FDEPS 2012, Research Seminar

Strengthening of the Brewer-Dobson circulation under climate change

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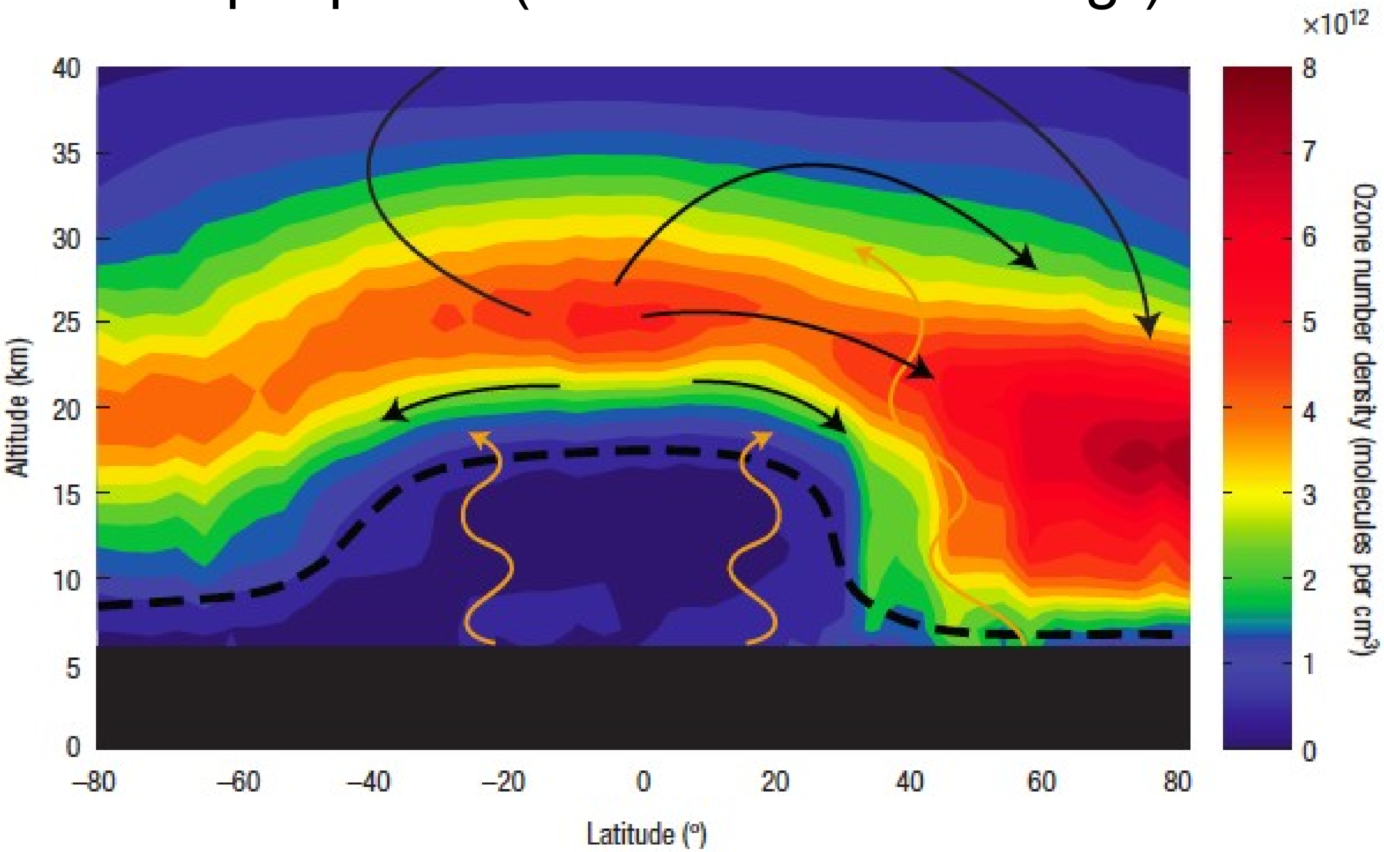
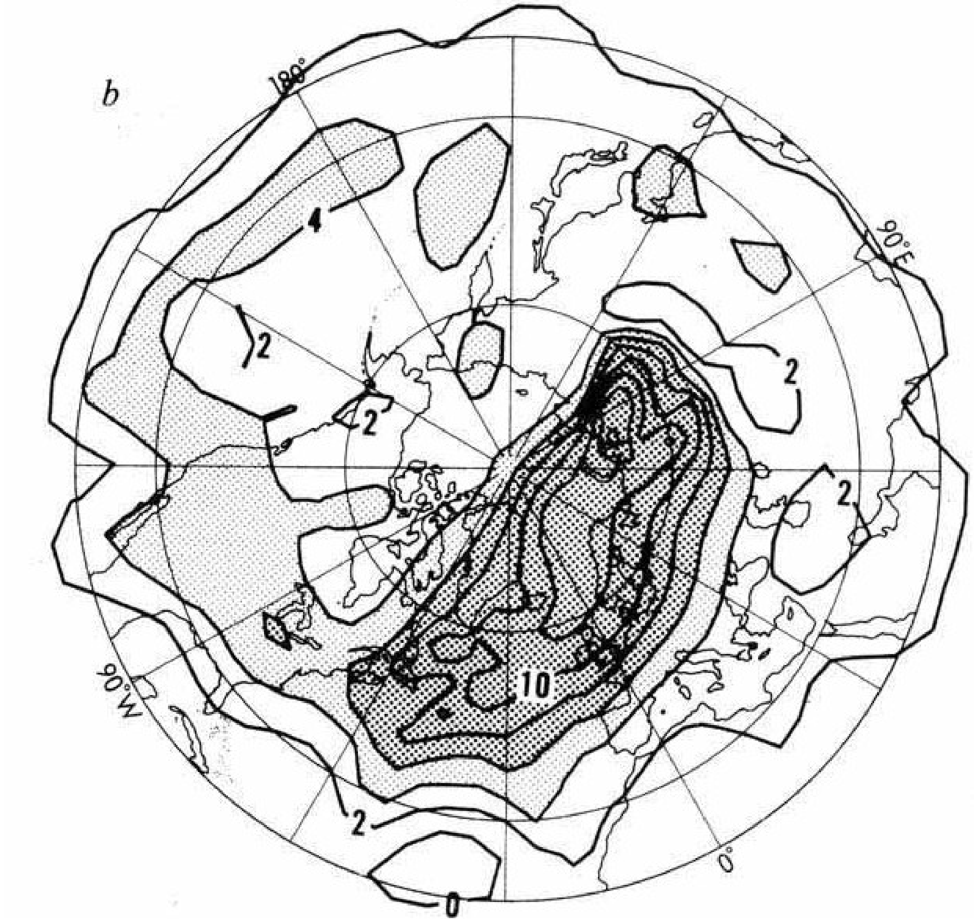
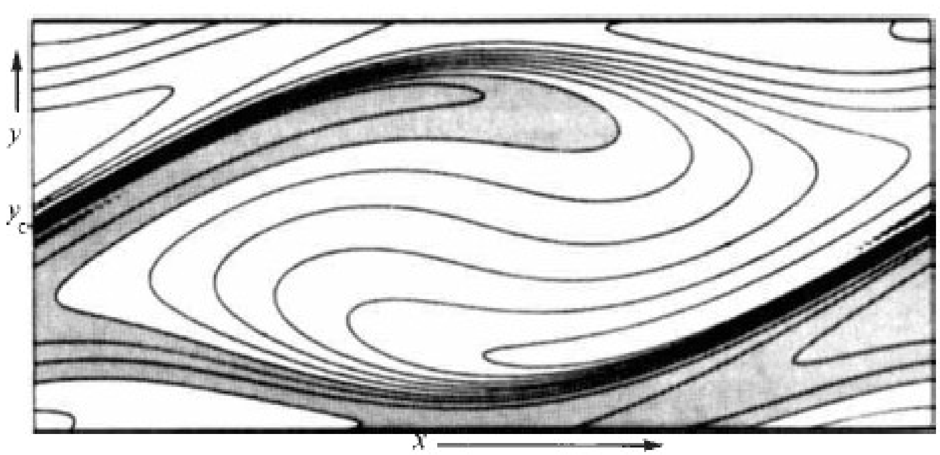
- The Brewer-Dobson circulation (BDC) controls the distribution of chemical species within the stratosphere
  - The circulation is mechanically driven (a refrigerator) by torques exerted by waves propagating up from the troposphere (so-called "wave drag")



March 2004 ozone from OSIRIS

Shaw & Shepherd (2008 Nature Geosci.)



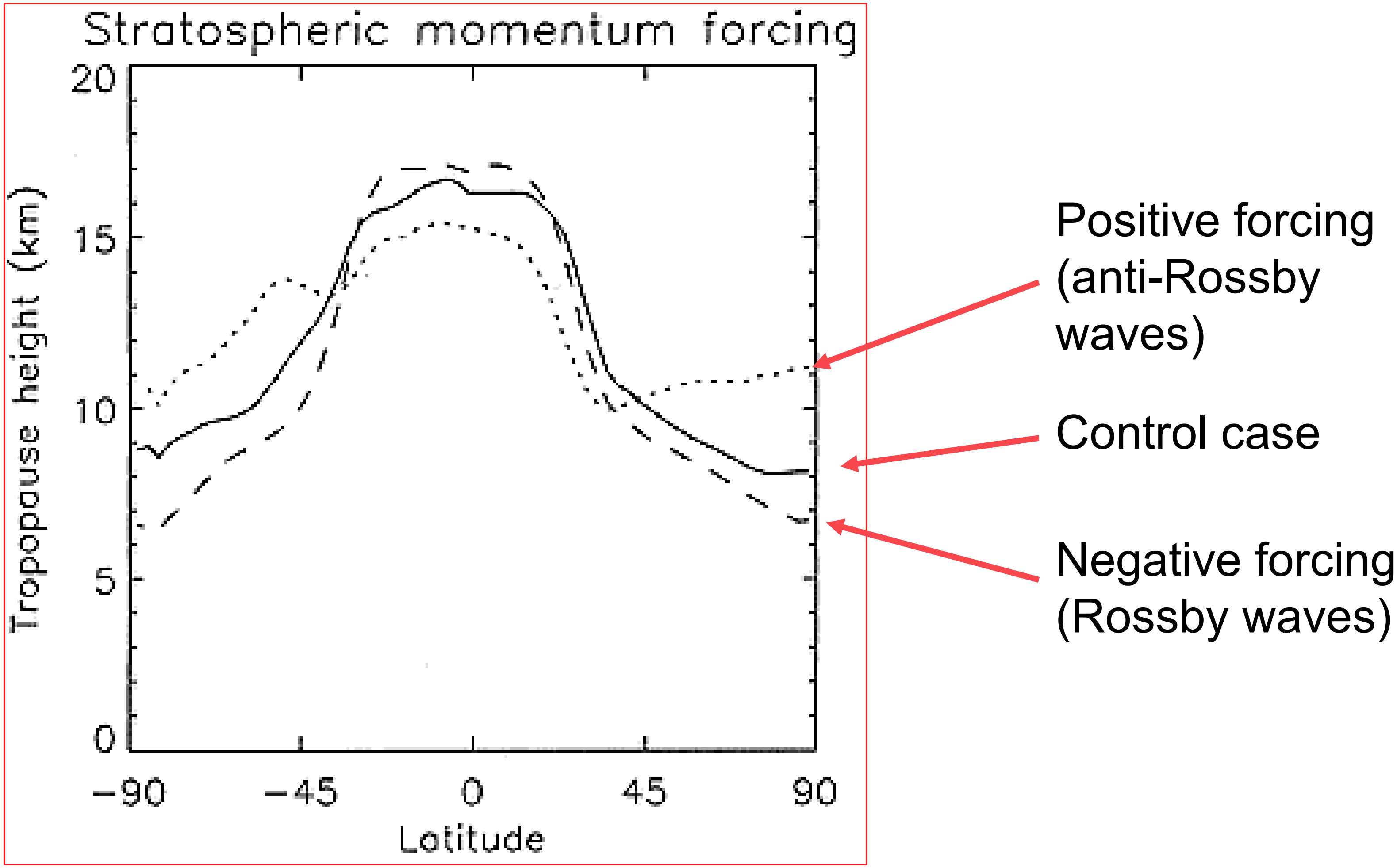


- The Rossby wave drag comes from breaking of upward propagating waves, seen dramatically in the stratospheric “surf zone” (top panel, PV on 850 K isentropic surface, approx. 30 km altitude)
- This behaviour was argued to be that of a nonlinear critical layer (bottom panel)

Critical layers occur where the wave phase speed equals the flow speed

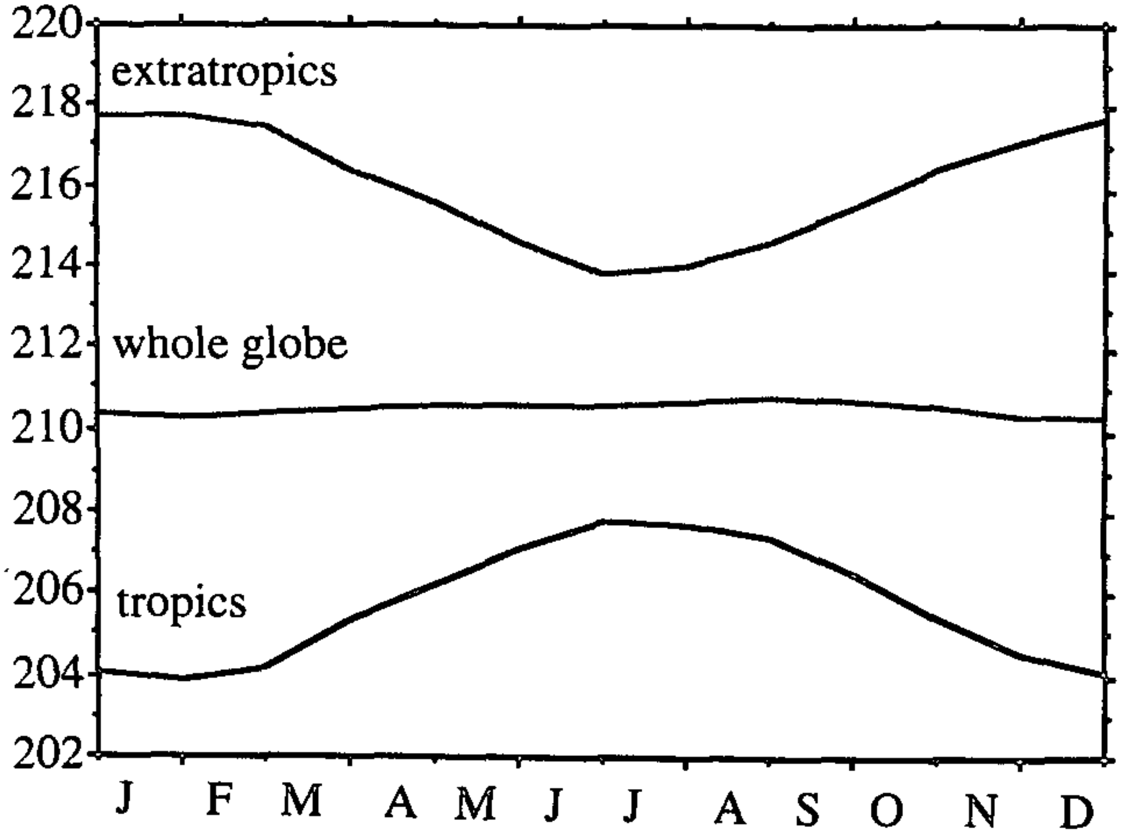
McIntyre & Palmer (1983 Nature)

