Mechanisms for the Acceleration of the Brewer-Dobson Circulation in a Climate Change Scenario

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Outline

- Motivation
- Model and Simulations – trends in AOA
- Trends in wave driving
- Analysis via Downward Control Principle
- Discussion
- Conclusions

Motivation: GHG increases influence stratospheric circulation

N. Butchart et al.: Simulations of anthropogenic change in the strength of the Brewer–Dobson circulation (2006) 27:727–741 735

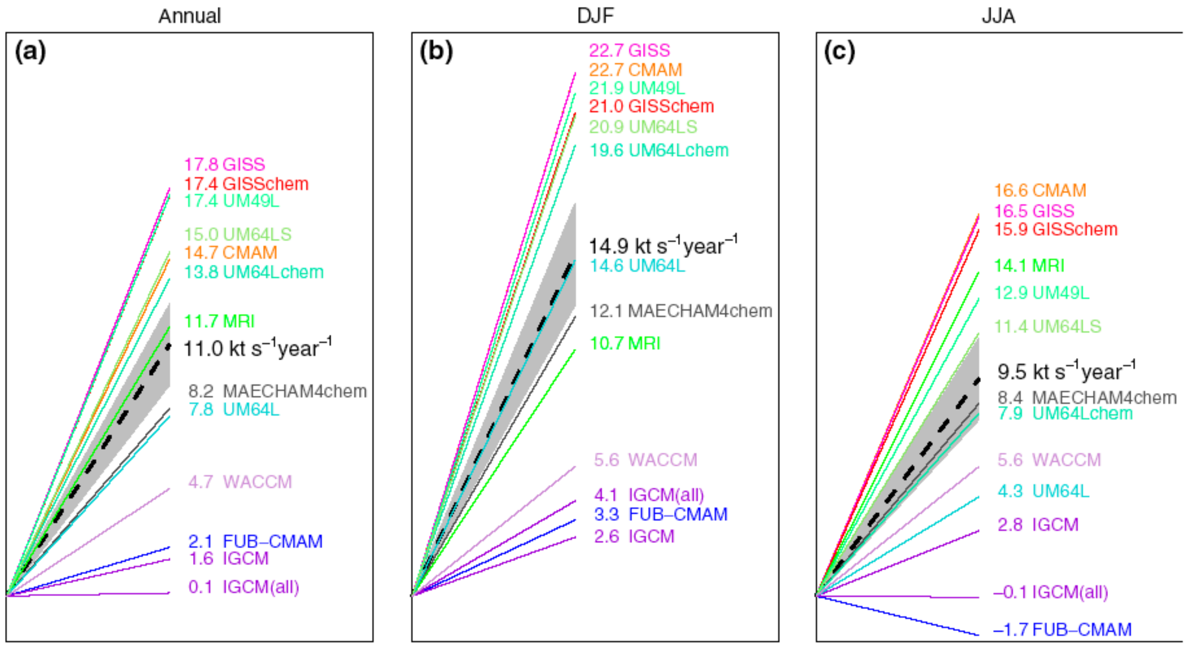


Fig. 6 Schematic representation of the trends in the upward mass flux in the tropical lower stratosphere for each model at the levels indicated in Fig. 1, in kt s^{-1} $year^{-1}$: **a** annual mean, **b** DJF mean, and **c** JJA mean. For the transient experiments, and also for the four MAECHAM4chem runs, trends are based on a least squares linear fit. The trend for the UM64LS is calculated from the difference between 1 × CO_2 and 2 × CO_2 runs. As with the CMAM experiment it is assumed that doubling of CO_2 took place over 70 years. The *dashed line* is the multi-model mean with the standard error given by the *grey shading*. So as not to give undue weight to the IGCM, the two trends from this model were averaged and treated as single trend when calculating the multi-model mean

Butchart et al., *Clim. Dyn.* (2006)

Mass flux trends ~ 10 kton sec^{-1} yr^{-1}: a robust result seen in many GCMs

Whole Atmosphere Community Climate Model, Version 3

WACCM3

- Extension of NCAR's CAM3 to lower thermosphere (domain 0-140 km; 66 levels)
- Fully interactive chemistry-dynamics; Lin (2004) FV advection
- Δz ~1 km (troposphere, UTLS) … ~3 km (MLT); Δx, Δy ~ 2°x 2.5° or 4°x 5°
- GW parameterization: orographic + spectrum
- UV, EUV heating and NLTE IR in MLT

References: Garcia et al. (2007), Kinnison et al. (2007), Marsh et al. (2007)

REF1 Simulation

- Ensemble of 4 simulations, 1950-2003
- Observed SST, GHG, CFC
- Volcanic aerosol effects

