# The Brewer-Dobson circulation:

## Interannual variability and climate change

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# Outline of this talk

- Something about zonal Fourier decomposition
- **The BDC: what it is and what it does**
- **Quantifying the wave driving of the BDC**

- **ERA-40: Observed interannual variability in NH (I)**

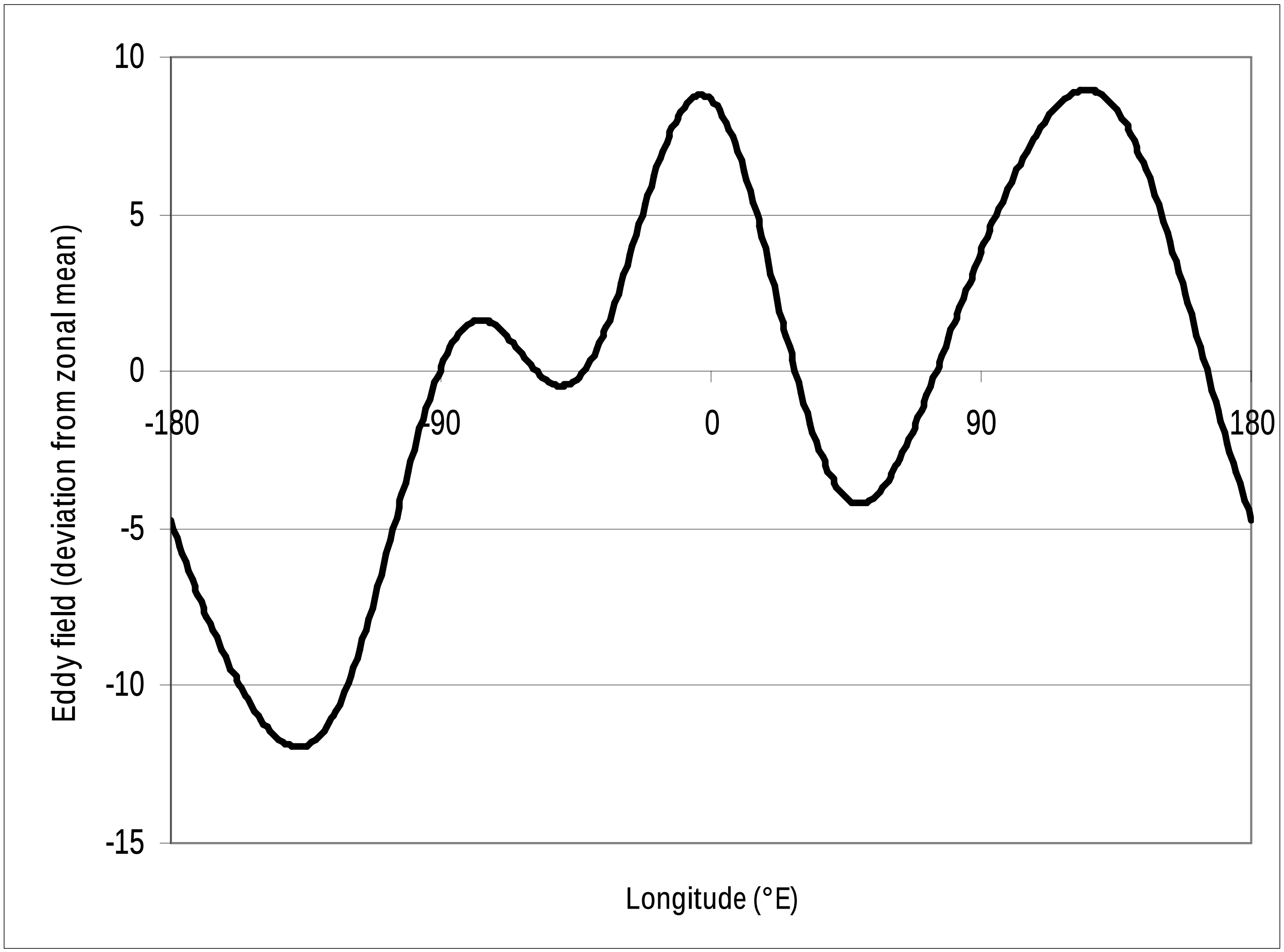
  - Associated with what wave type?

- **MA-ECHAM4: Doubled-$CO_2$ climate experiment (II)**

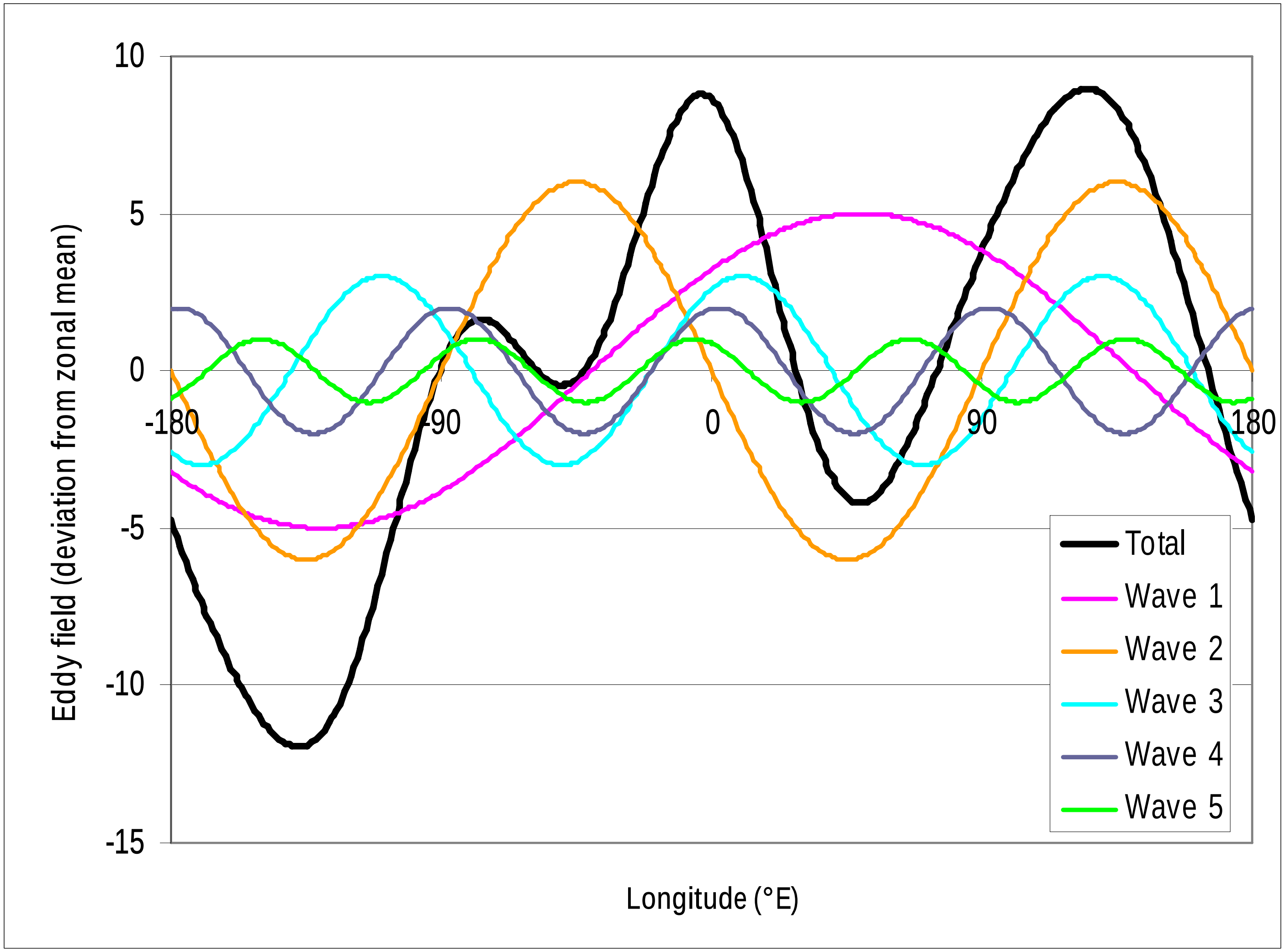
  How does the mean forcing of the BDC change?