- The BDC raises and cools the tropical tropopause, and lowers and warms the extratropical tropopause



GCM calculations by Thuburn & Craig (2000 JAS)

- The seasonal variation in the BDC leads to a seasonal variation in lower stratospheric temperature
  - Tropical temperatures are lowest in boreal winter, when the tropical upwelling is the strongest

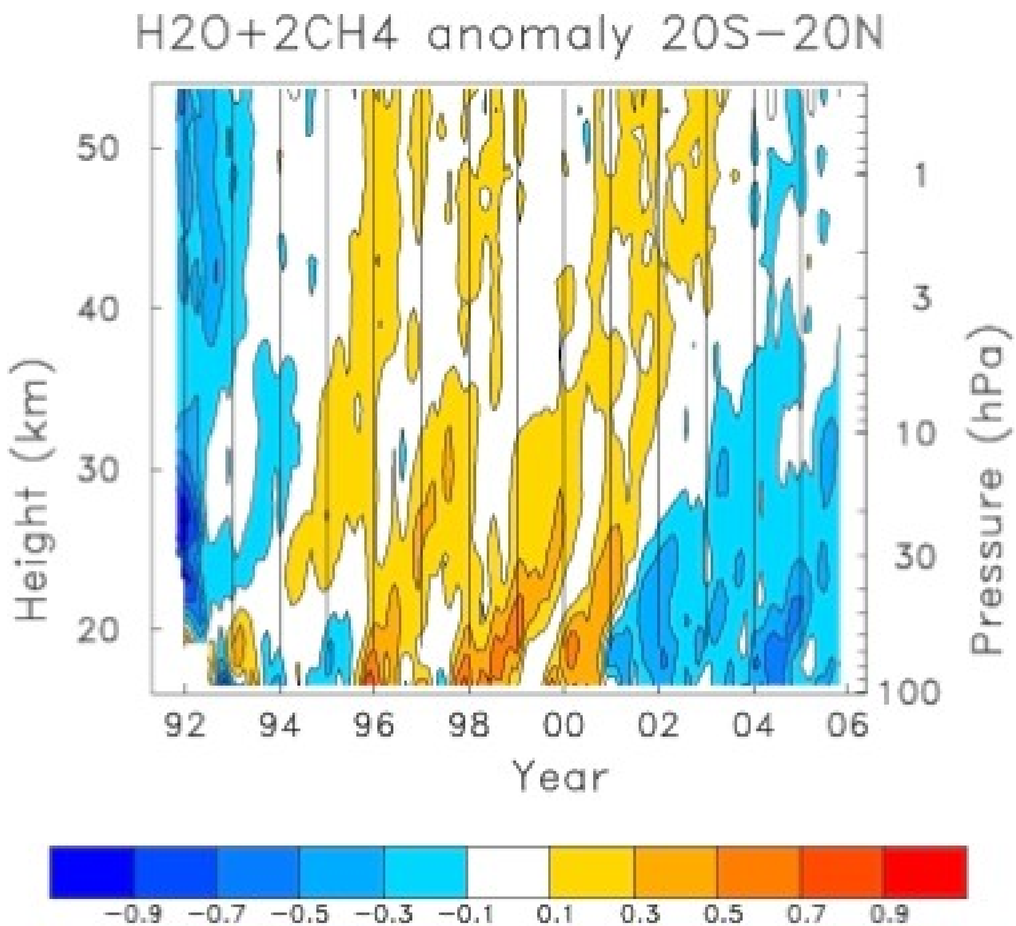


Yulaeva, Holton & Wallace (1994 JAS)

MSU Channel 4 temperature (approx 100 hPa, ~ 17 km)

Compensation between tropics and extratropics suggests the influence of the BDC

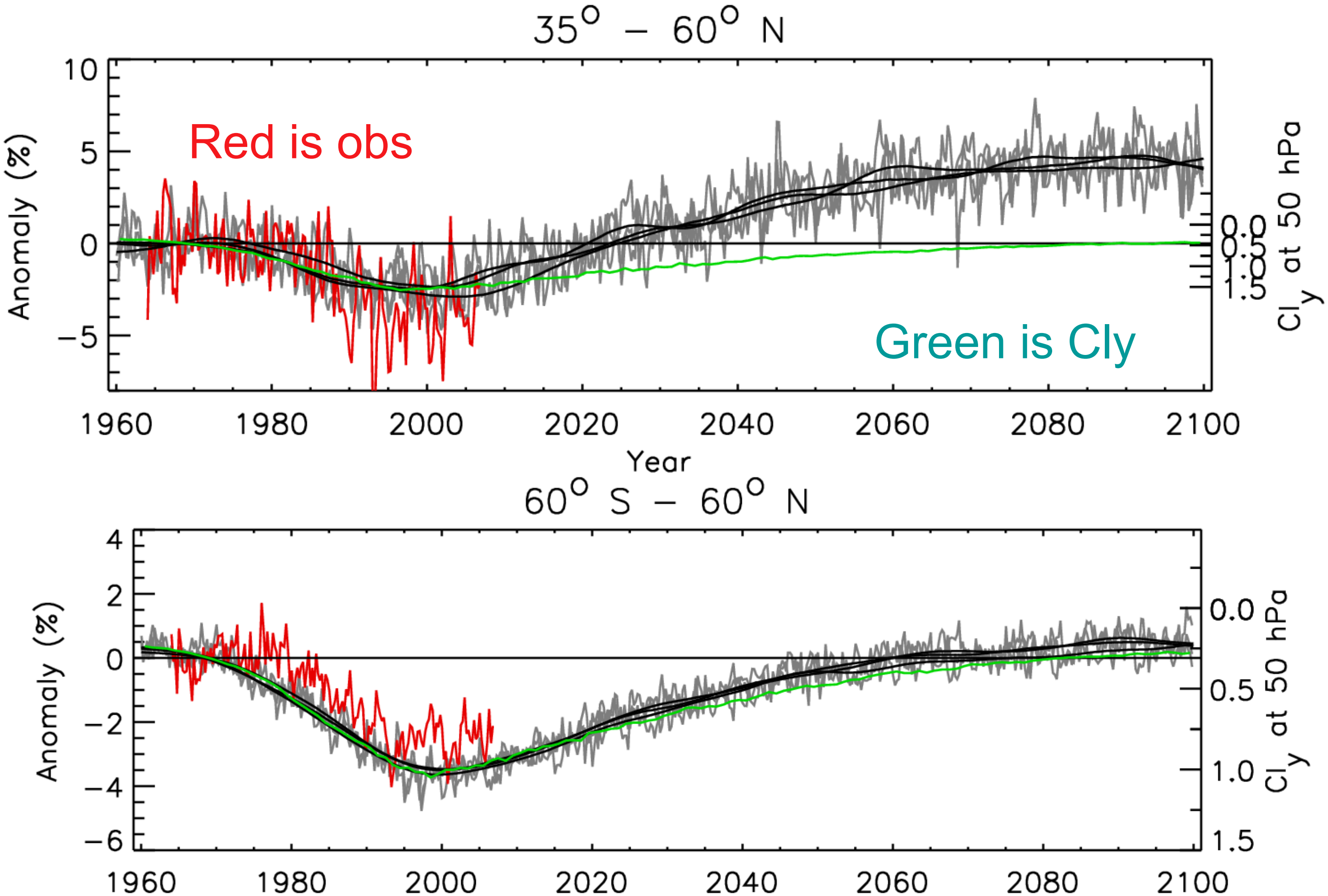
- This causes a seasonal cycle in dehydration which is imprinted on the water vapour entering the stratosphere: the “tropical tape recorder” (Mote et al. 1996 JGR)
- Tropical tropopause temperature also controls stratospheric water vapour on interannual timescales



Interannual anomalies in the “tropical tape recorder” as seen in HALOE measurements from the UARS satellite

Updated from Randel et al. (2004 JAS)

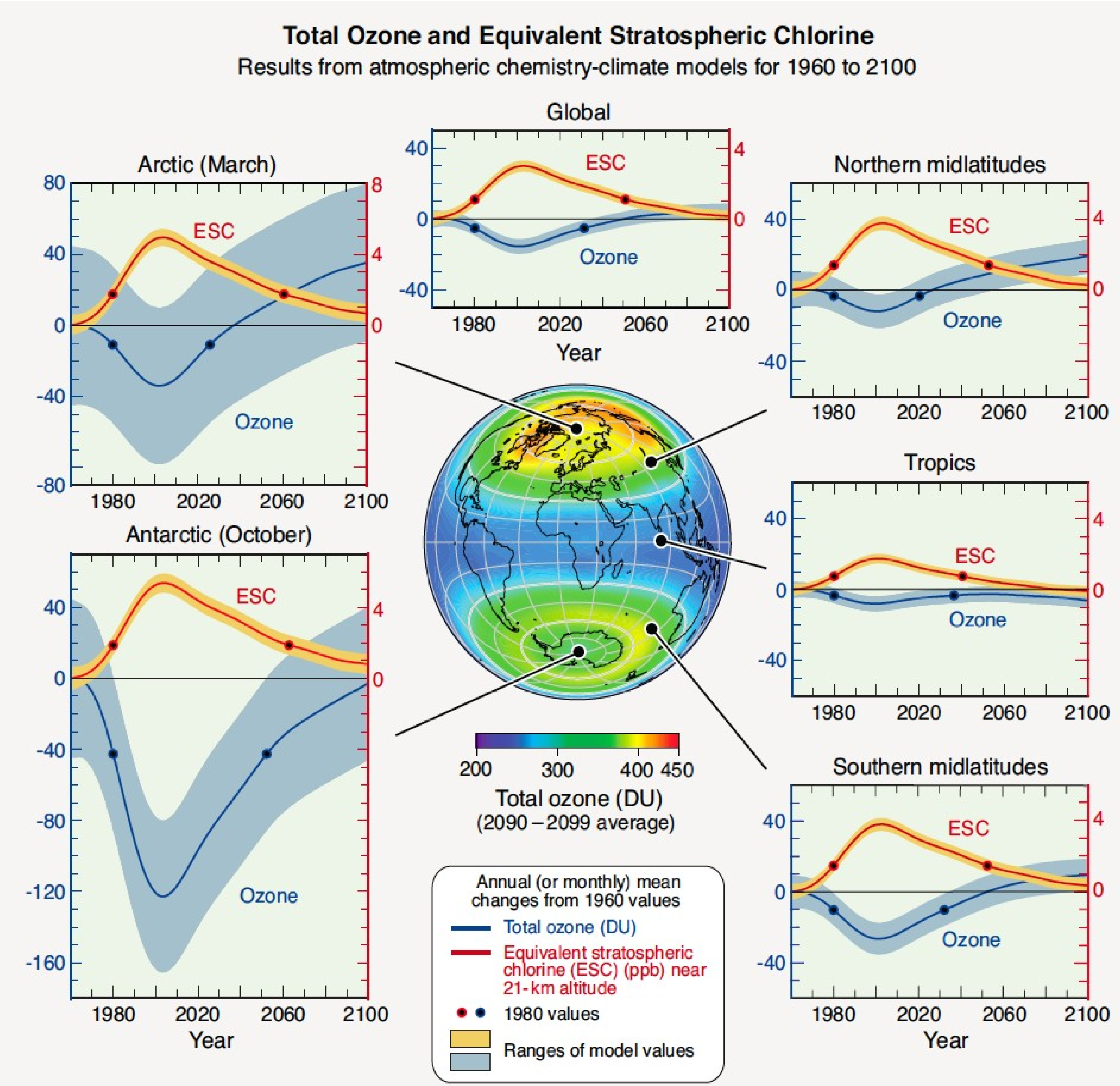
- Climate models consistently predict a strengthened Brewer-Dobson circulation in response to climate change



Would increase ozone in NH midlat's

There is a compen-sating decrease in the tropics

CMAM simulations from Shepherd (2008 Atmos-Ocean)



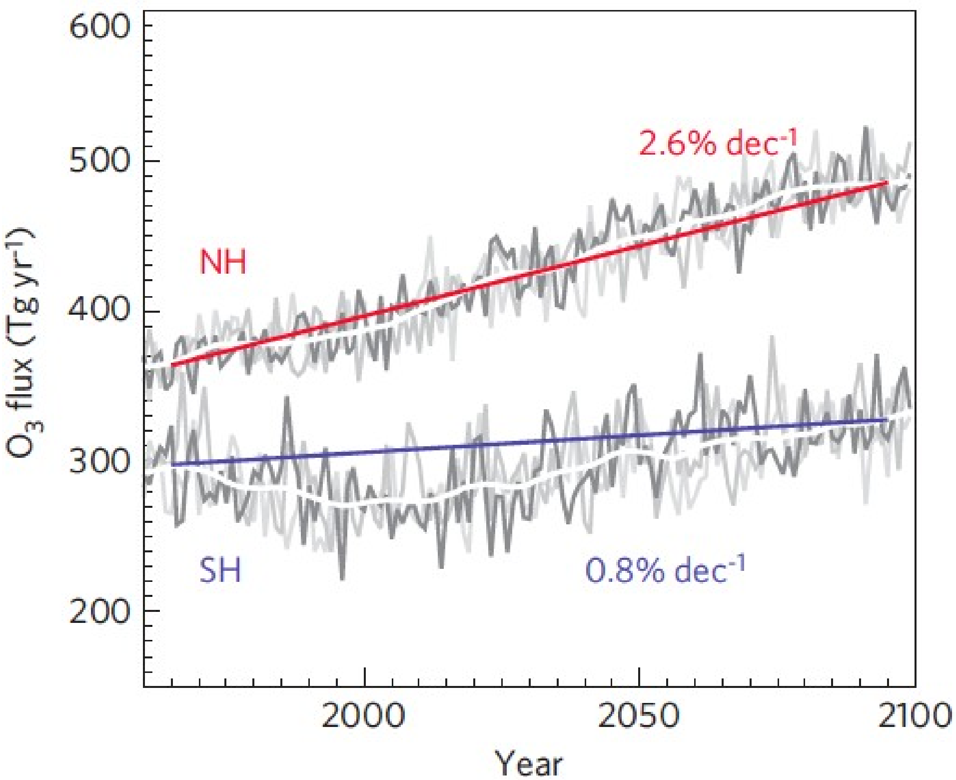
Fahey and Hegglin (2011)