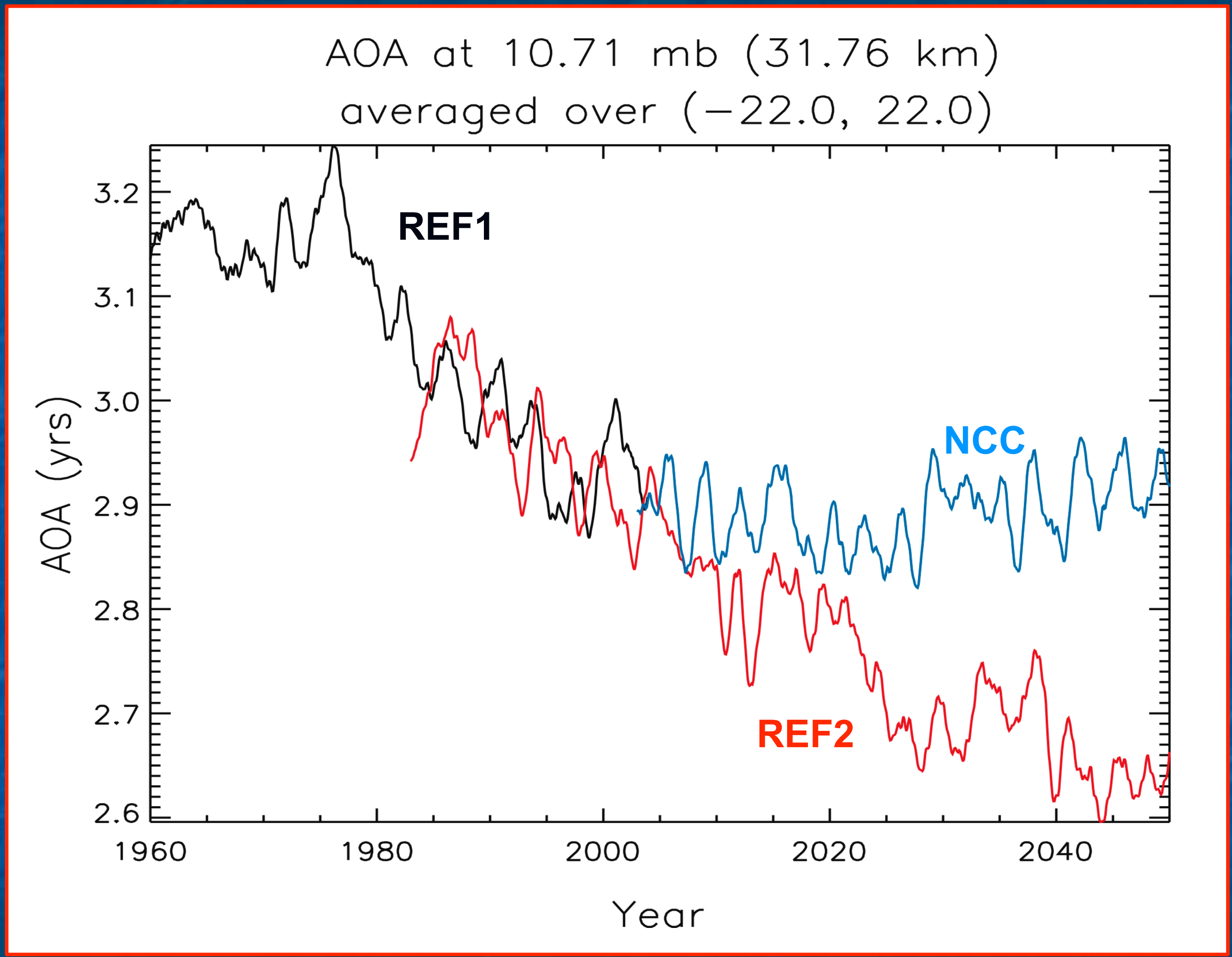
REF2 Simulation

- Ensemble of 3 simulations, 1975-2050
- SSTs from CCSM3 IPCC A1b simulation
- Trends in trace gases from A1b scenario 1995-2050

NCC Simulation

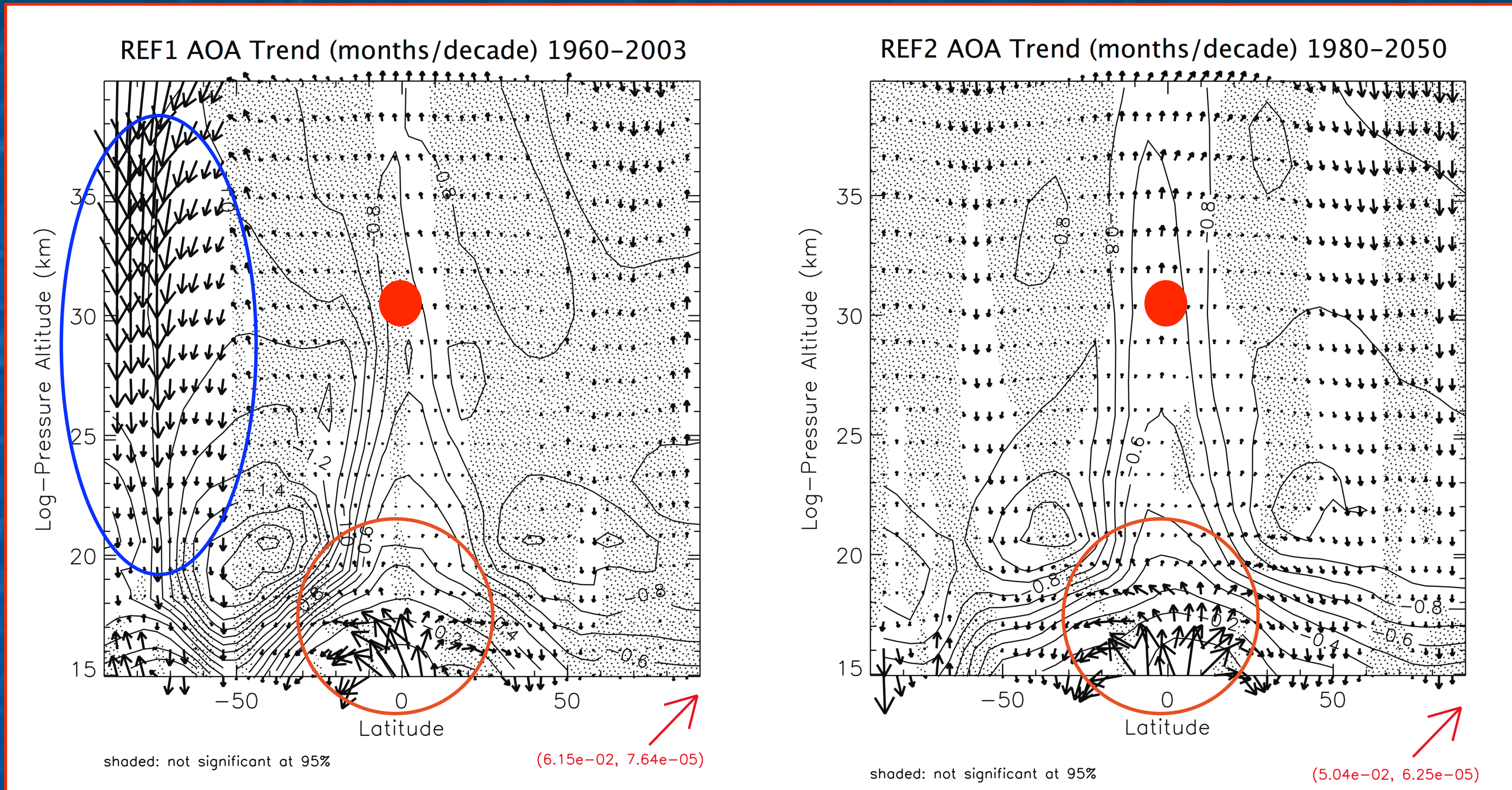
- "No climate change"
- Ensemble of 3 simulations, 1995-2050
- Same as REF2, *except that CO_2, CH_4 and N_2O are held constant to 1995 values*