  - Can we understand this change?

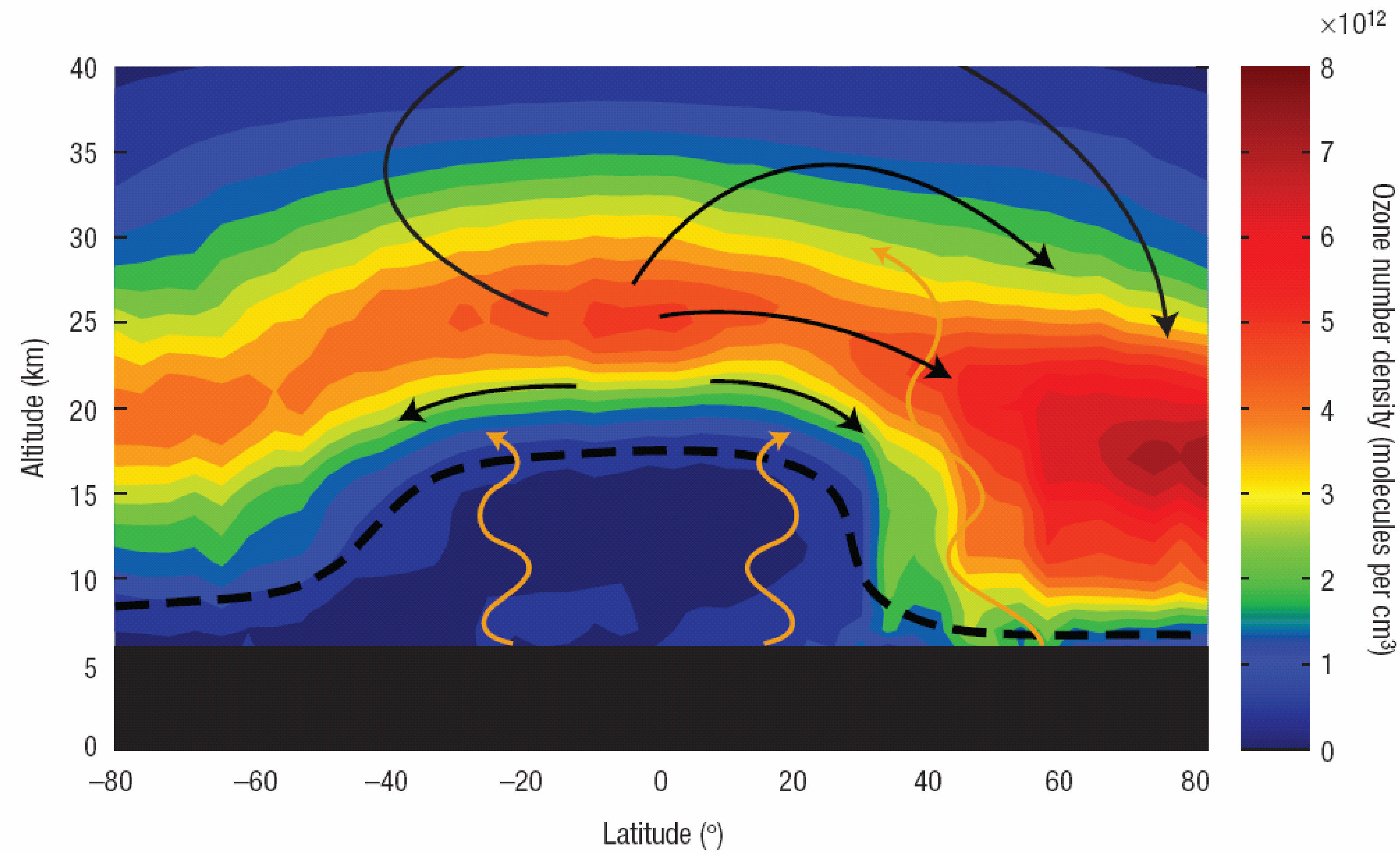
# Decomposition in zonal wavenumbers



# Decomposition in zonal wavenumbers

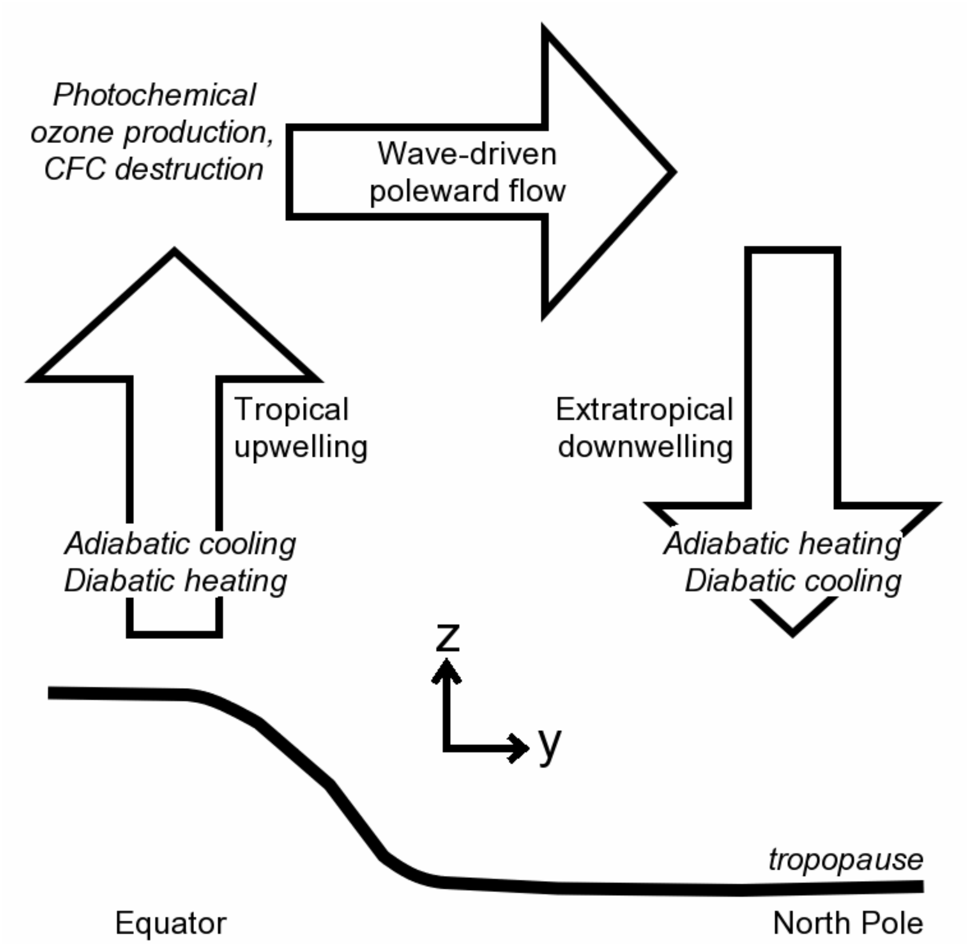


# The BDC: what it is and what it does




Ozone distribution in March 2004. Shaw and Shepherd, *Nature Geoscience* **1**, 12 - 13 (2008)

# The BDC: what it is and what it does




- BDC draws ozone-rich air poleward from the tropics
- Little ozone loss at high latitudes, new ozone production in the tropics by the adjustment towards photochemical equilibrium >> net production
- BDC is a CFC processor: it brings CFCs into the tropical upper stratosphere (> 25 km) where they are photochemically destroyed
- Adiabatic compression of air in downward branch at the pole yields higher early-spring temperatures → less PSC's