- The extent to which the future evolution of ozone will follow the decline in ESC varies considerably between regions
- Shaded areas show multi-model ensemble, including natural variability, based on SPARC CCMVal-2 simulations

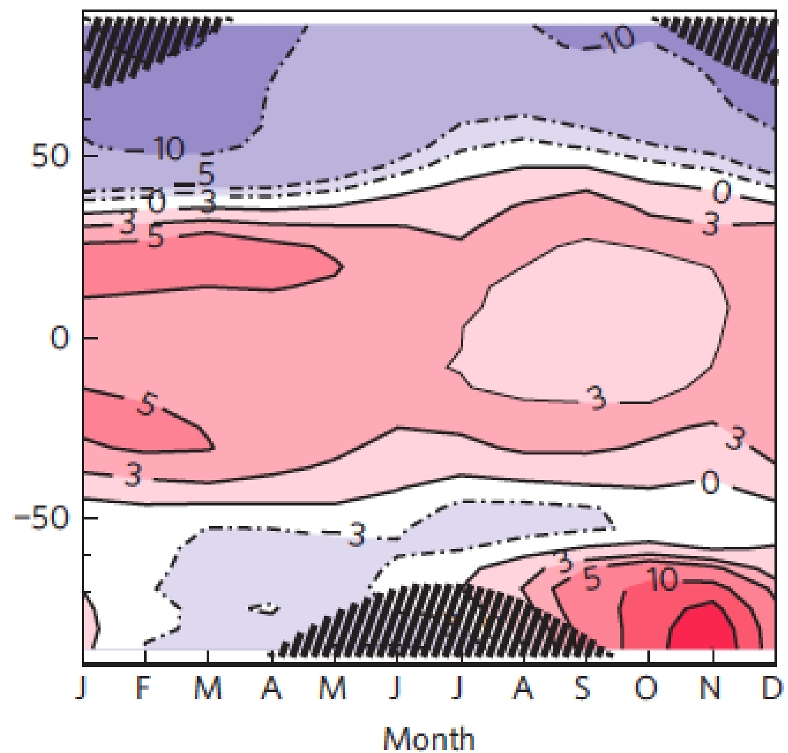
WMO 20 Q&A (2011)

- This has implications for the flux of stratospheric ozone into the troposphere, and clear-sky UV radiation
  - Over the extratropical NH the decrease in clear-sky UV radiation would have adverse health implications

STE ozone flux

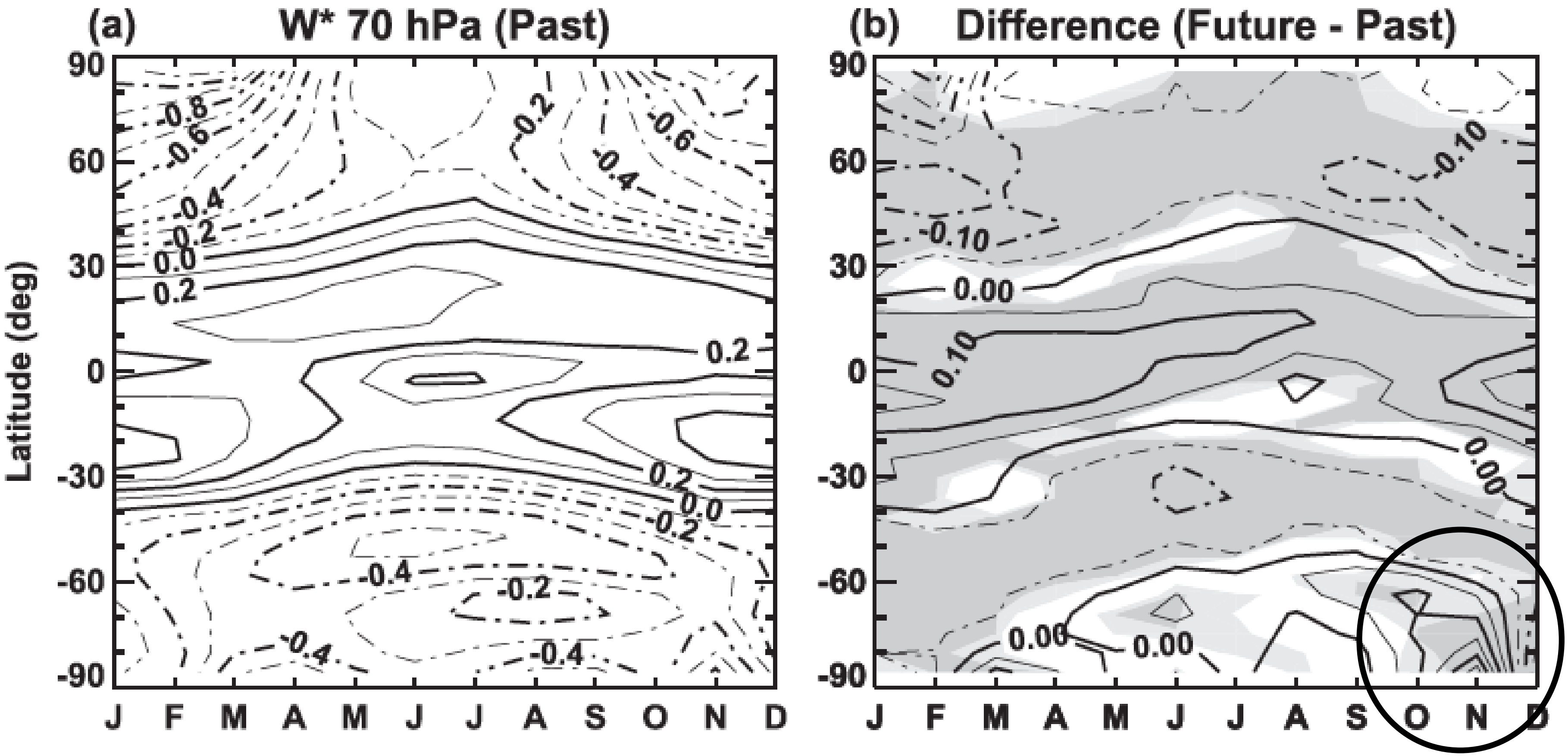


Change in clear-sky UV index between 1960s and 2090s



CMAM results from Hegglin & Shepherd (2009 Nature Geosci.)

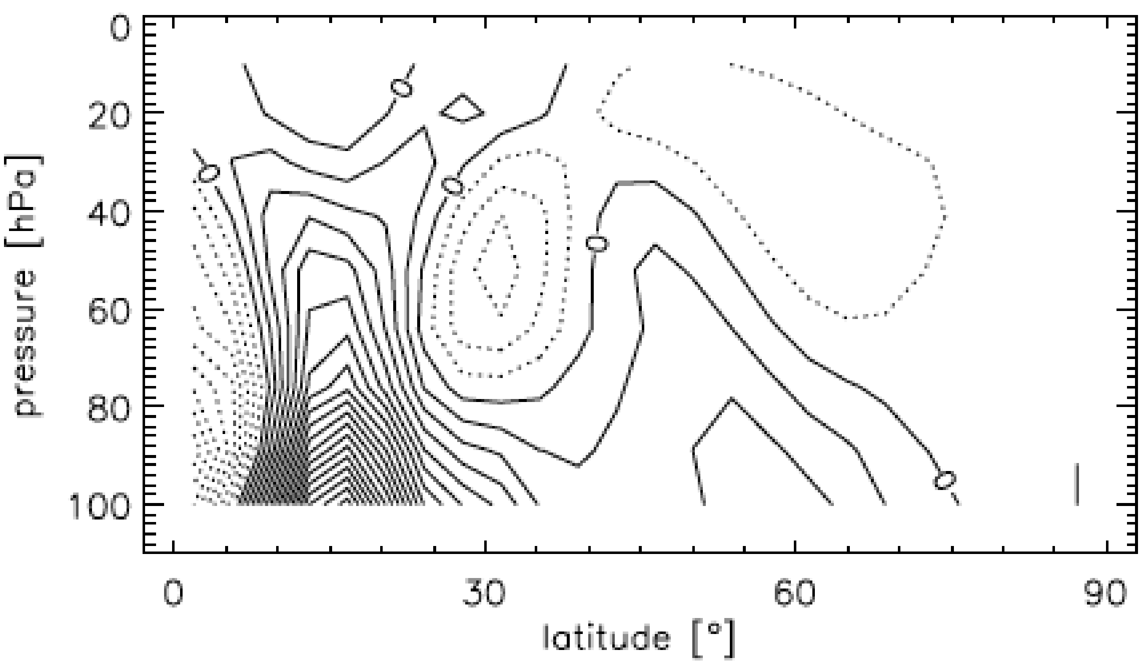
- The strengthened tropical upwelling does not necessarily imply strengthened polar downwelling
  - Here the focus is on the net mass overturning at 70 hPa, which is dominated by the extrapolar circulation



McLandress & Shepherd (2009 J. Clim.)

- In principle, there are three ways to change the BDC:
  - Change the amount of wave forcing generated within the troposphere
    - No GCM study has identified such an effect, and several have explicitly found no detectable change
  - Change the penetration of wave propagation into the stratosphere
    - First suggested by Rind et al. (1990 JAS), and confirmed by many subsequent GCM studies
  - Change the latitudinal distribution of wave drag within the stratosphere (Shepherd & Shaw 2004 JAS)
    - Not really investigated

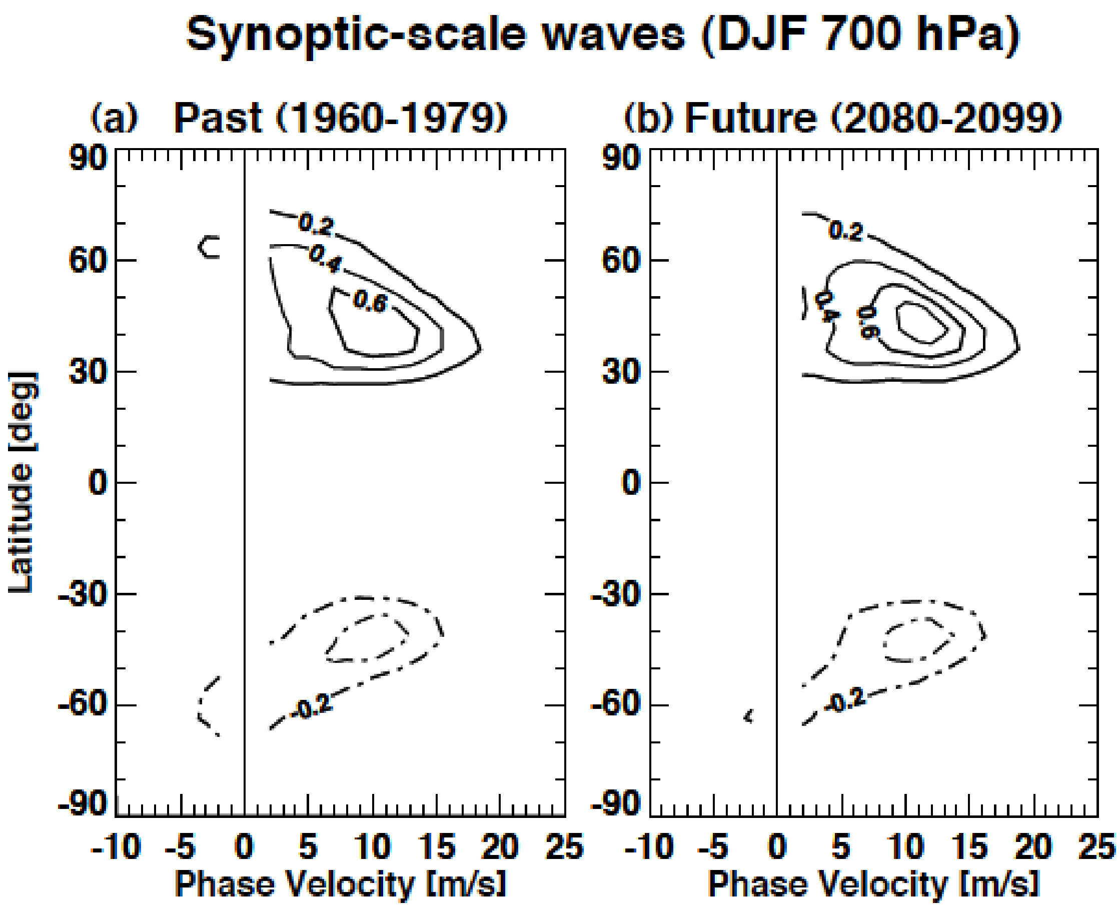
- Several modelling studies have proposed increased upwelling driven by drag from convectively forced quasi-stationary equatorial waves (in a warming climate) as the origin of the strengthened BDC, but this upwelling is necessarily confined within the tropics
  - Also it peaks in northern summer, not winter