Age of Air: Tropical Average at 10 mb



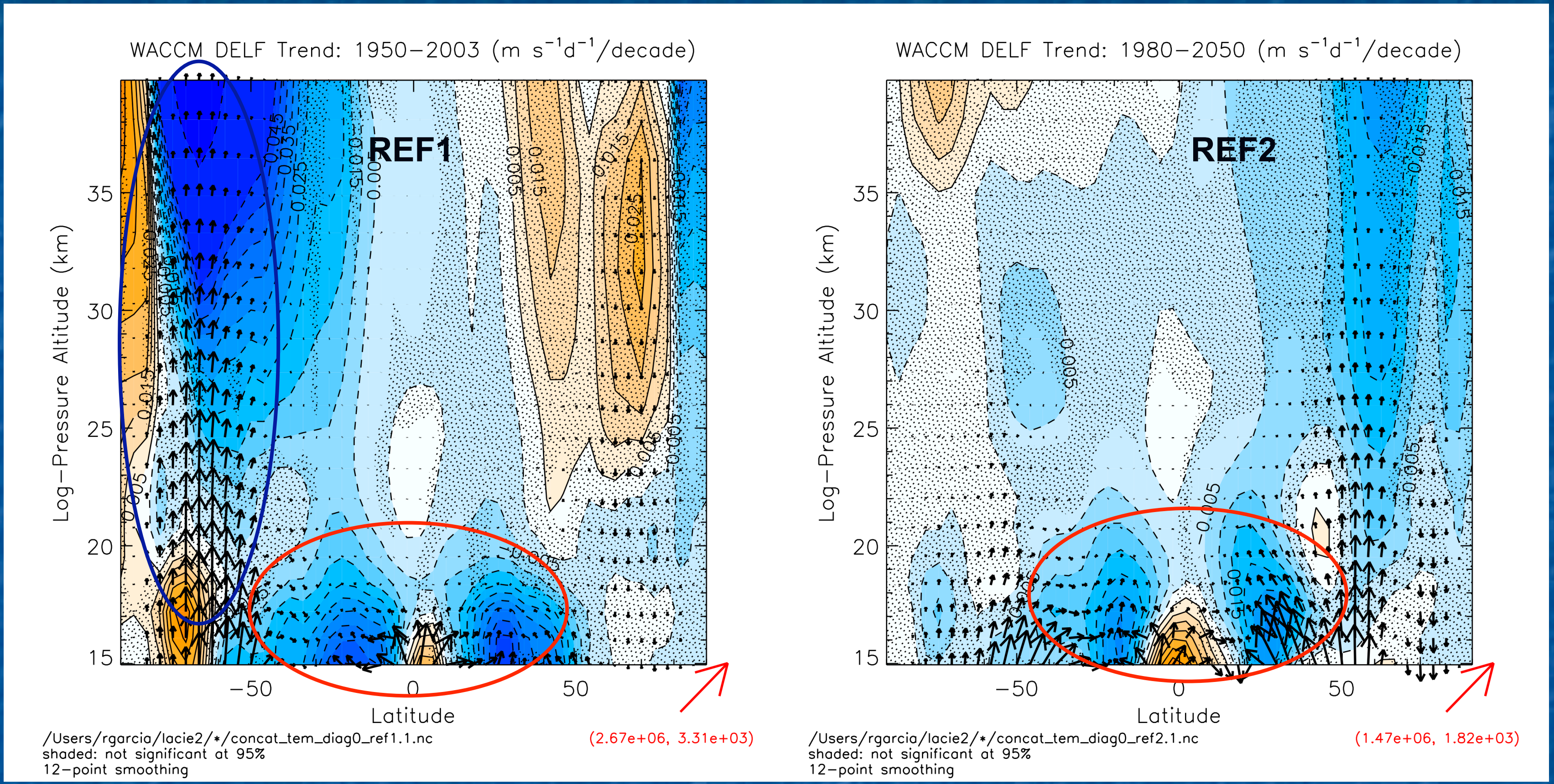
AOA decreases systematically in REF1, REF2; does not change significantly in NCC

Trends in AOA (months decade^{-1})
Trends in Vector BD Circulation (ms^{-1}decade^{-1})



- Much of the change in AOA occurs *in the lower stratosphere*; much of the cumulative trend at 10 mb (red dots) shown earlier is due to changes below 50 mb (~20 km; red circles)
- The lower stratosphere trend is associated with an increase in the BDC in the Tropics and subtropics (arrows)
- In REF1 there is also significant change over the SH polar cap at most altitudes (blue oval)

