:
  - Historical (1960-2000) CMIP5 simulations
  - Historial ERA-Interim re-analyses (1989-2009)
  - Projections (2006-2100) RCP 8.5 (extreme) simulation
- Models: "High-top" only, one member/model
- Diagnostic: Monthly mean residual vertical velocity

Palmeiro:

- "De-seasonalized" monthly means
- Time periods:
  - Three historical (1960-2005) simulations
  - RCP 2.6, 4.5, 8.5 Projections (2005-2100)
- Models: WACCM4 (atmosphere, ocean, land, sea ice models, 2.5 x 1.9 deg, 66 vert levels, up to 140 km)
- Diagnostic: TEM residual "upwelling" between the turnaround latitudes (individ. wave types)

Hardiman:

Palmeiro:

Transformed Eulerian Mean Residual-Mean Circulation:

$$\overline{v}^* \equiv \overline{v} - \frac{1}{\rho_0}\left(\frac{\rho_0 \overline{v'\theta'}}{\overline{\theta}_z}\right)_z,$$

$$\overline{w}^* \equiv \overline{w} + \frac{1}{a\cos\phi}\left(\frac{\cos\phi\,\overline{v'\theta'}}{\overline{\theta}_z}\right)_\phi.$$

Combining diabatic circ. (Murgatroyd & Singleton), mass continuity, eddy heat flux:

Parameterized wave drag (gravity waves)

Eliassen-Palm Flux Divergence

$$\langle \overline{w}^*(z)\rangle = \frac{\frac{1}{\rho(z)}\left|\int_z^\infty \{\rho a\cos^2\phi[(\rho a\cos\phi)^{-1}\nabla\cdot F(\phi,z') + X(\phi,z')]/\overline{m}_\phi\}\,dz'\right|_{\phi_1}^{\phi_2}}{|\sin\phi|_{\phi_1}^{\phi_2}},$$

Zonal mean angular momentum

Evaluate at turn-around latitudes

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TUNGSTEN-185 FROM NUCLEAR BOMB TESTS AS A TRACER FOR STRATOSPHERIC METEOROLOGY

By Dr. HERBERT W. FEELY and Prof. JEROME SPAR*
Isotopes, Inc., Westwood, New Jersey

A Radio-Active Fall-Out Study at Melbourne, Australia

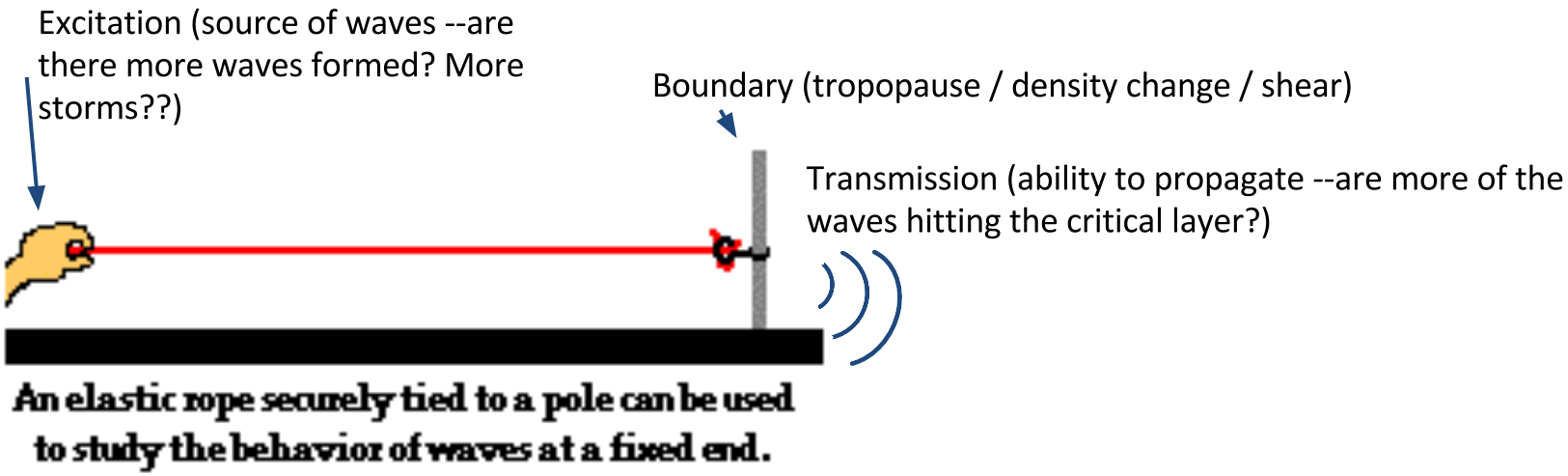
By A. J. DYER and MISS S-A. YEO
Division of Meteorological Physics, Commonwealth Scientific & Industrial Research Organisation, Melbourne, Australia.