Modelled change in TEM streamfunction for July-August

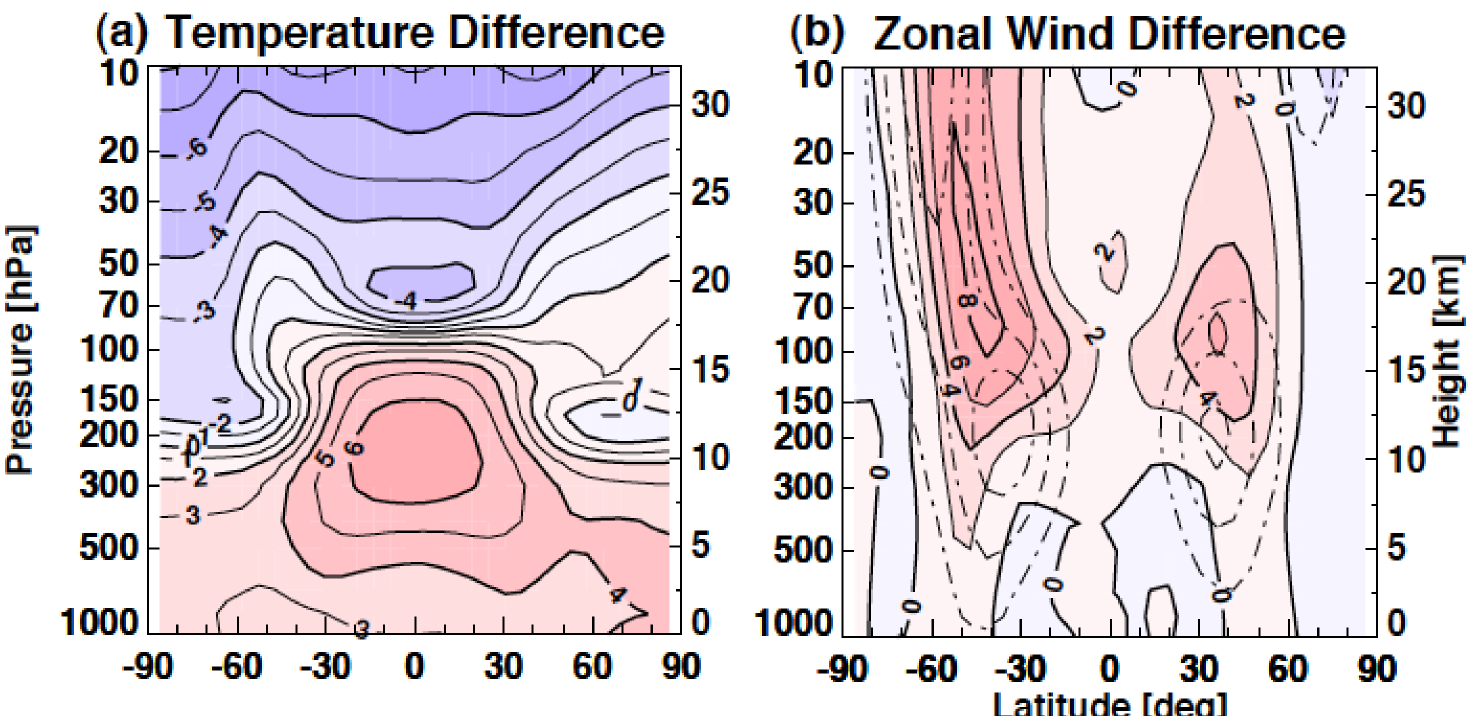
Deckert & Dameris (2008 GRL)

- Using a highly idealized model, Eichelberger & Hartmann (2005) had found strengthened synoptic-scale wave forcing from climate change due to increased baroclinicity
  - There is no evidence for this in CMAM



Shepherd & McLandress (2011 JAS)

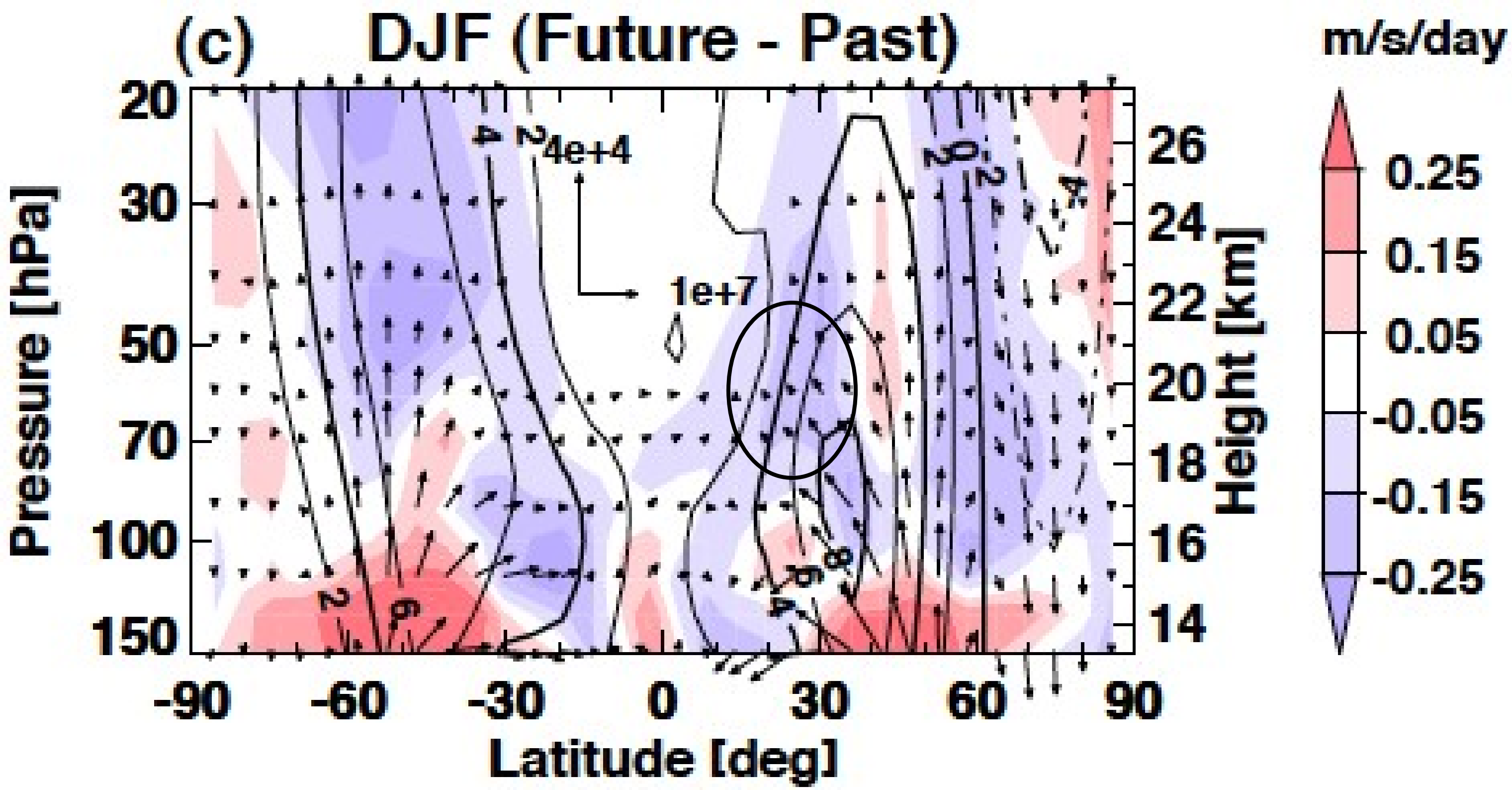
- Since the first BDC study (Rind et al. 1990 JAS), attention has focused on the strengthened subtropical jets that are a robust outcome of tropospheric warming
  - Several studies have shown that BDC changes result from tropospheric warming, not stratospheric cooling
    - Some authors argue for effect of SST changes, but this is the same as tropospheric warming!



Shepherd & McLandress (2011 JAS)

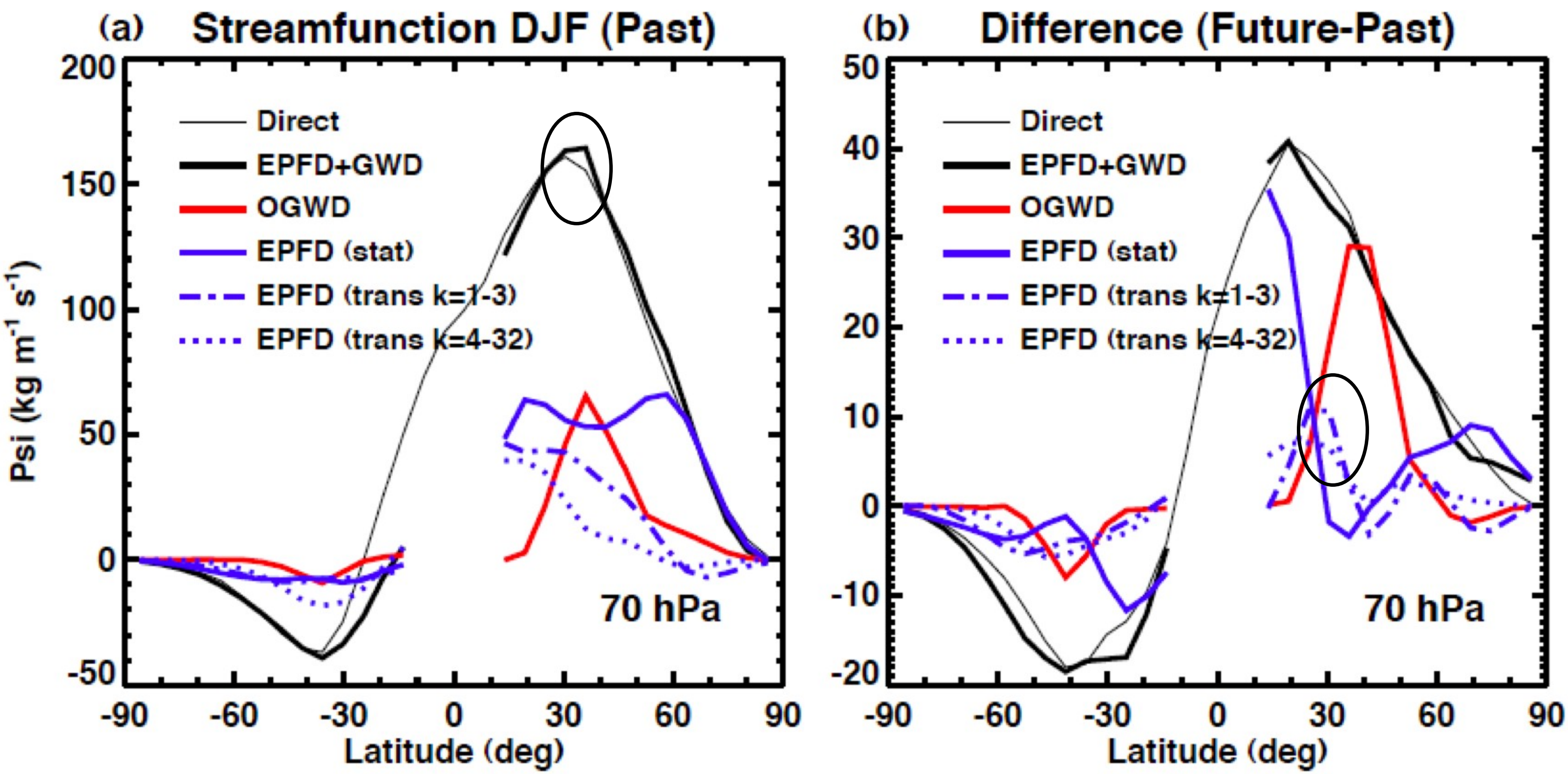
- The strengthened resolved wave drag results from increased penetration of Rossby waves into the subtropical lower stratosphere (the critical region for driving of the BDC) — as pointed out by many authors
  - But what is the mechanism?

Changes in transient EP flux, EPFD, and zonal wind



Shepherd & McLandress (2011 JAS)

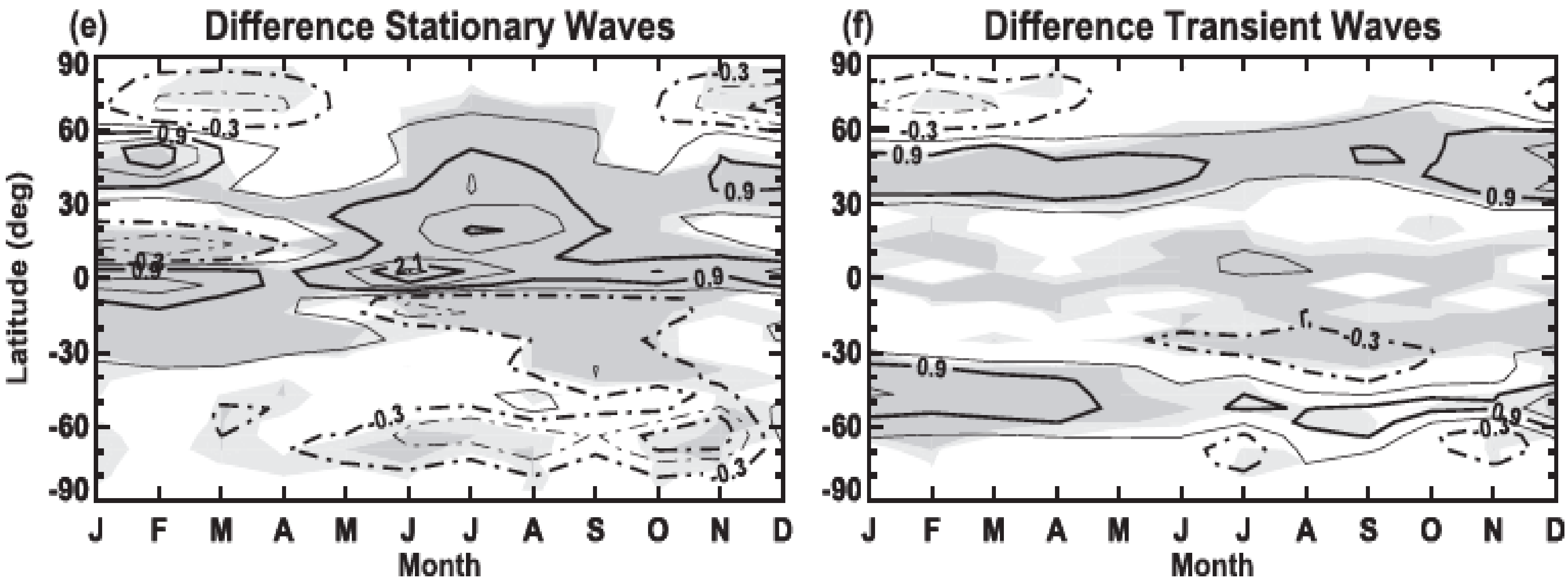
- The key region for driving of the BDC is the *subtropics*
- In CMAM the strengthened BDC results from a roughly equal combination of transient planetary, transient synoptic, and parameterized orographic gravity waves



Shepherd & McLandress (2011 JAS)