Trends in (resolved) div(**F**) (m s^{-1} day^{-1} $decade^{-1}$) and **F** (kg s^{-2} $decade^{-1}$)



- Except for the *SH polar cap* in the period of rapid ozone loss (REF1; blue oval), statistically significant changes in div(**F**) are confined mainly to the *lower subtropical stratosphere* (red ovals); it is shown next that these account for much of the change in the BD circulation
- A *robust result* for REF1 and REF2, although the morphology of the trend in **F** varies somewhat

Attribution: mass flux from Downward Control

The Downward Control (DC) Principle (Haynes et al., 1991) yields the following expression for the vertical mass flux, *M*, averaged between latitudes θ_1 and θ_2:

$$M = \int_{\theta_1}^{\theta_2} 2\pi a^2 \rho \cos\theta\, w^*\, d\theta = 2\pi a^2 \left| \int_z^{\infty} \frac{\rho \cos^2\theta \left[(\rho a \cos\theta)^{-1} \nabla \bullet \mathbf{F} + \mathbf{X} \right]}{\overline{m}_\theta} dz' \right|_{\theta_1}^{\theta_2}$$

where:

- θ is latitude, z is log-pressure altitude, and a is the Earth's radius
- $\rho = \rho_0 \exp(-z/H)$ is the density in log-pressure coordinates
- m_θ is the zonal-mean angular momentum
- **F** is the Eliassen-Palm flux and **X** is the zonal-mean force due to parameterized gravity waves

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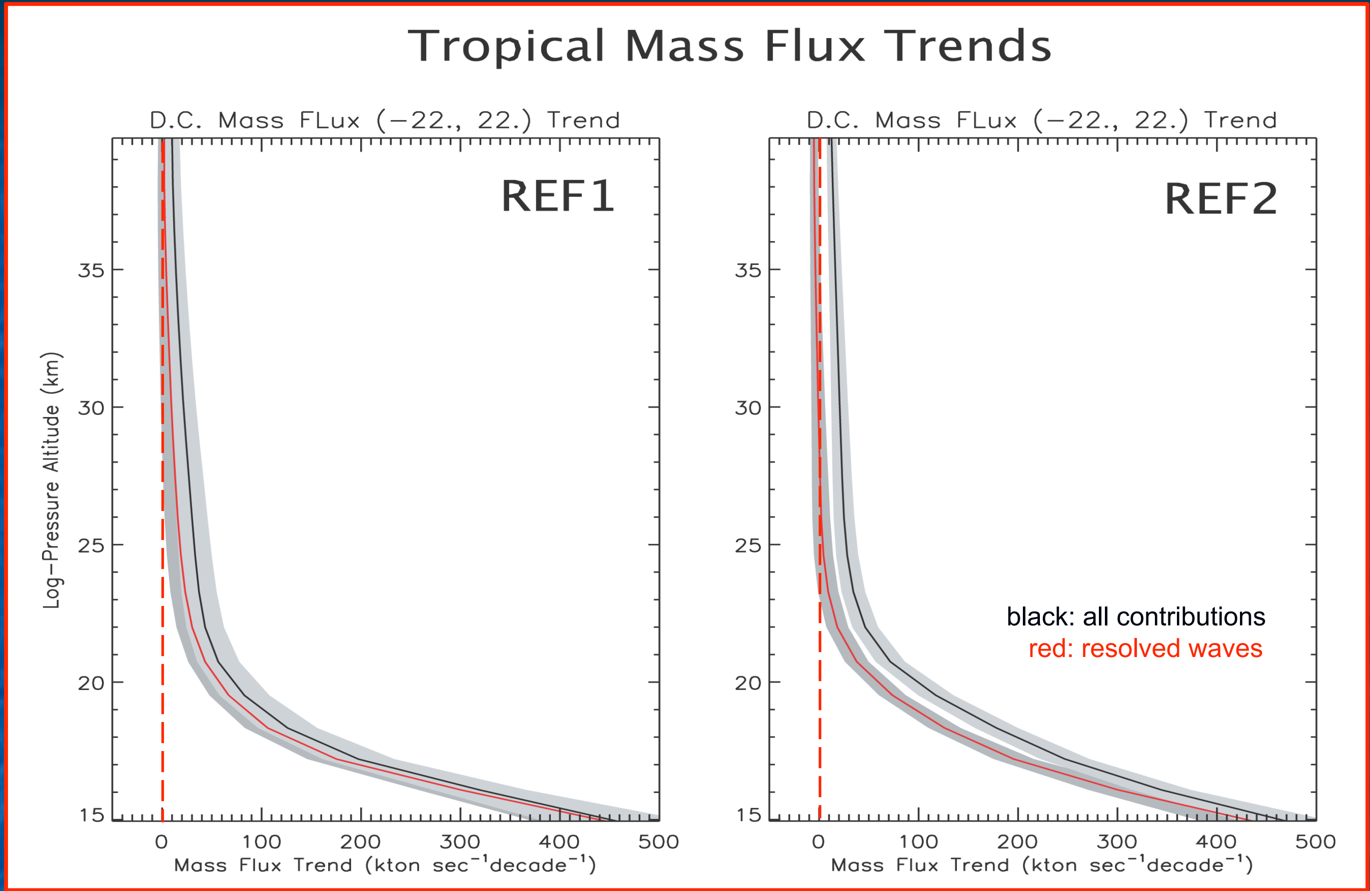
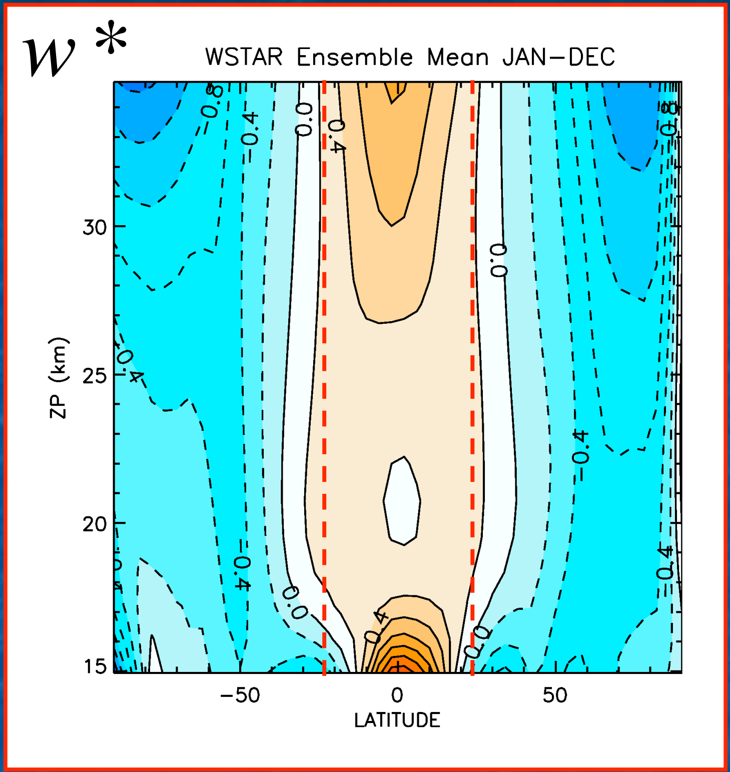
M **depends only on the vertical integral of the wave forcing at the edges of the region bounded by the latitudes (θ_1, θ_2). The expression may be applied over any latitude range where DC is expected to hold; it is used here to evaluate trends in tropical upwelling, as well as the compensating trends in downwelling in extratropical regions.**