# The BDC: what it is and what it does

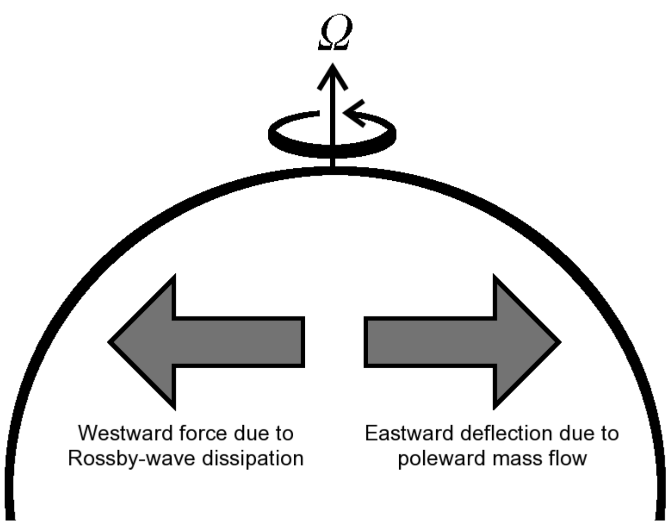
- Zonal-mean zonal momentum equation

$$\frac{\partial [u]}{\partial t} - f\tilde{v} = \frac{1}{a\cos\phi}\nabla\cdot\mathbf{F} + [R]$$

**[illegible] ward wave forcing**

**$\mathbf{F} = (F_y, F_z)$ Eliassen-Palm flux**

**Forcing due to unresolved waves [*R*] relatively small in the extratropical NH winter stratosphere**



# Quantifying the wave driving

- The polar-cap average of the downward mass flux north of latitude $\phi_r$ is proportional to $F_z$ at $\phi_r$ at mid- to high latitudes:

$$-\frac{\int_{\phi_r}^{90^\circ}\tilde{w}\cos\phi}{\int_{\phi_r}^{90^\circ}\cos\phi} \propto F_z\Big|_{\phi_r} \propto [v^*T^*]\Big|_{\phi_r}$$

**Poleward eddy heat flux [*v***T**] at mid- to high latitudes good proxy for northern-winter wave driving of BDC**

Lower-stratospheric $F_z$ and [*v***T**] should be highly correlated with

- Advection of ozone at midlatitudes
- Polar-cap temperature tendency

$v$ = meridional wind
$T$ = temperature
[ . . . ] = zonal average
* = local departure from zonal average

# Quantifying the wave driving

- Advection of ozone at midlatitudes indeed highly correlated with $F_z$ (Fusco and Salby, 1999)

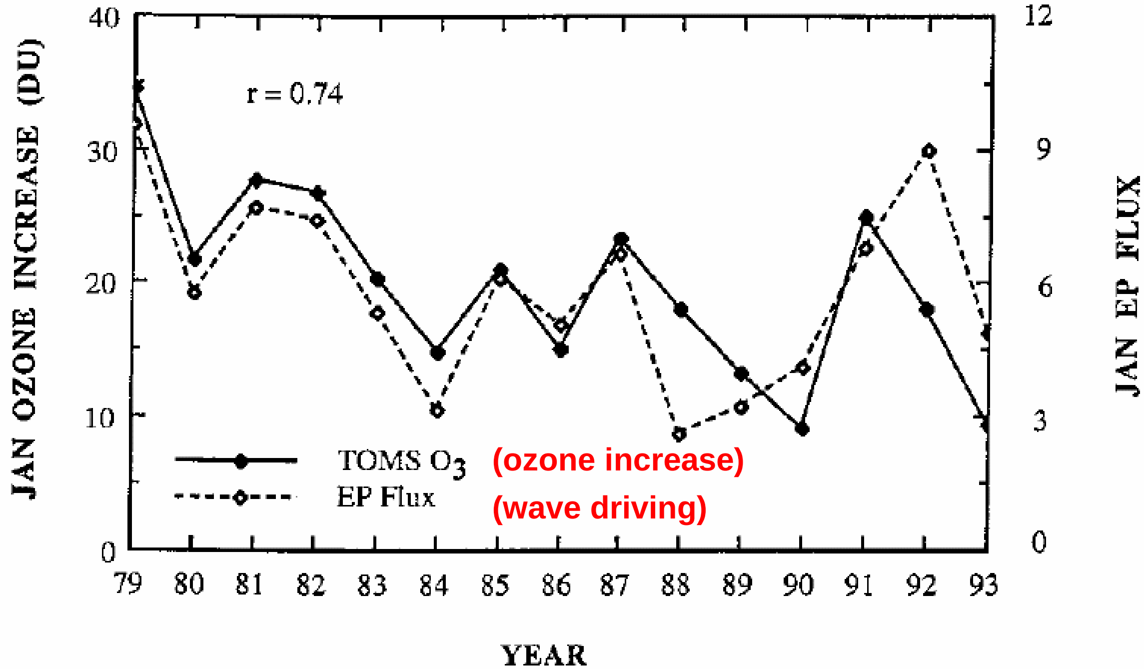
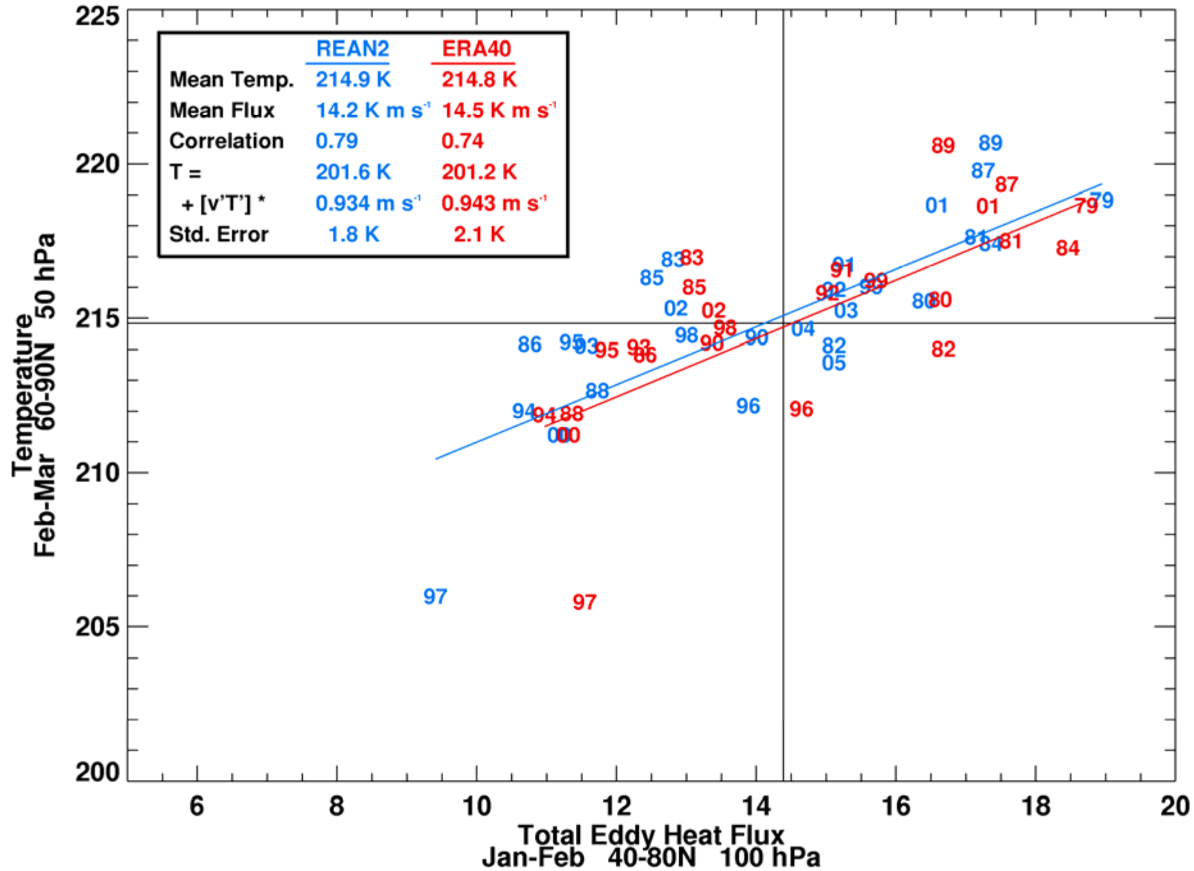



FIG. 4. Upward EP flux at 100 mb during Jan (normalized), averaged over the winter hemisphere $\overline{F}_z$ (dashed), compared against the corresponding increase of extratropical total ozone $\Delta\overline{O_3}$ (solid).