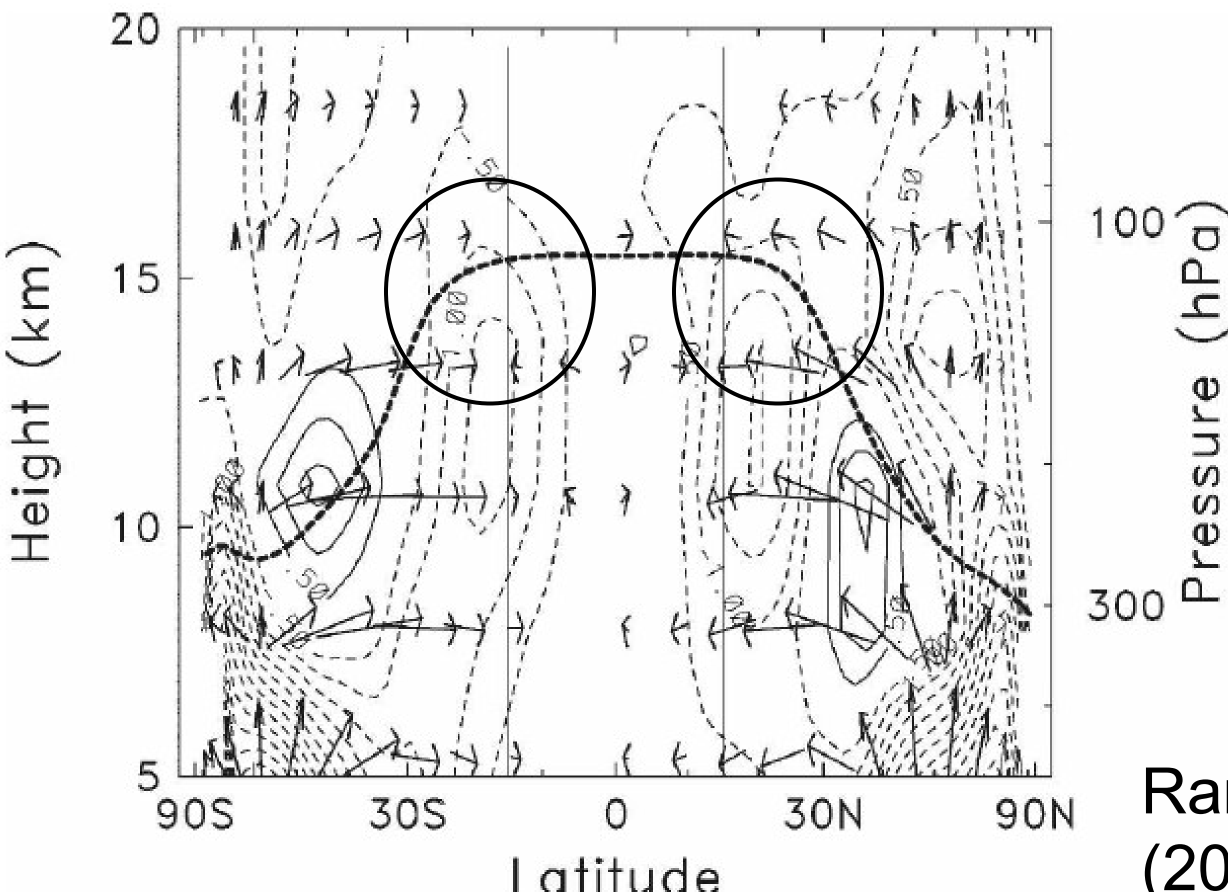
- Transient waves are not often discussed in the context of the BDC, but their drag is strategically located close to the turnaround latitudes
- In CMAM, the stationary wave changes are largely confined to the tropics and higher latitudes

Changes in vertical EP flux at 100 hPa



McLandress & Shepherd (2009 J. Clim.)

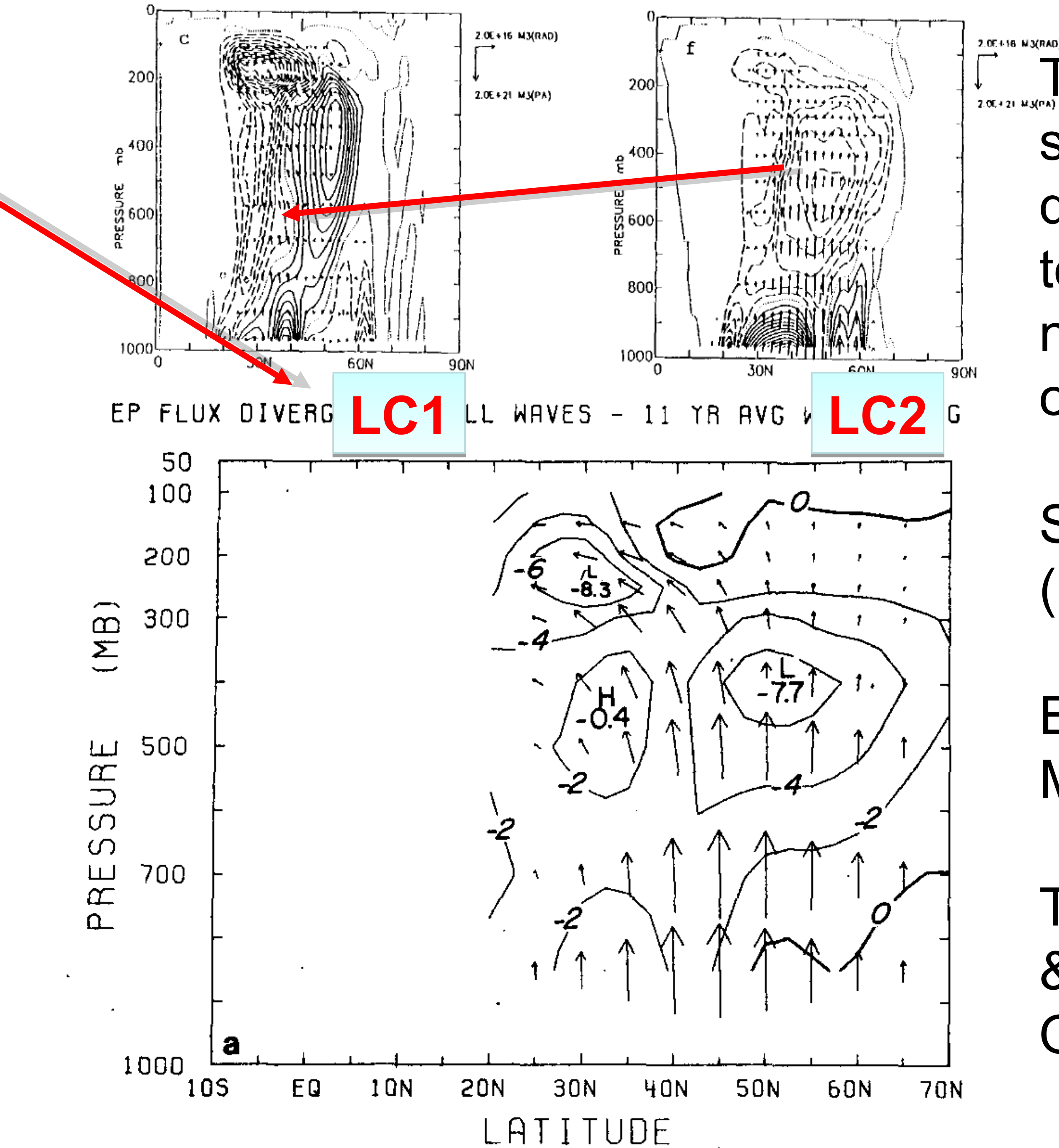
- The importance of synoptic-scale Rossby waves to the BDC may seem surprising, but the drag from synoptic-scale waves extends continuously into the subtropical lower stratosphere



Annual mean observed EP flux and flux divergence from ERA-40

Tropopause shown with thick line

Randel, Garcia & Wu (2008 JAS)



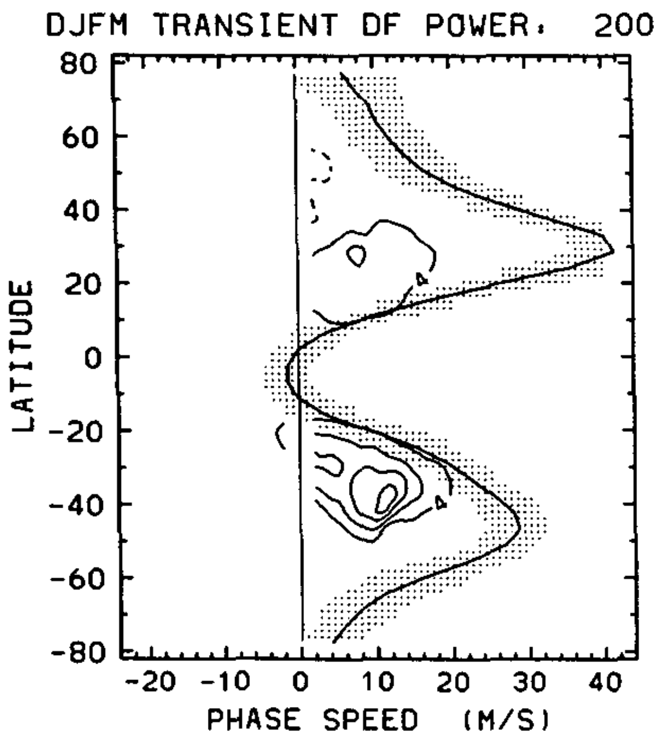
The subtropical synoptic-scale wave drag is understood to arise from the nonlinear breaking of baroclinic waves

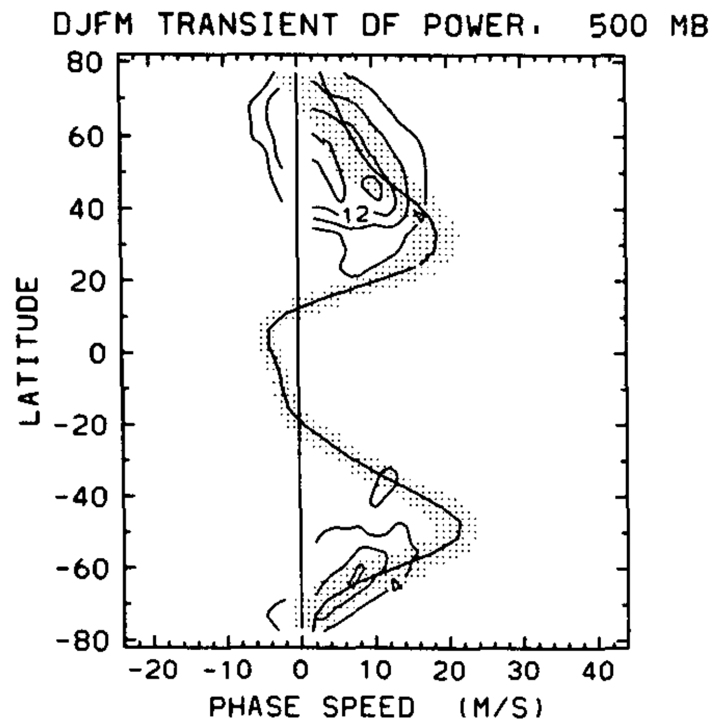
Simmons & Hoskins (1978 JAS)

Edmon, Hoskins & McIntyre (1980 JAS)

Thorncroft, Hoskins & McIntyre (1993 QJRMS)

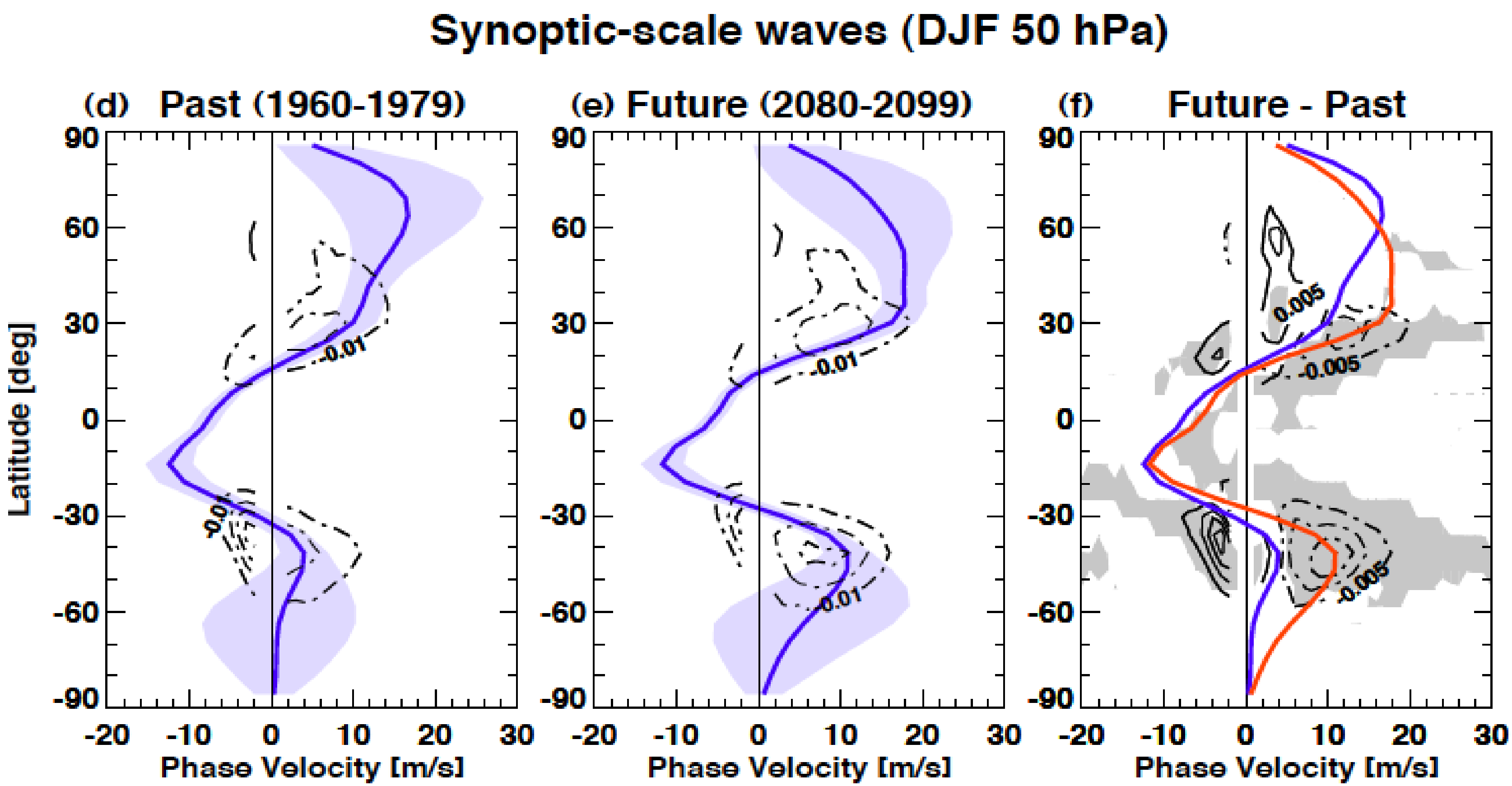
- The breaking of synoptic-scale Rossby waves occurs in nonlinear critical layers
  - The subtropical critical layer in the upper troposphere, and the midlatitude critical layer in the middle troposphere
  - Here for northern winter; northern summer is similar