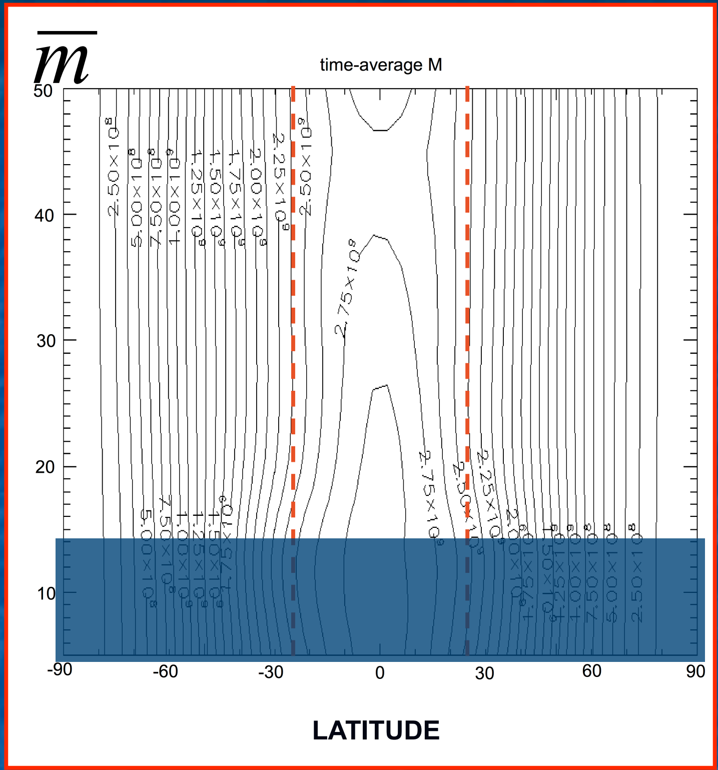
Trends in Tropical Mass Flux from D.C.



- Tropical-mean vertical mass flux profiles reveal clearly *two distinct regimes: above and below ~20 km*
- Most of the trend in mass flux trend occurs in the *lowermost stratosphere* (< 20 km) and is due to changes in del(**F**) due to resolved waves (*tropical Rossby waves*)
- In the *middle/upper stratosphere* (> 20 km) the trend is dominated by changes in *parameterized GW forcing*; however, in REF1 a significant fraction comes from resolved waves (*extratropical planetary Rossby waves*)