# Quantifying the wave driving

- Temperature tendency at high latitudes indeed highly correlated with [*v***T**] (Newman, 2005)



# Quantifying the wave driving

NH wave driving of the BDC quantified by $H_{100}$:

$H_{100}$ = [$v$*$T$*] at 100 hPa (lower stratosphere),

averaged over

- January/February
- 40°-80°N

Total wave driving:

**- sum of zonal wavenumber components**

**- sum of stationary and transient components**

(stationary component is obtained by multiplying the Jan-Feb mean *v** field by the Jan-Feb mean *T** field)

# Observed interannual variability in NH

- Variations in the wave driving of the BDC possibly due to:
  - variations in shape of the wave spectrum (only waves with the lowest zonal wavenumbers can enter the stratosphere)
  - variations in total tropospheric Rossby-wave generation
  - variations in total wave amplitude
  - variations in total wave ‘efficiency’

- Data:

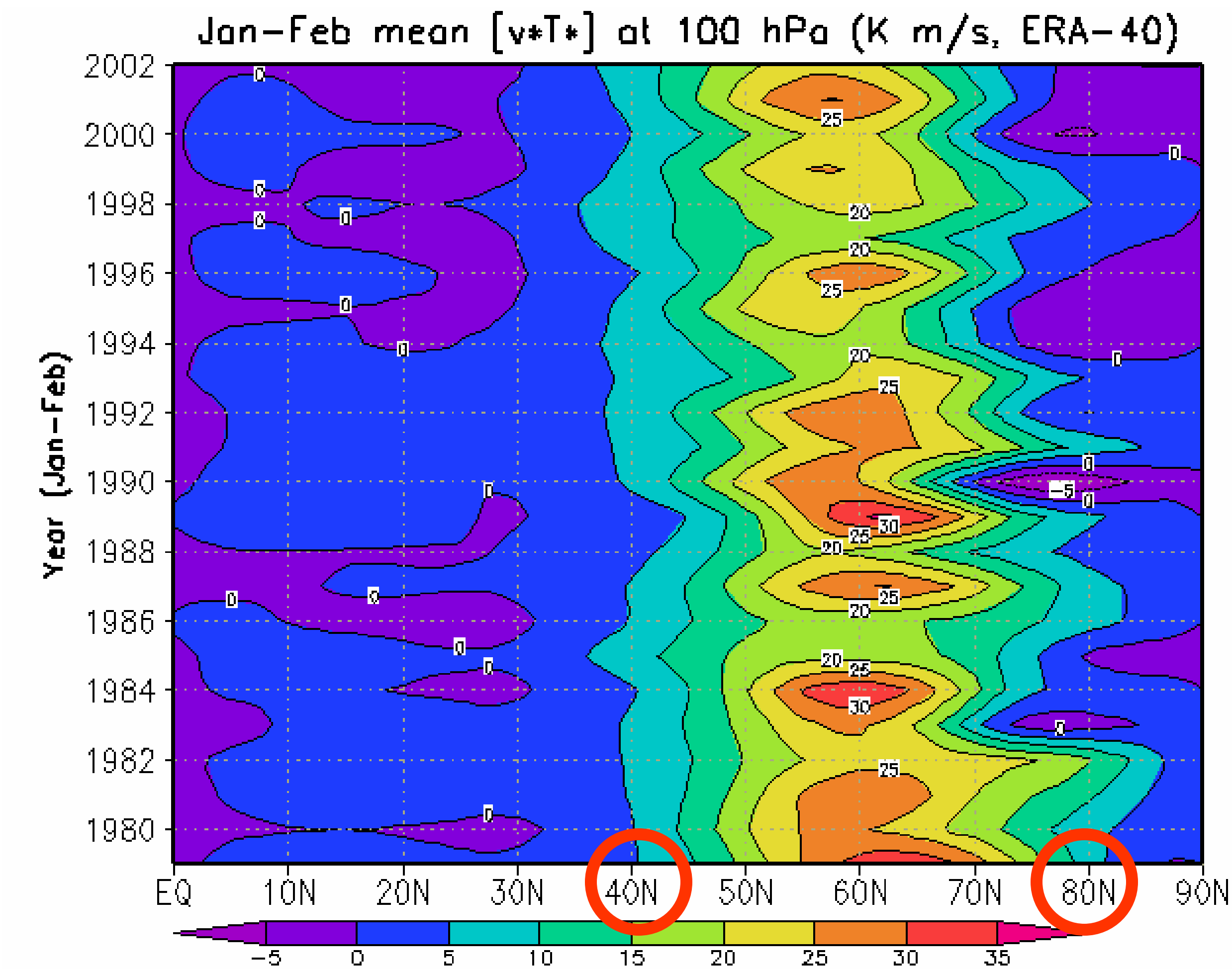
  ERA-40 reanalysis data for 1979-2002

  *2.5° × 2.5° lat-lon grid*

  *6-hourly wind and temperature fields*

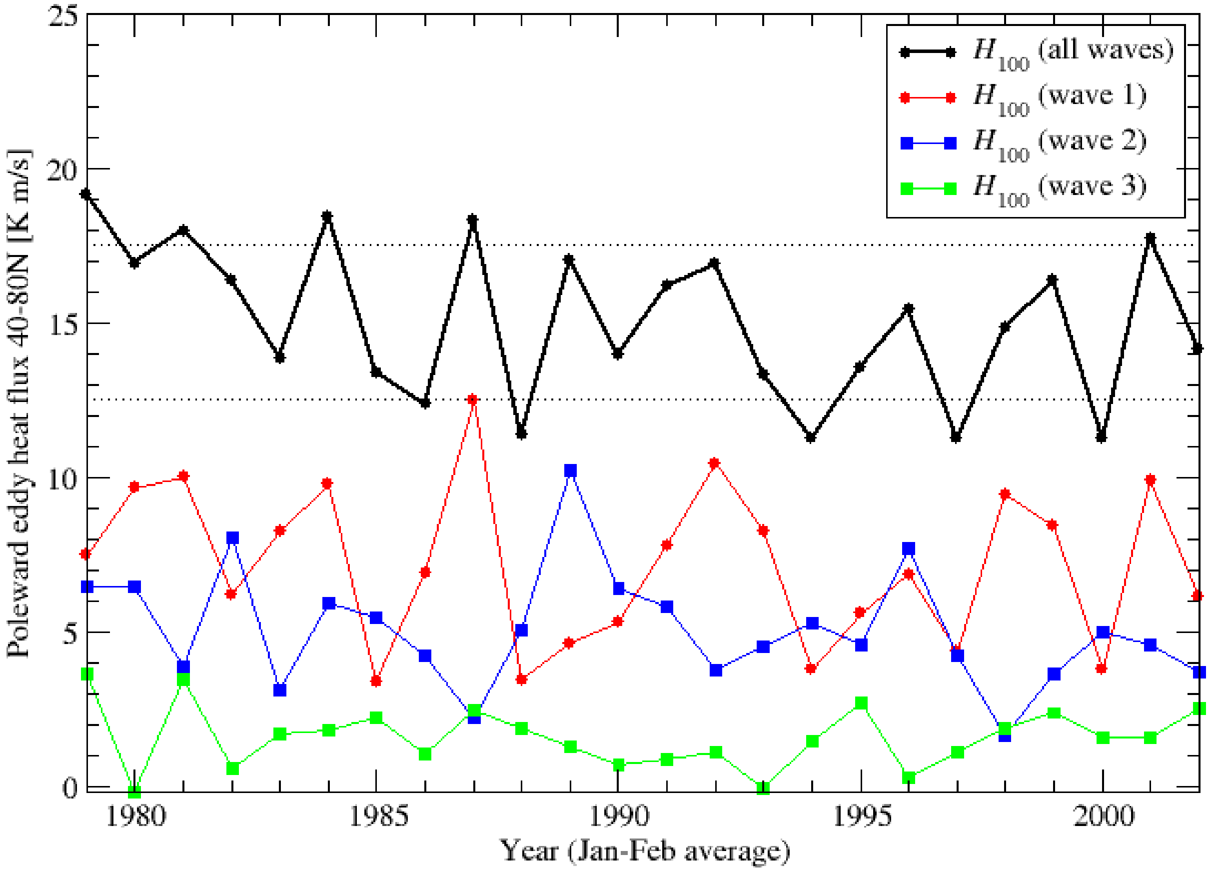
  *23 levels between 1000 and 1 hPa*

# Observed interannual variability in NH



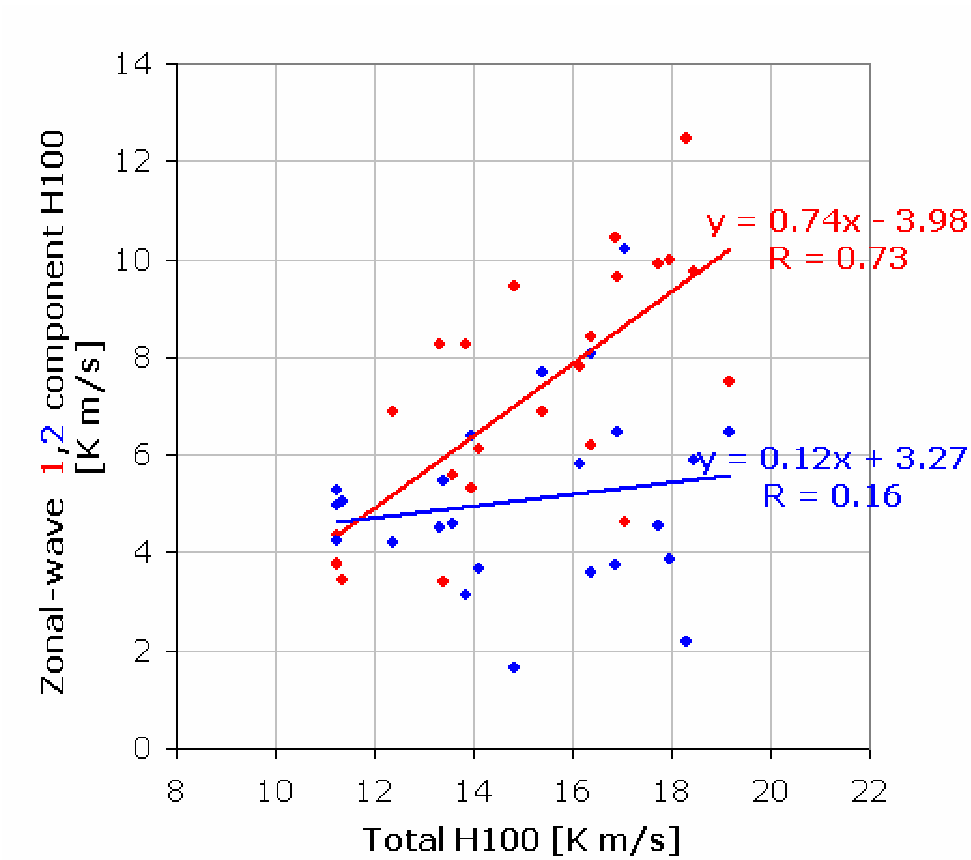

$H_{100}$ is the average over 40-80°N

# Observed interannual variability in NH




- $H_{100}$ ranges between 11.2 and 19.2 K m/s (average 14.5)
- Zonal waves 1-3 account for >90% of $H_{100}$

# Observed interannual variability in NH




Linear regression analysis:

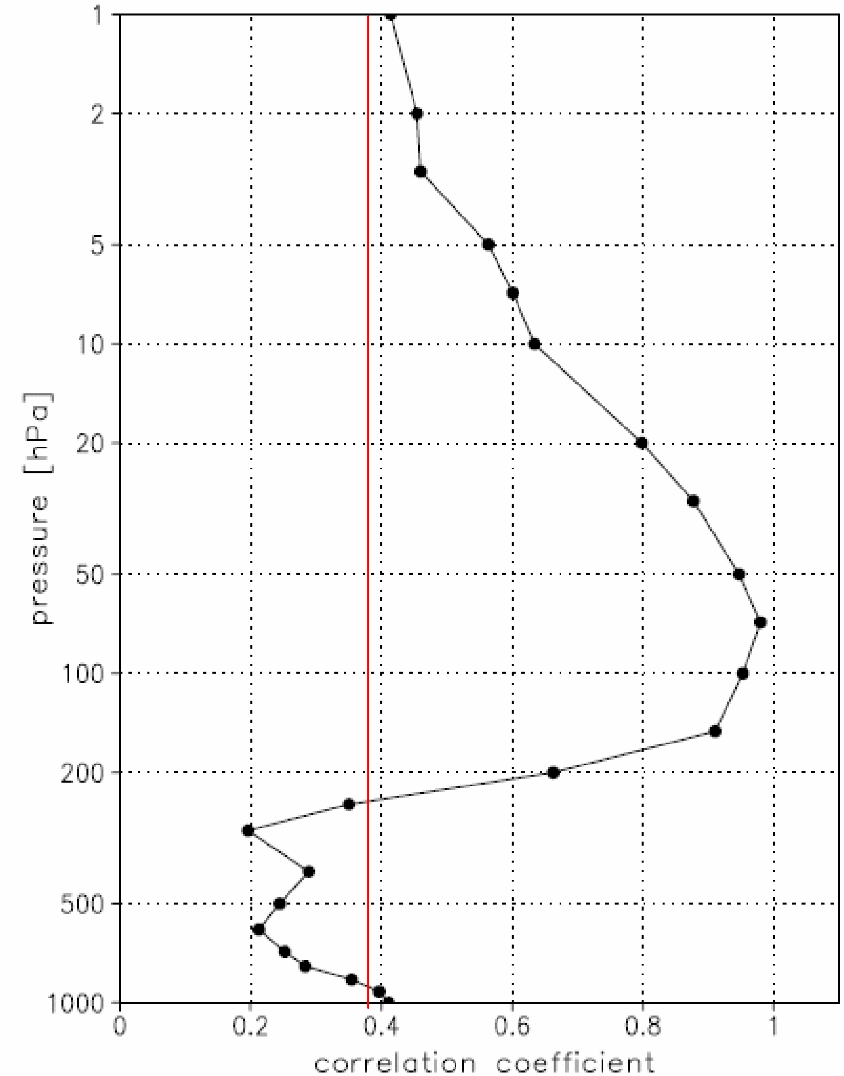
Total $H_{100}$ = sum of zonal wavenumber components

Sum of regression coefficients is 1.