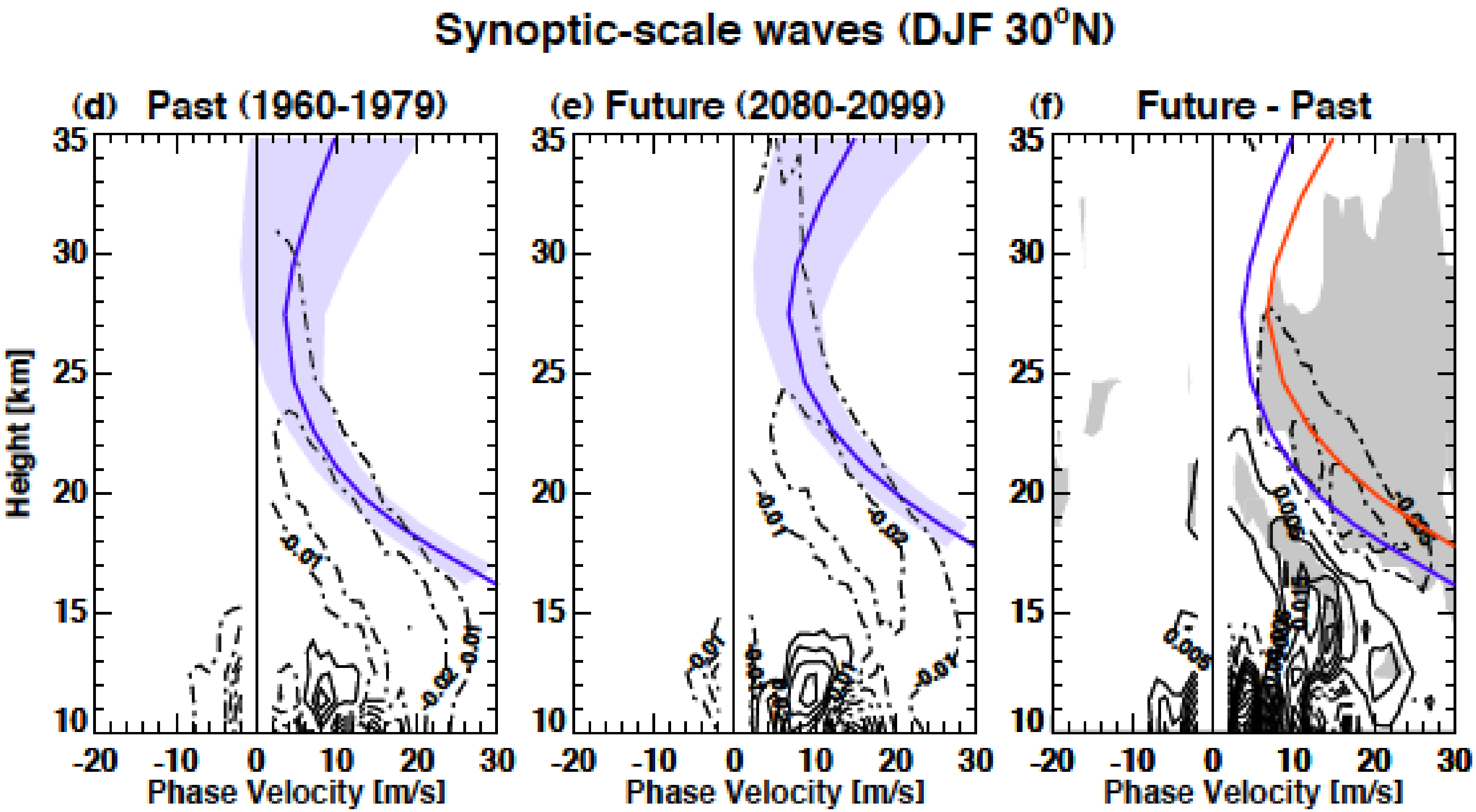
Randel & Held (1991 JAS)

- Rossby-wave drag responds to the strengthened subtropical jet from climate change via the mechanism of critical-layer control
  - Plots show EP flux divergence and zonal wind



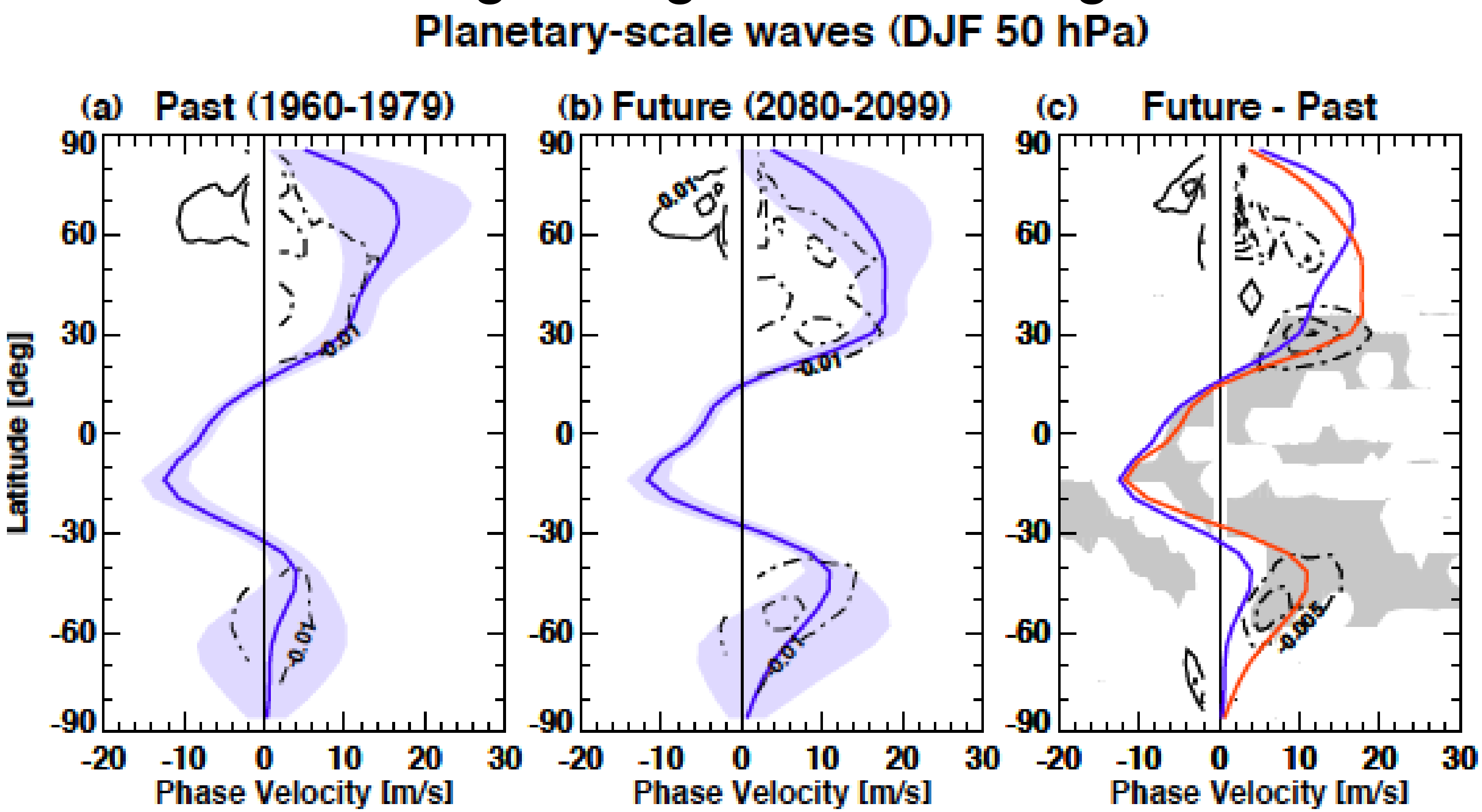
Shepherd & McLandress (2011 JAS)

- The synoptic-scale wave drag shifts upward into the lower stratosphere, following the upward shift in the critical layers
  - No apparent change in the amount of wave drag



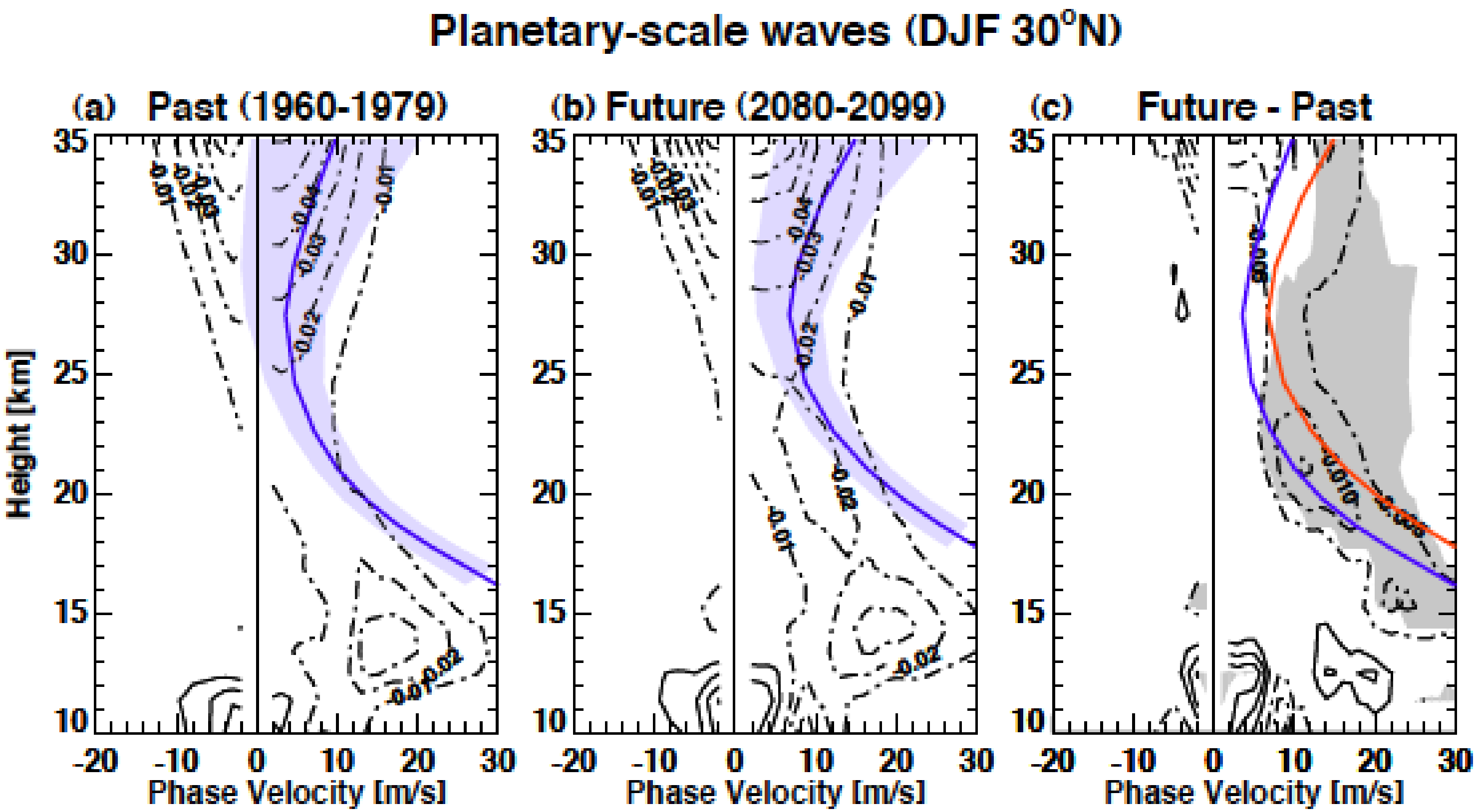
Shepherd & McLandress (2011 JAS)

- Critical-layer control is similarly seen to explain the changes in planetary-scale wave drag in the NH subtropical lower stratosphere
  - Critical layer control holds in the SH in DJF, and in the NH in JJA for synoptic and planetary waves, but the wave drag changes occur at higher latitudes



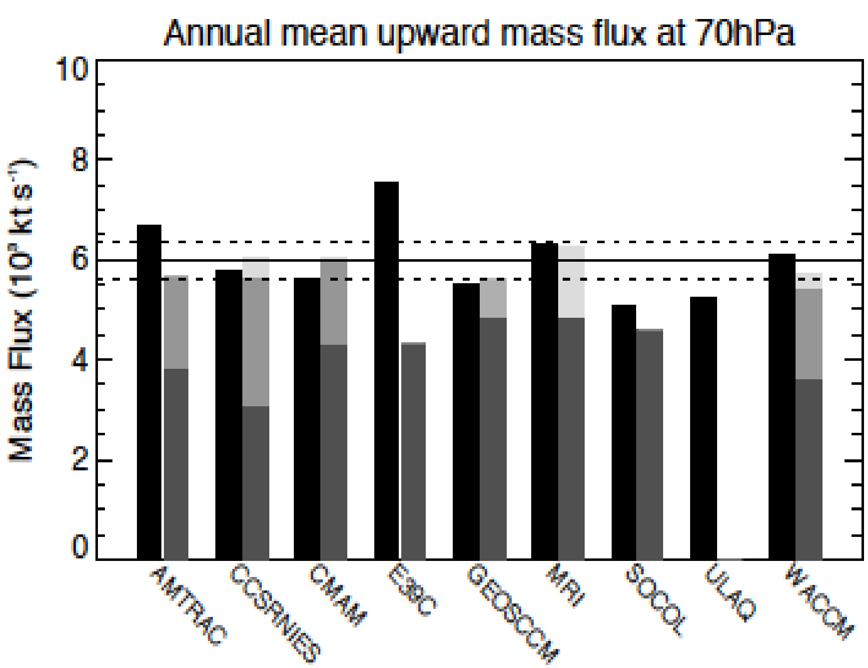
Shepherd & McLandress (2011 JAS)