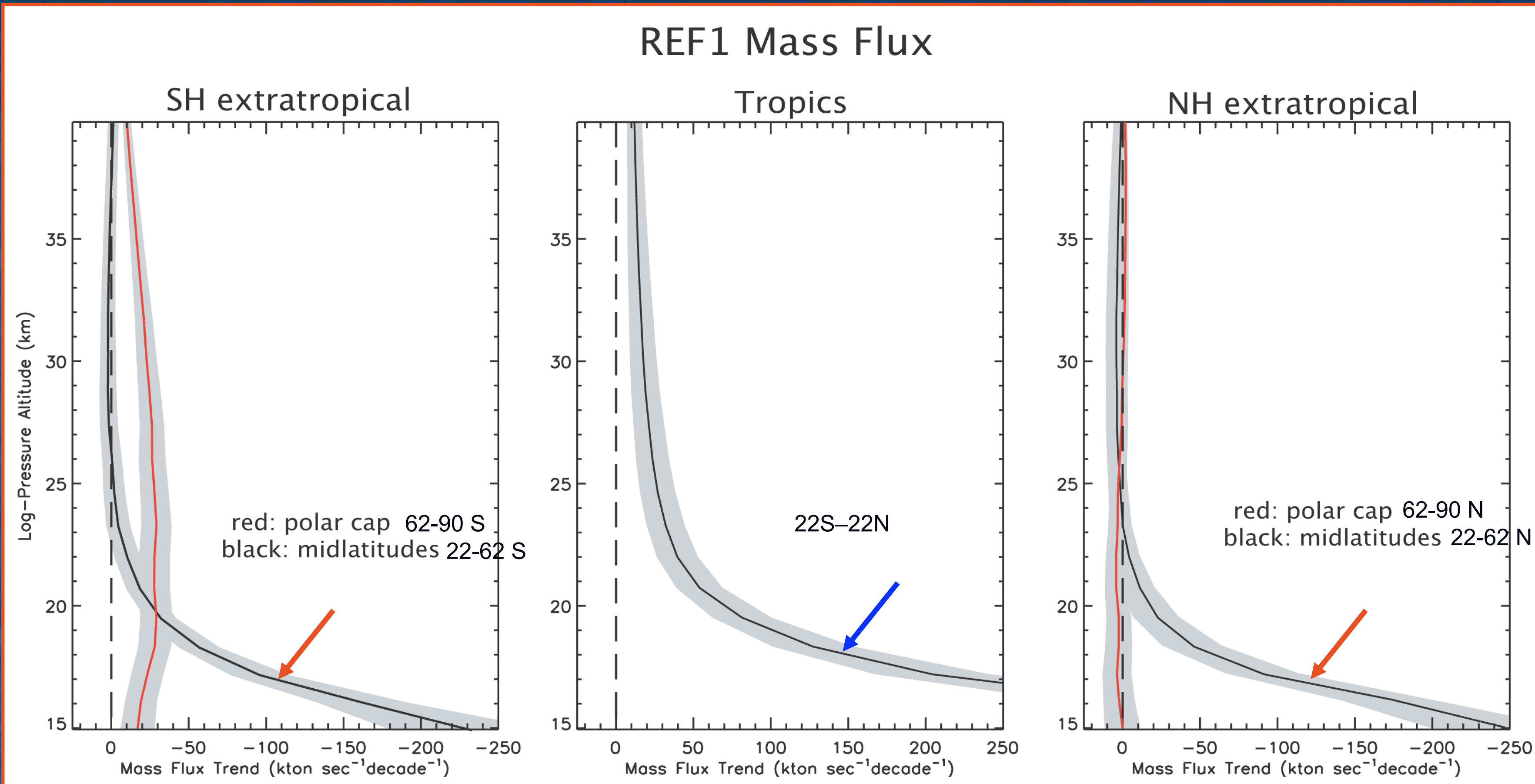
Applicability of the DC Principle





- The width of the tropical upwelling and extratropical downwelling regions varies with altitude (left panel)
- Choice of tropical region cannot be too broad in lower stratosphere or else tropical averages will include both upwelling and downwelling
- Defining the Tropics to encompass ±22° is a good compromise: (a) coincides with the conventional definition; (b) includes mainly upwelling in the lower stratosphere; (c) includes the strongest upwelling in the middle and upper stratosphere
- Angular momentum distribution (right panel) indicates that DC should be applicable at ±22°

Tropical vs. Extratropical *M* Trends (REF1)



- In the lower stratosphere (< 20 km) tropical trend in *M* (blue arrow) is balanced by the trend *in midlatitudes only* (red arrows)
- In the middle and upper stratosphere (> 20 km), much of the extratropical trend in *M* occurs over the SH polar cap
- The SH polar trend is forced partly by the large trend in extratropical div(**F**) shown earlier (which is related to changes in SH winter westerlies associated with the development of the ozone hole), and partly by parameterized GW trends (not shown)
- REF2 results are similar, *but* the SH polar cap no longer dominates the extratropical trend, and trends are due mainly to changes in GW forcing

Discussion:

- Changes in AOA are driven by changes in the BD circulation
- Most of the change in AOA occurs in the lower stratosphere and is driven by the acceleration of the BDC in the Tropics and subtropics
- Changes in the BDC below 20 km are explained largely by changes in div(**F**) in the subtropical lower stratosphere