Wavenumbers 1+2 account for ~86% of interannual variability

Stationary component of wave 1: ~56% (not shown in plot)

# Observed interannual variability in NH




**Vertical coupling:**

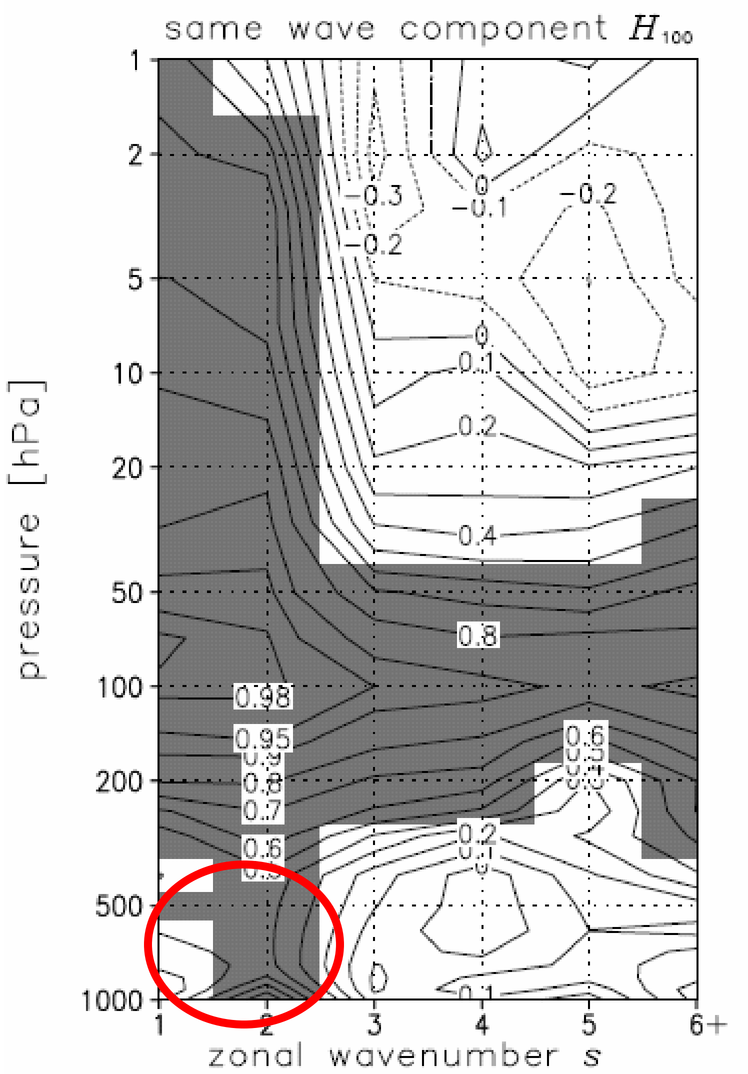
How important is the total wave driving at other (esp. lower) levels?

Correlate $H_{100}$ with [$v^*T^*$] averaged over 20-90°N at other levels

No significant correlation below 200 hPa

Interannual variability wave driving not due to variability **total** wave activity in troposphere

# Observed interannual variability in NH

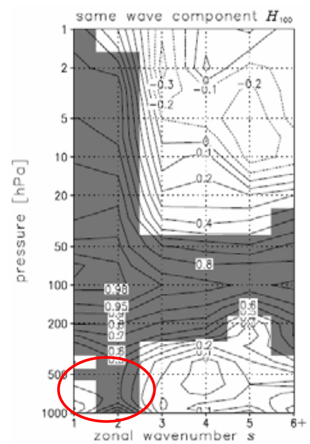



**Vertical coupling per individual wavenumber:**

Correlate **wave component** of $H_{100}$ with **the same wave component** of [$v^*T^*$] averaged over 20-90°N at other levels

Only individual wave 1 and 2 components show significant coupling between 100 hPa and the troposphere

# Observed interannual variability in NH

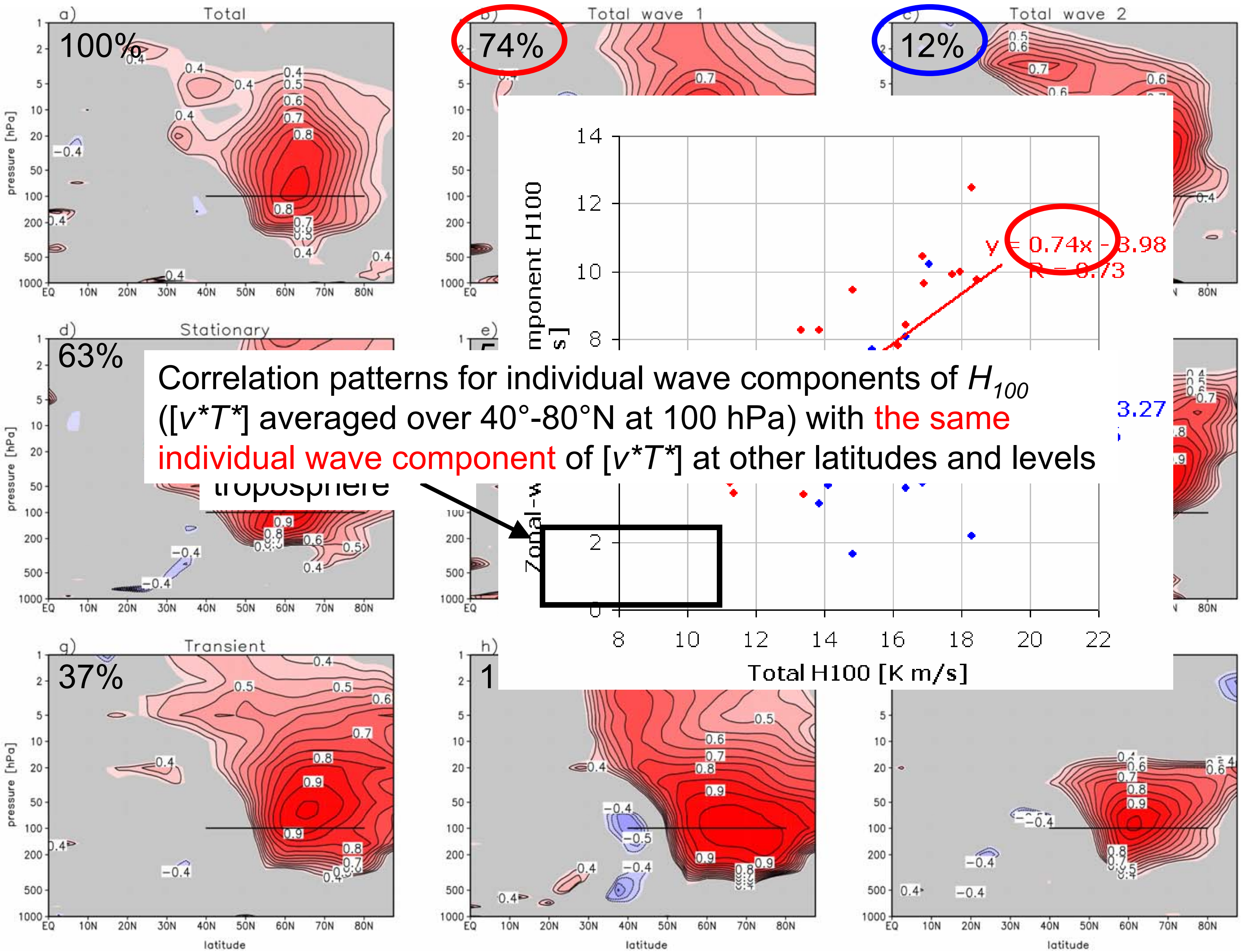



From previous slide:

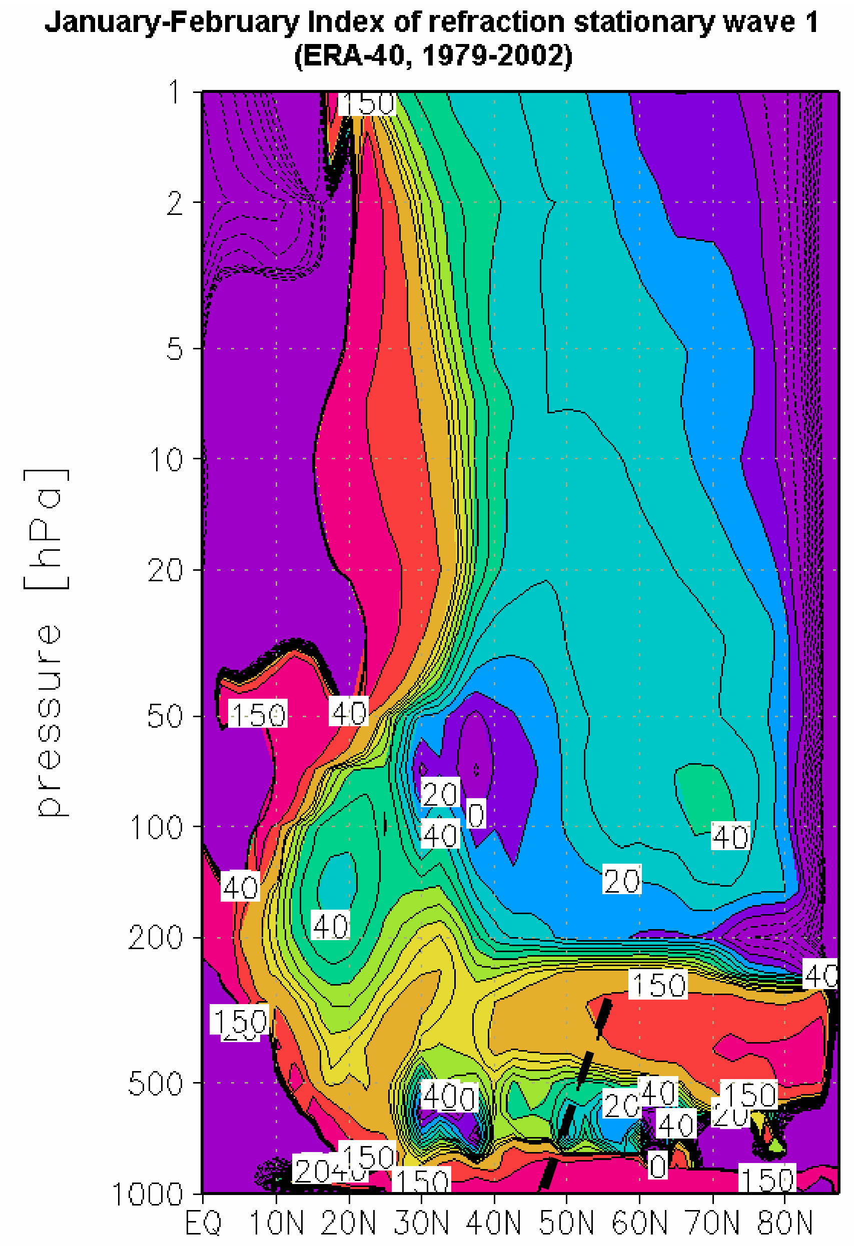
Only year-to-year variations in the individual wave 1 and 2 components show significant vertical coupling between 100 hPa and troposphere

Next slide:

What does this vertical coupling look like in the meridional plane, for the separate wave components?

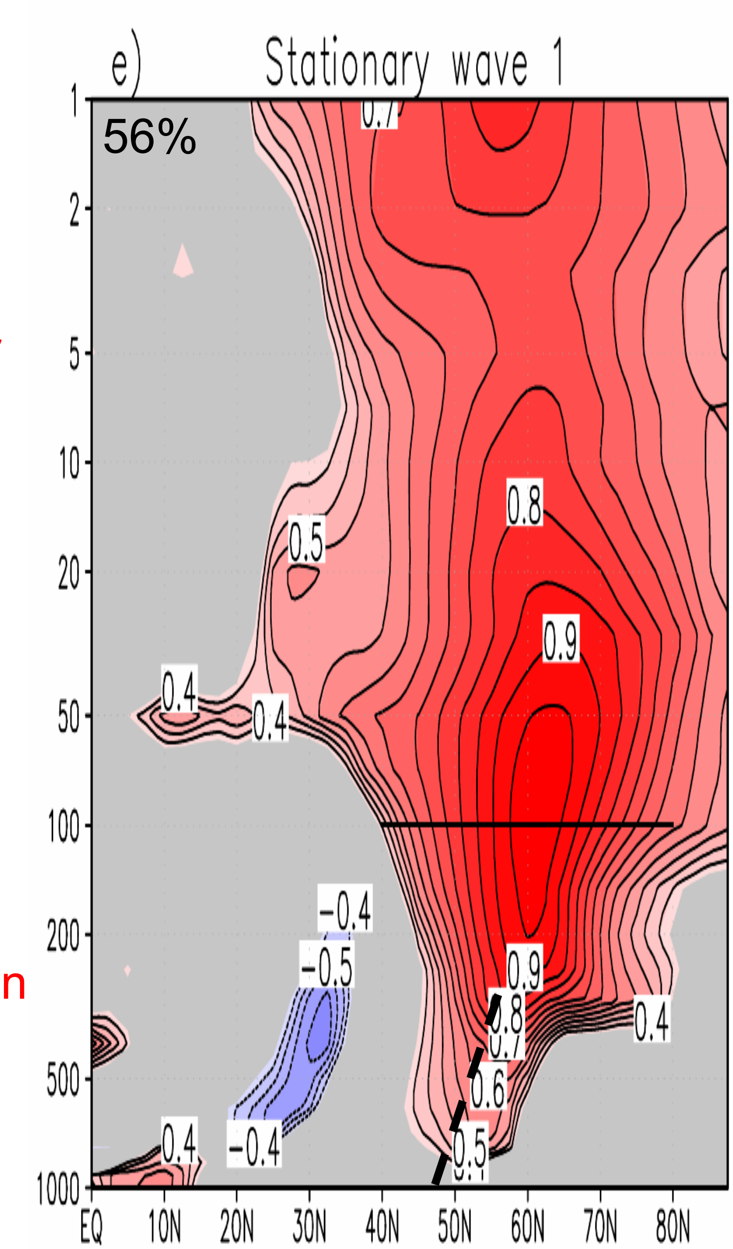


100%
74%
12%
63%
37%
Total
Total wave 1
Total wave 2
Stationary
Transient
y = 0.74x - 3.98
R = 0.73
Total H100 [K m/s]
Correlation patterns for individual wave components of $H_{100}$ ([$v^*T^*$] averaged over 40°-80°N at 100 hPa) with the same individual wave component of [$v^*T^*$] at other latitudes and levels




Waves tend to propagate towards higher values of the index of refraction.

Climatological midlatitude tropospheric waveguide might explain dipole pattern in correlation coefficients



# Conclusions Part I

- Wave 1 + 2 account for ~86% of the interannual variability in the wave forcing of the BDC
- For both wave 1 and 2, interannual variability at 100 hPa is significantly correlated with troposphere, however only for the stationary components
- Stationary wave 1 accounts for most (~56%) of the interannual variability
- The magnitude of the stationary wave-1 component of the wave driving seems to depend on the latitude of the tropospheric wave source (ability to enter waveguide)

Haklander, A. J., P. C. Siegmund, and H. M. Kelder: Interannual variability of the stratospheric wave driving during northern winter, *Atmos. Chem. Phys.*, **7**, 2575–2584, 2007.