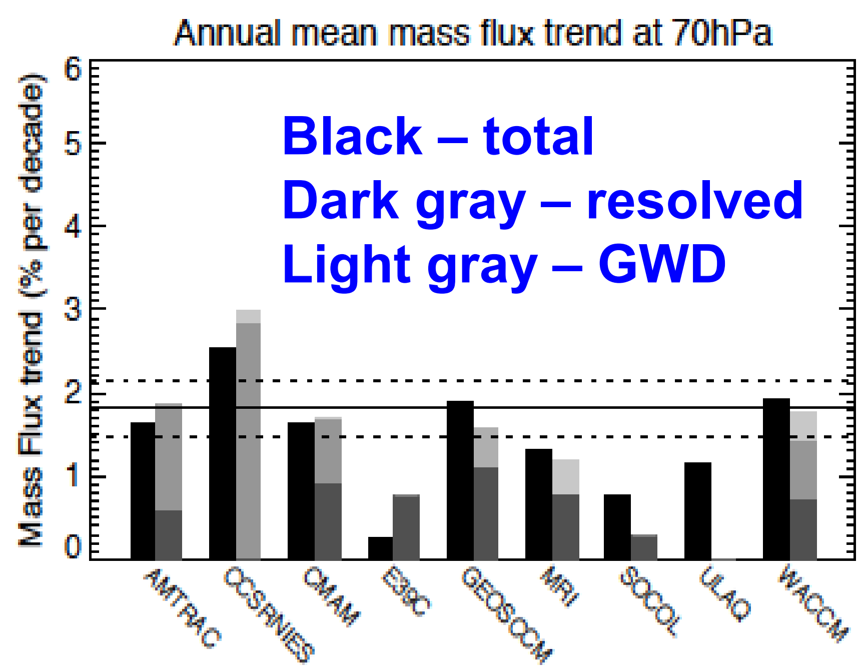
- For planetary-scale wave drag, the changes are not just an upward shift, suggesting either meridional redistribution or an increased forcing of planetary waves from the troposphere (but still with critical-layer control) — needs further investigation



Shepherd & McLandress (2011 JAS)

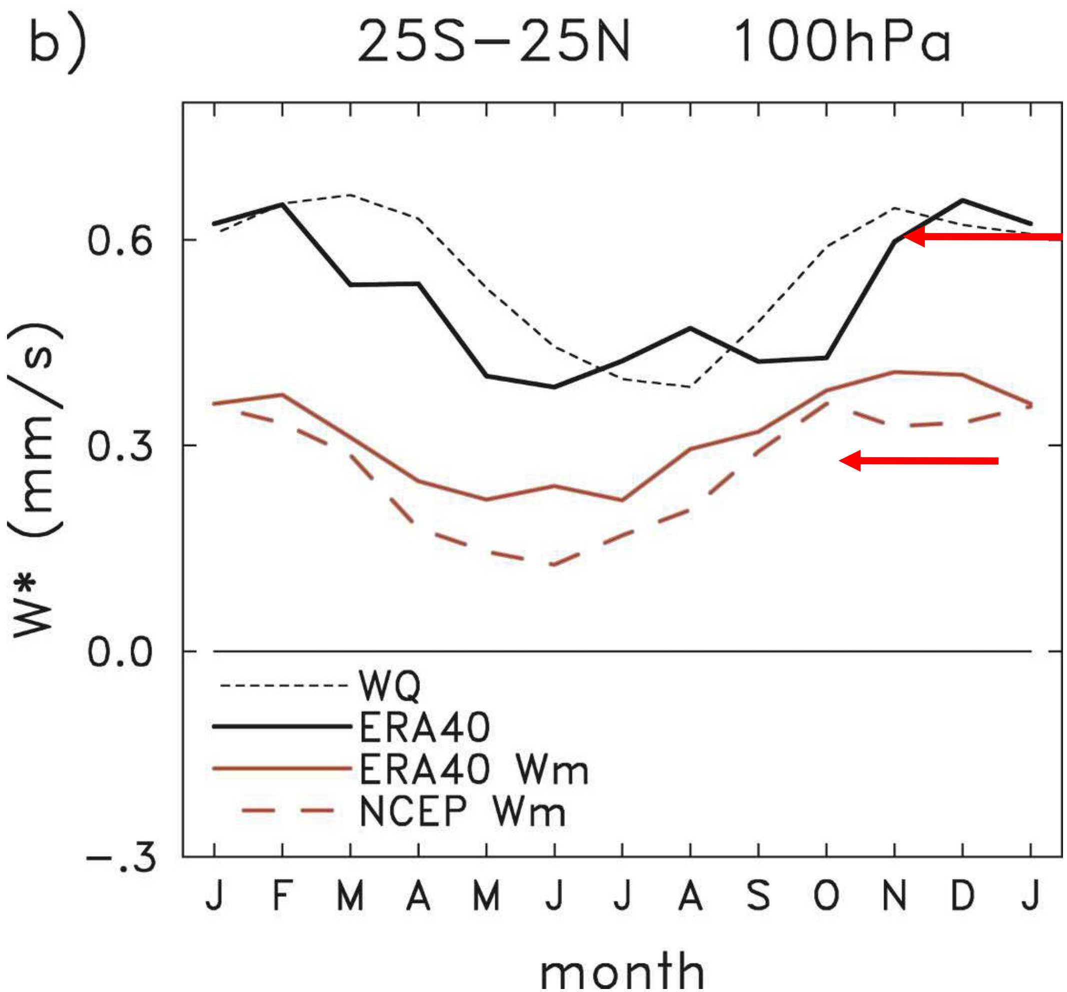
- The contribution of parameterized (mainly orographic) gravity-wave drag (GWD) to the strengthened tropical upwelling can be substantial, albeit with large differences between models
  - These CCMVal-1 results are corroborated by the more recent CCMVal-2 comparison (Chapter 4 of SPARC CCMVal Report, 2010)





Butchart et al. (2010 J. Clim.)

- Reanalyses corroborate the notion that something like one-third of the climatological BDC upwelling may come from unresolved (presumably gravity wave) drag

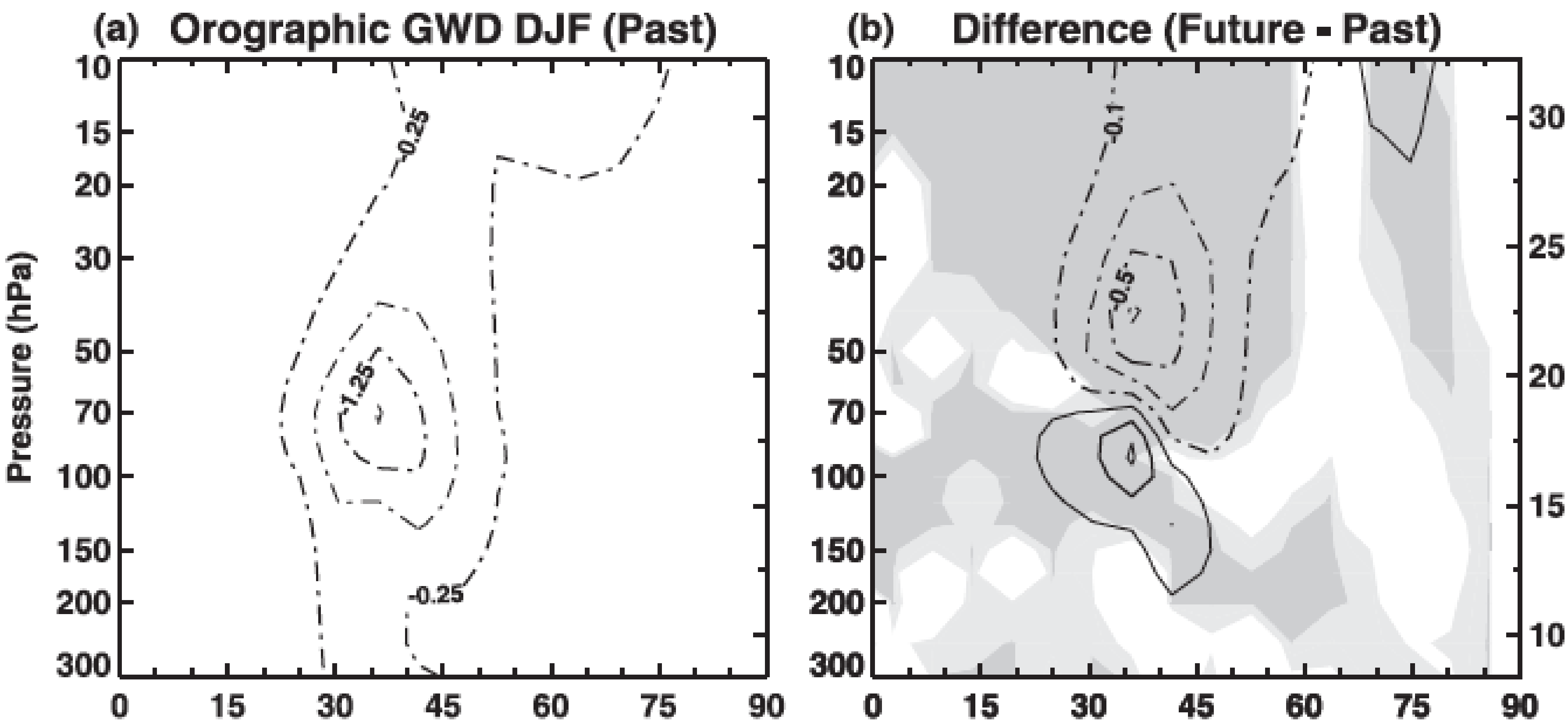


Estimates of total upwelling

Estimates of upwelling induced by resolved wave drag

Randel, Garcia & Wu (2008 JAS)

- The orographic GWD contribution to the strengthened BDC arises from an upward shift in gravity-wave breaking levels induced by the strengthened lower stratospheric westerlies (Li et al. 2008 J. Clim.)



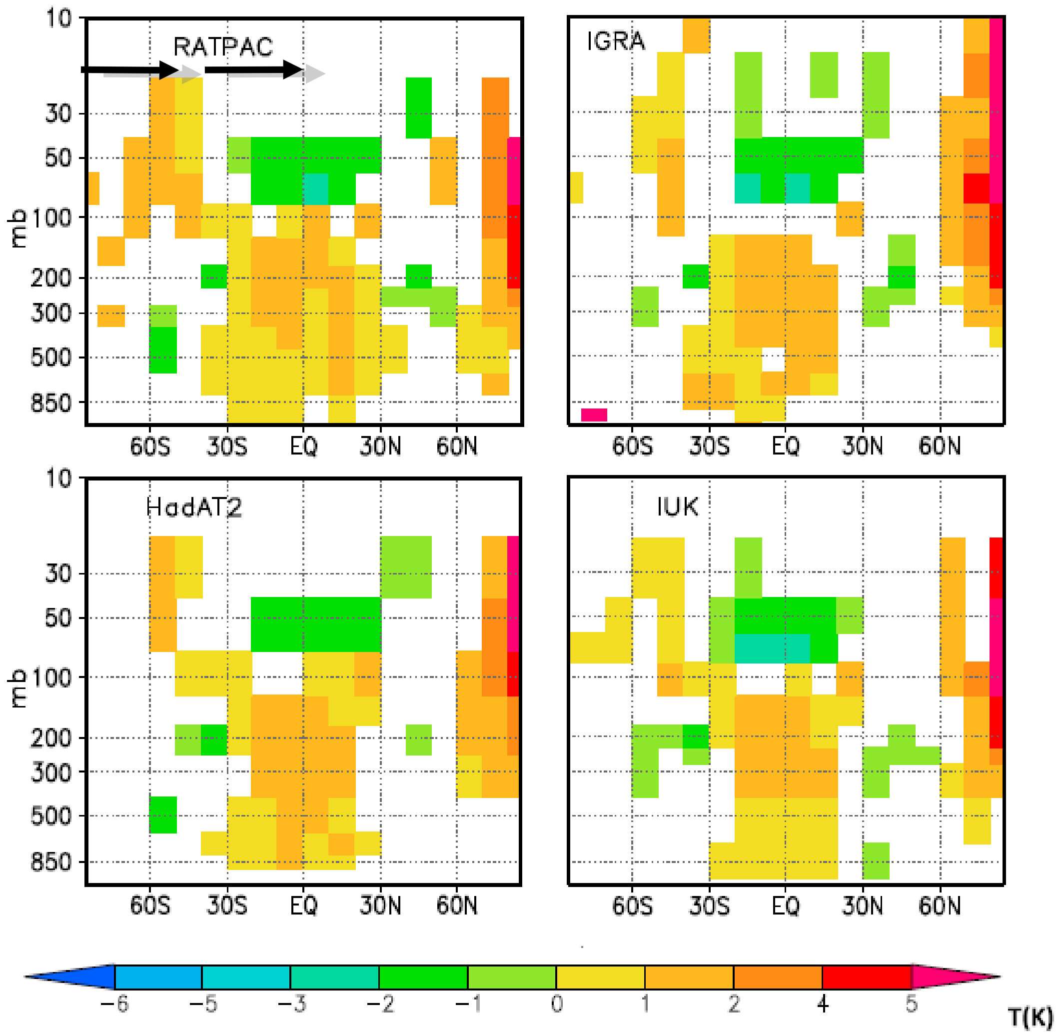
McLandress & Shepherd (2009 J. Clim.)