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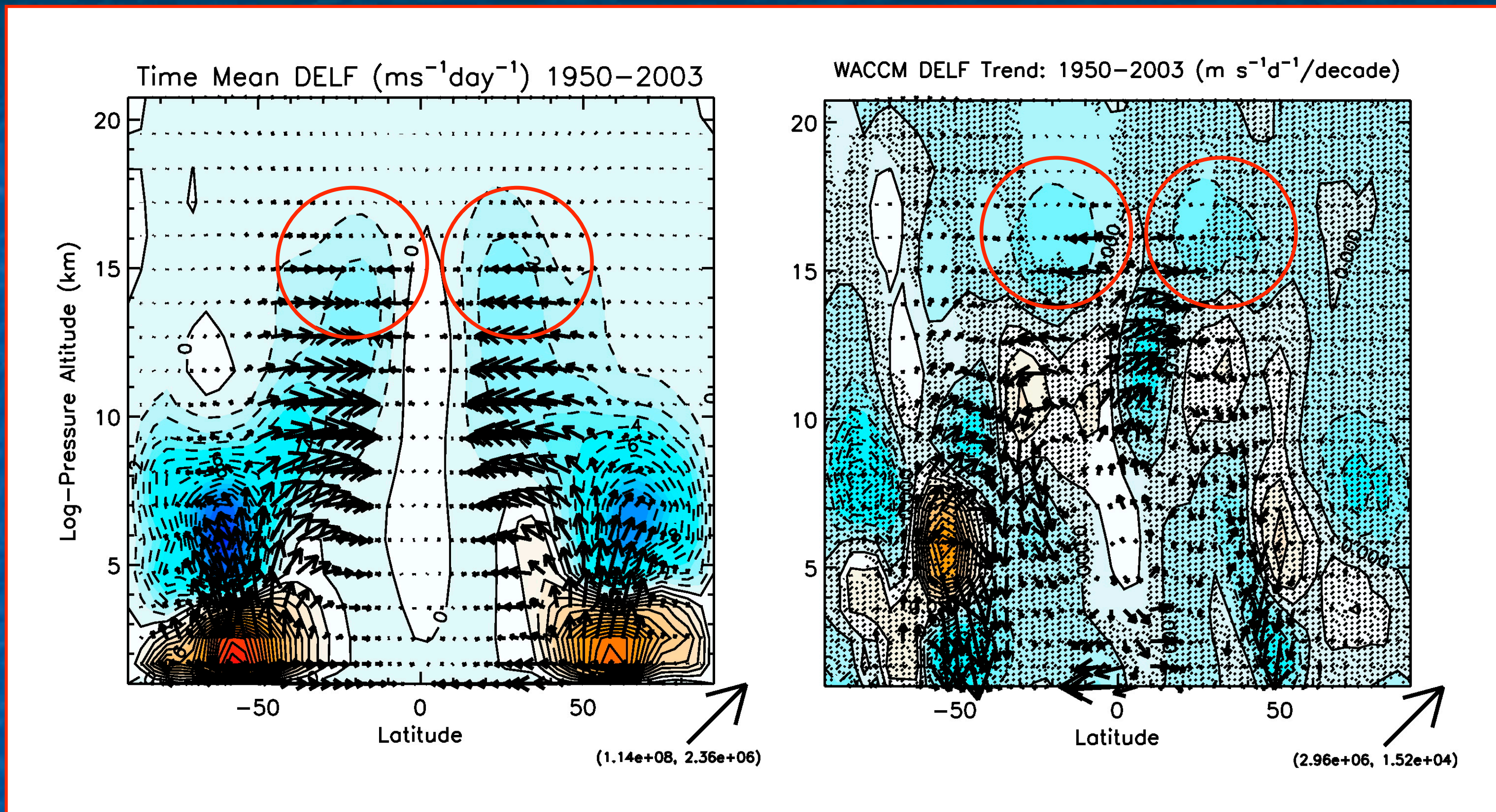
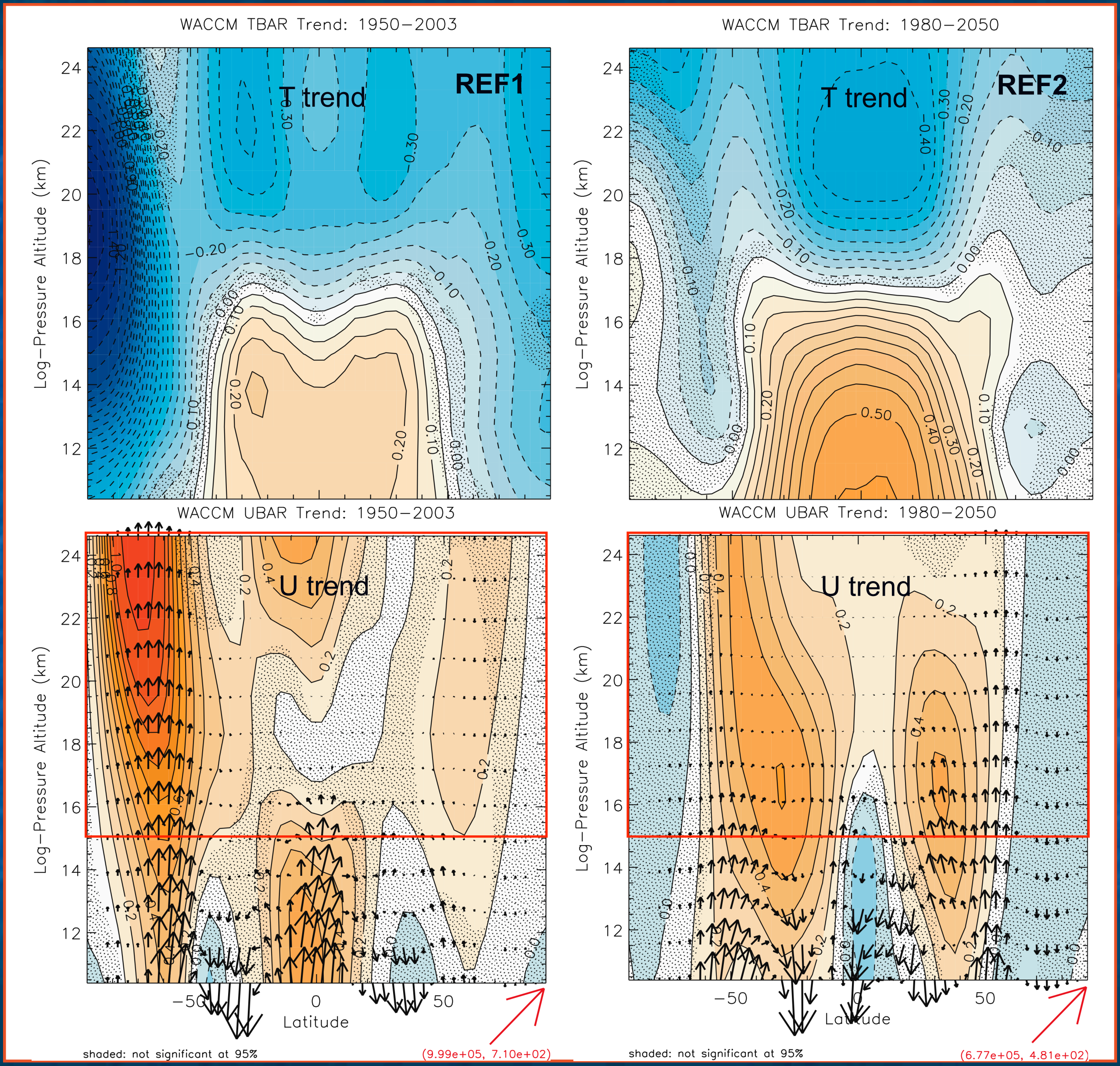
– *What causes the trend in* div(**F**) *in the lower stratosphere?*