(Manuscript received August 31, 1959)

- M

http://www.atmosp.physics.utoronto.ca/SPARC/News15/15_Norton.html

Wave excitation versus transmission (big picture: what's changing about the easterly momentum flux?)



General findings of papers (Butchart et al., 2006):

Calvo & Garcia, 2009:

- Past: transmission of waves
- Future: excitation of waves caused by convective activity changes

Olsen et al., 2007:

- Future: propagation of waves by warmer SSTs

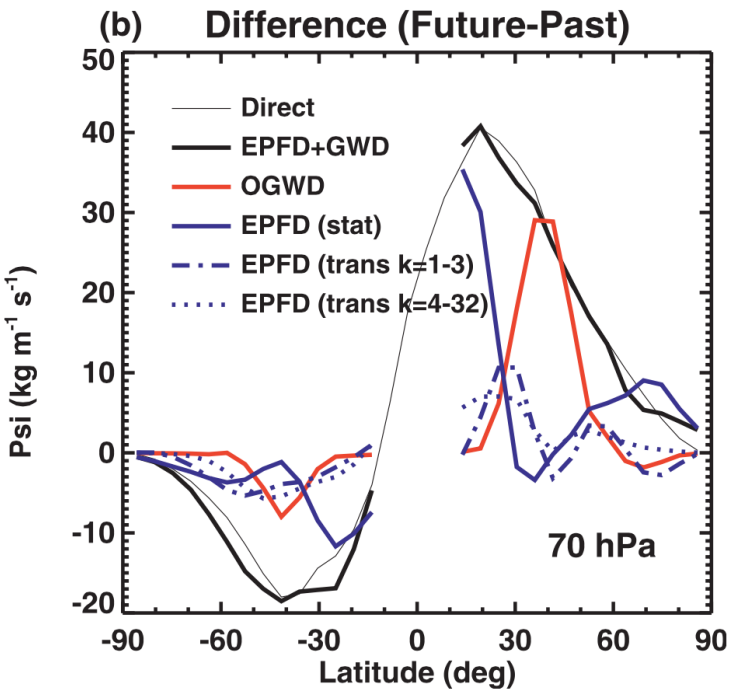
Deckert & Dameris, 2008; Garny et al., 2011:

- Future: excitation and propagation poleward of waves caused by convection enhanced by SSTs

Shepherd & McLandress, 2011:

- Future: effects of changes in wave patterns determined by the location of the subtropical lower stratospheric boundaries ("critical layers")

Shepherd & McLandress,2011:



Question: Which wave types are important?

Answer: Planetary and synoptic scale Rossby waves important --strengthening, upward movement of ST jet pushes critical layer up and allows more waves to penetrate ST lower strat.

Methods:

- Time periods:
  - Historical 1960-1979
  - Projections 2080-2099
- Models: CCMVal-1
- Diagnostic: Eliassen-Palm Flux Divergence (wave contributions to eddy momentum flux)

Hadley et al., 2014

The morphology of the Brewer–Dobson circulation and its response to climate change in CMIP5 simulations

- Tropical uplift region:
- Increase in strength
- Narrowing below 20 mbar
  - equatorward shift in the stationary wave critical line allows waves to propagate further into the Tropics
- Widening above 20 mbar
  - increase in the extratropical zonal mean westerly jet leads to a reduced equatorward refraction of planetary waves
- Different structure in winter downwelling