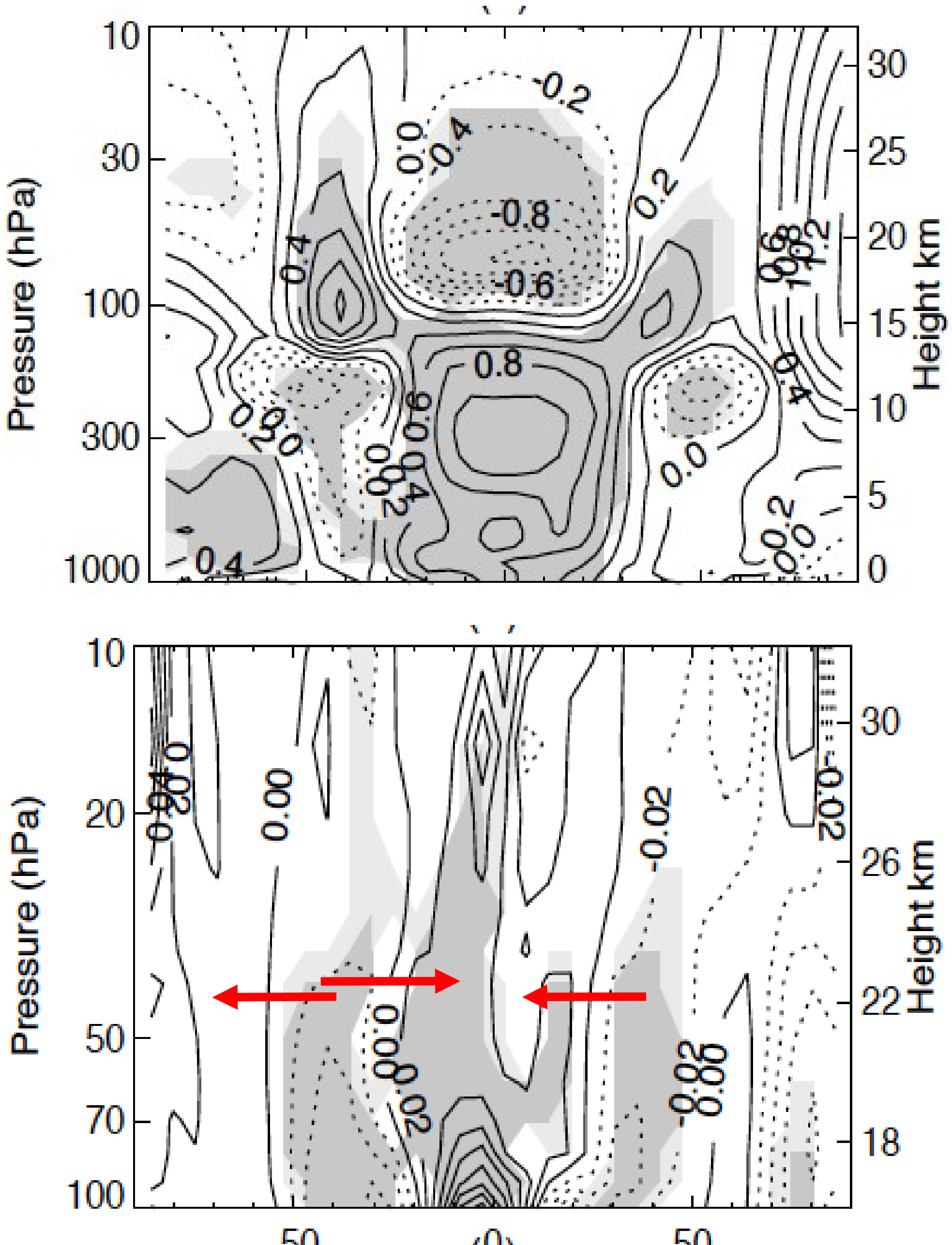
- Radiosonde observations show a lower stratospheric cooling above the tropical warming from El Niño, along with midlatitude lower stratospheric warming — the latter mainly in the SH

Regression of DJF temperature onto Nino 3.4 index

These stratospheric features must be dynamically driven

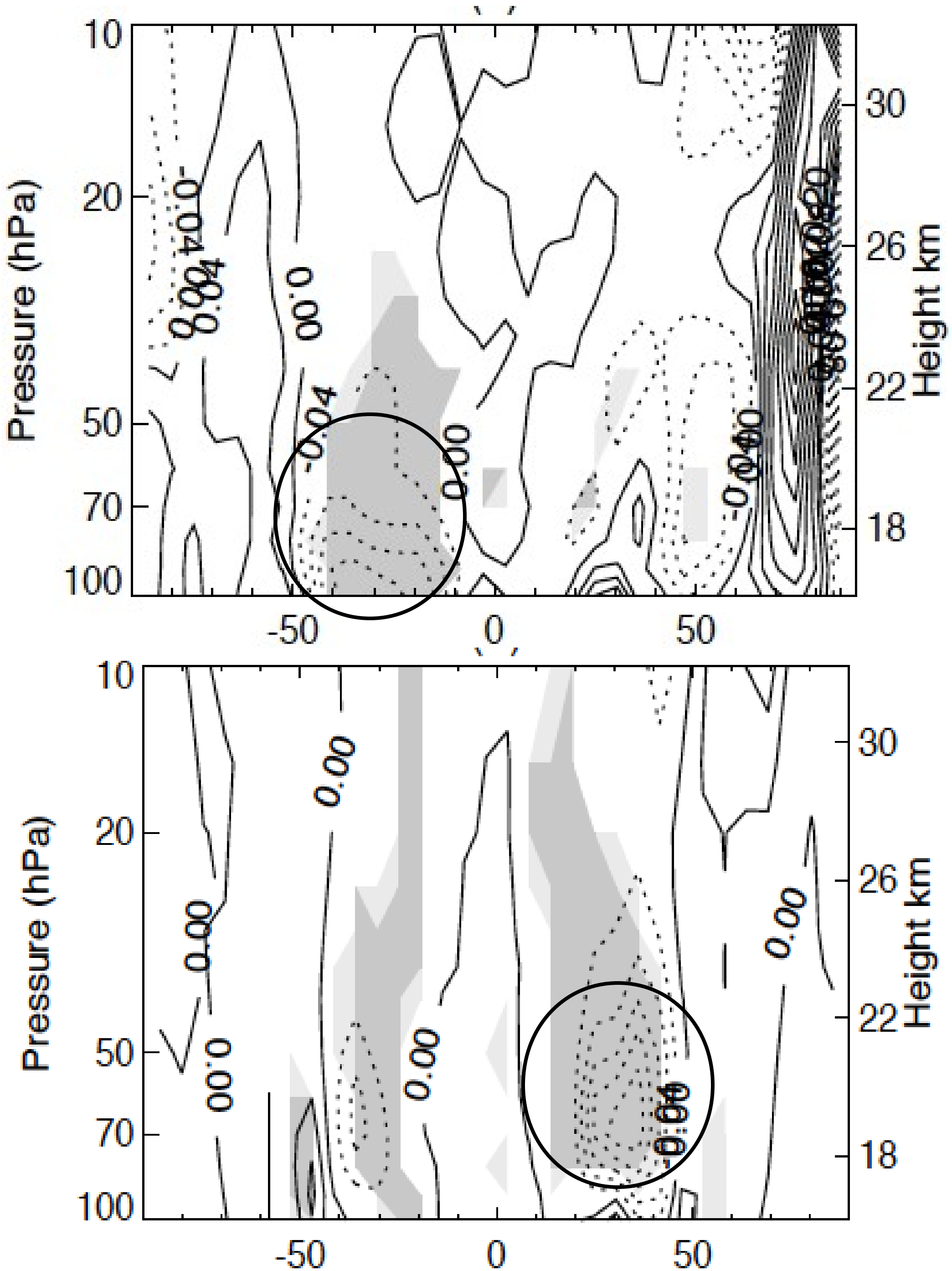
Free & Seidel (2009 JGR)





- The CMAM shows a temperature response (top) consistent with observations
  - DJF is shown
- Symmetric between El Niño and La Niña
- The stratospheric anomalies are associated with changes in upwelling/downwelling (bottom)
  - Largest response is in the SH

Simpson, Shepherd & Sigmond (JAS 2011)



- The SH response is driven mainly by anomalous drag from resolved transient (i.e. Rossby) waves, mainly of synoptic scale (top)
- The NH response is driven mainly by anomalous parameterized orographic gravity wave drag (bottom)

Simpson, Shepherd & Sigmond (JAS 2011)

Summary

- The strengthened BDC from climate change consistently predicted by models must be a result of increased wave drag in the subtropical lower stratosphere
  - Increased wave drag within the tropics cannot increase the mass flux out of the tropics
- Many studies have appealed to "improved propagation conditions" from strengthened subtropical winds, but no clear mechanism has been previously identified
  - Role of stationary waves appears to be small
- Critical-layer control of Rossby-wave breaking provides a robust mechanism for a strengthened BDC in CMAM
  - Planetary and synoptic-scale waves both contribute
  - Same mechanism applies to orographic GWD
  - Explains why the effect is so robust among models

- The high-latitude stratospheric circulation response to climate change is a completely separate issue
  - Driven by stationary planetary waves; not understood
- Stratospheric response to ENSO may differ in significant ways from response to GHG-induced tropospheric warming
  - While response also maximizes in DJF, the low-latitude response is strongest in the SH rather than in the NH
  - OGWD response in NH subtropics appears to be driven by the same dynamics as the OGWD response to climate change (cf. Calvo et al. 2010 JAS)
  - Synoptic Rossby-wave response in SH subtropics does not seem explainable from critical-layer control
    - Rather it appears (in CMAM) to result from increased wave forcing from the troposphere, with distinct responses in the Pacific and elsewhere

Reference 1

- Butchart, N., Cionni, I., Eyring, V., Shepherd, T. G., Waugh, D. W., Akiyoshi, H., Austin, J., Bruhl, C.,Chipperfield, M. P., Cordero, E., Dameris, M., Deckert R., Dhomse, S., Frith, S. M., Garcia, R. R., Gettelman, A., Giorgetta, M. A., Kinnison, D. E., Li, F., Mancini, E., McLandress, C., Pawson, S., Pitari, G., Plummer, D. A., Rozanov, E., Sassi, F., Scinocca, J. F., Shibata, K., Steil, B., Tian, W., 2010: Chemistry--Climate Model Simulations of Twenty-First Century Stratospheric Climate and Circulation Changes, J. Clim., 23, 5349-5374
- Calvo, N., Garcia, R. R., Randel, W. J. R., Marsh, D. R.,2010: Dynamical Mechanism for the Increase in Tropical Upwelling in the Lowermost Tropical Stratosphere during Warm ENSO Events, J. Atmos. Sci., 67, 2331-2340
- Deckert, R., Dameris, M., 2008: Higher tropical SSTs strengthen the tropical upwelling via deep convection, Geophys. Res. Lett., 35, L10813, 5pp
- Edmon, H. J., Hoskins, B. J., McIntyre, M. E., 1980: Eliassen-Palm cross sections for the troposphere, J. Atmos. Sci., 37, 2600-2616
- Eichelberger, S. J., Hartmann, D. L., 2005: Changes in the strength of the Brewer-Dobson circulation in a simple AGCM, Geophys. Res. Lett., 32, L15807, 5pp
- Fahey, D.W., Hegglin, M.I., 2011: Twenty Questions and Answers About the Ozone Layer: 2010 Update, World Meteorological Organization, 72pp
- Free, M., Seidel, D. J., 2009: Observed El Nino Southern Oscillation temperature signal in the stratosphere, J. Geophys. Res., 114, D23108
- Hegglin, M. I., Shepherd, T. G., 2009: Large climate-induced changes in ultraviolet index and stratosphere-to-troposphere ozone flux, Nature Geoscience, 2, 687-691
- Li, F., Austin, J., Wilson, J., 2008: The Strength of the Brewer–Dobson Circulation in a Changing Climate: Coupled Chemistry–Climate Model Simulations, J. Climate, 21, 40-57
- McIntyre, M. E., Palmer, T. N., 1983: Breaking planetary waves in the stratosphere, Nature, 305, 593-600
- McLandress, C., Shepherd, T. G., 2009: Simulated anthropogenic changes in the Brewer–Dobson c circulation, including its extension to high latitudes, J. Climate, 22, 1516–1540

Reference 2

- Mote, P. W., Rosenlof, K. H., McIntyre, M. E., Carr, E. S., Gille, J. C., Holton, J. R., Kinnersley, J. S., Pumphrey, H. C., Russell, J. M. III., Waters, J. W. 1996: An atmospheric tape recorder: The imprint of tropical tropopause temperatures on stratospheric water vapor, J. Geophys. Res., 101, D2, 3989-4006
- Randel, W. J., Garcia, R., Wu, F., 2008: Dynamical Balances and Tropical Stratospheric Upwelling, J. Atmos. Sci., 65, 3584–3595
- Randel, W. J., Held, I. M., 1991: Phase Speed Spectra of Transient Eddy Fluxes and Critical Layer Absorption, J. Atmos. Sci., 48, 688–697
- Randel, W. J., Wu, F., Oltmans, S. J., Rosenlof, K., Nedoluha G. E., 2004: Interannual Changes of Stratospheric Water Vapor and Correlations with Tropical Tropopause Temperatures, J. Atmos. Sci., 61, 2133–2148
- Rind, D., Suozzo, R., Balachandran, N. K., Prather, M. J., 1990: Climate Change and the Middle Atmosphere. Part I: The Doubled CO2 Climate, J. Atmos. Sci., 47, 475–494
- Shaw, T. A., Shepherd, T. G., 2008: Atmospheric science: Raising the roof, Nature Geoscience, 1, 12—13
- Shepherd, T. G., 2008: Dynamics, stratospheric ozone, and climate change, Atmosphere-Ocean
- Shepherd, T. G., McLandress, C., 2011: A Robust Mechanism for Strengthening of the Brewer–Dobson Circulation in Response to Climate Change: Critical-Layer Control of Subtropical Wave Breaking., J. Atmos. Sci., 68, 784–797
- Shepherd, T. G., Shaw, T. A., 2004: The Angular Momentum Constraint on Climate Sensitivity and Downward Influence in the Middle Atmosphere, J. Atmos. Sci., 61, 2899–2908
- Simmons, A., Hoskins, B., 1978: The life-cycles of some nonlinear baroclinic waves. J. Atmos. Sci., 35, 414-432
- Simpson, I. R., Shepherd, T. G., Sigmond, M., 2011: Dynamics of the Lower Stratospheric Circulation Response to ENSO., J. Atmos. Sci., 68, 2537–2556
- Thorncroft, C. D., Hoskins, B. J., McIntyre, M. E., 1993: Two paradigms of baroclinic-wave life-cycle behaviour, Q. J. R. Meteorol. Soc., 119, 17–55
- Thuburn, J., Craig, G. C., 2000: Stratospheric Influence on Tropopause Height: The Radiative Constraint, J. Atmos. Sci., 57, 17–28
- Yulaeva, E., Holton, J. R., 1994: On the cause of the annual cycle in tropical lower-stratospheric temperatures, J. Atmos. Sci., 51, 169-174