Time-mean and Trend of div(**F**) (REF1)



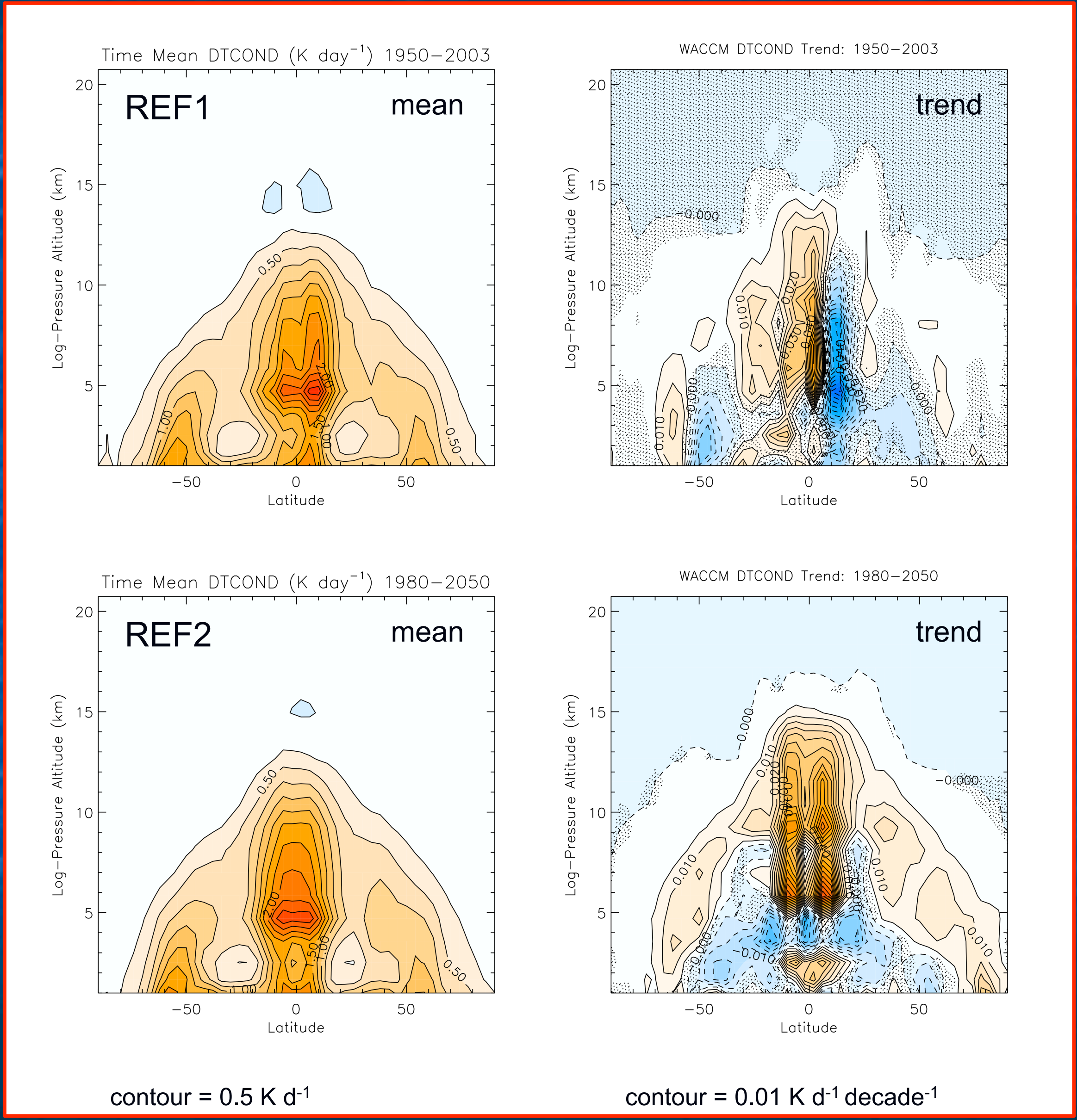
- Most wave activity generated in the troposphere [div(**F**) > 0] is dissipated there [div(**F**) < 0] (left panel)
- Trends in wave activity are mostly insignificant except in Tropics (right panel)
- BD circulation in lower stratosphere is driven by subtropical div(**F**) < 0 between 15-20 km
- BD circulation trends result from intensification and upward extension of subtropical div(**F**) centers (red circles)
- Results for REF2 case are similar, although details differ

Zonal-mean T, U and **F** Trends: focus on UTLS



- Tropospheric warming and stratospheric cooling driven by GHG sharpens zonal-mean T gradients in the lower stratosphere
- Zonal-mean U changes accordingly
- Trends in **F** (superimposed on U trends) coincide with regions of increasing westerlies in the lower stratosphere
- Suggests trends in div(**F**) in subtropical lower stratosphere may also be related to enhanced wave propagation into the region

Zonal-mean Trends in Convective Heating Q



- Changes in Q are not large compared to maximum time-average values
- But they are comparatively much larger in the upper troposphere above 10 km
- Therefore, changes in the excitation of tropical Rossby waves may play a role in the increased wave driving documented here

Conclusions

- Increasing GHG lead to stronger stratospheric BD circulation
- Acceleration of BD circulation (and decrease in AOA) occurs *mainly in lower stratosphere*
- Trends are driven mainly by changes in div(**F**) *in subtropical lower stratosphere* (15-20 km)
- Trends in div(**F**) in the lower stratosphere related to:
  - increases in convective heating in the Tropics?
  - enhanced wave propagation into the lower stratosphere following from changes in the zonal wind distribution?
- There are also significant trends in the *SH high latitudes* associated with the development of the *ozone hole*
- Results are consistent in two simulations (REF1, 1950-2003) and (REF2, 1980-2050), although details differ