# Part II: Change BDC in 2×$CO_2$ climate

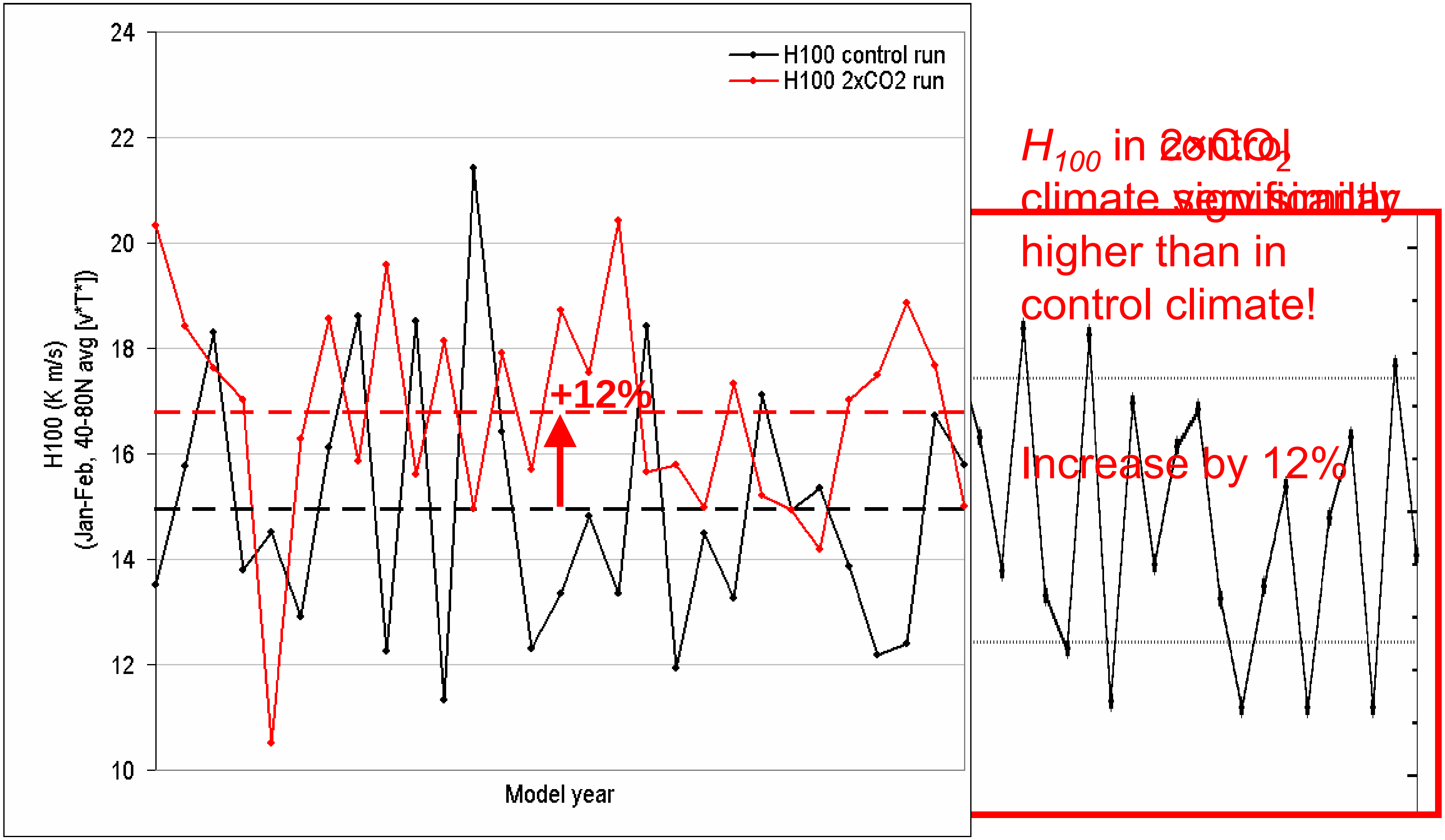
- **Model:**
  MA version of ECHAM4 GCM
  - Vertical resolution: 39 layers, up to 0.01 hPa ~ 80 km
  - Horizontal resolution: T42 ~ 2.8° × 2.8°

- **Two 30-year experiments** (Michael Sigmond, 2004)**:**
  1) Control run with $CO_2$ at global-mean 1990 level (353 ppm)
  2) Perturbation run with doubled $CO_2$ concentrations

- **SSTs prescribed from low-top ECHAM4 + slab layer ocean control runs**

- **Ozone prescribed (identical for both runs)**

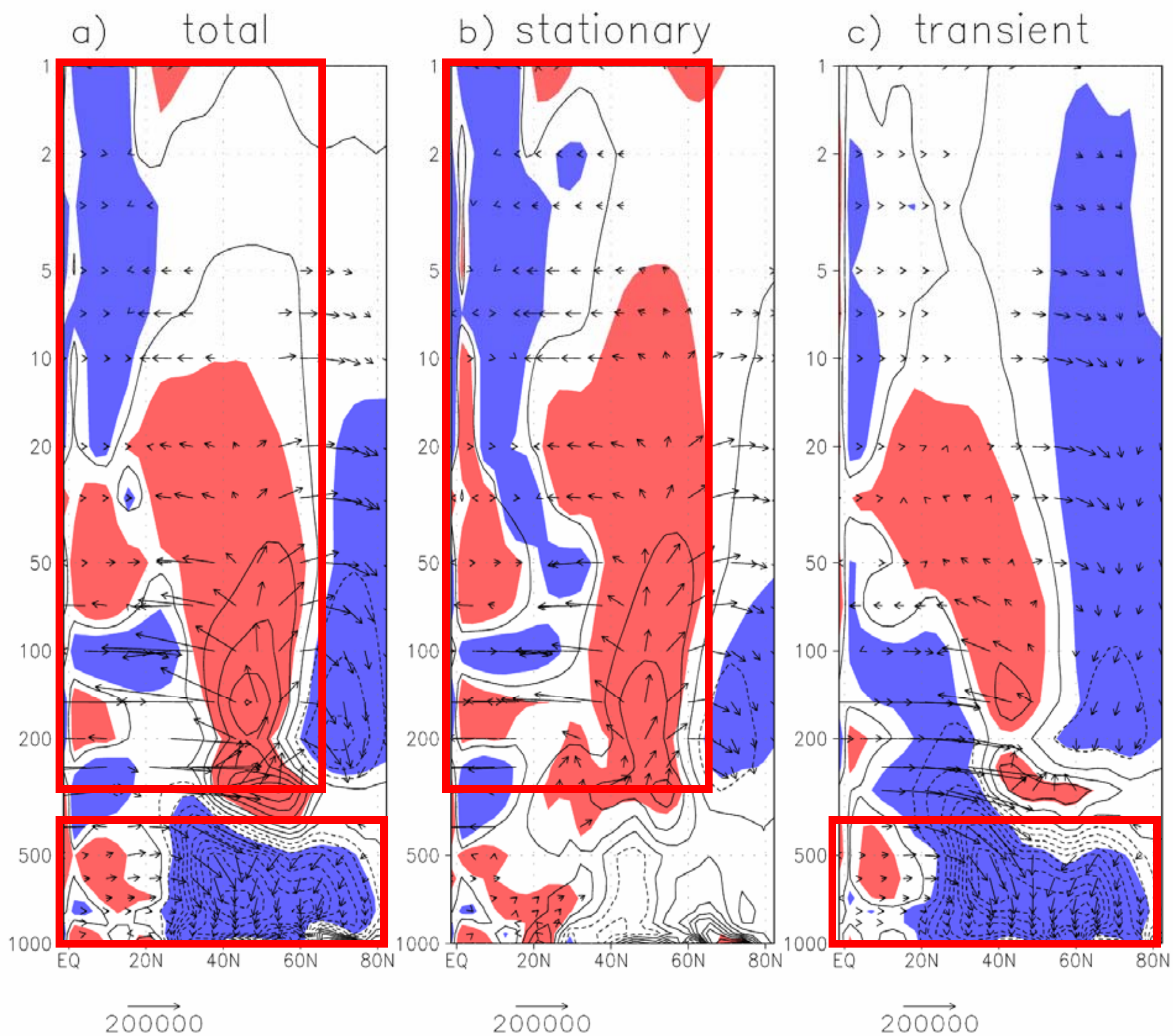
# Change in BDC in 2×$CO_2$ climate




$H_{100}$ in 2×$CO_2$ climate significantly higher than in control climate!

Increase by 12%

# Change in BDC in 2×$CO_2$ climate

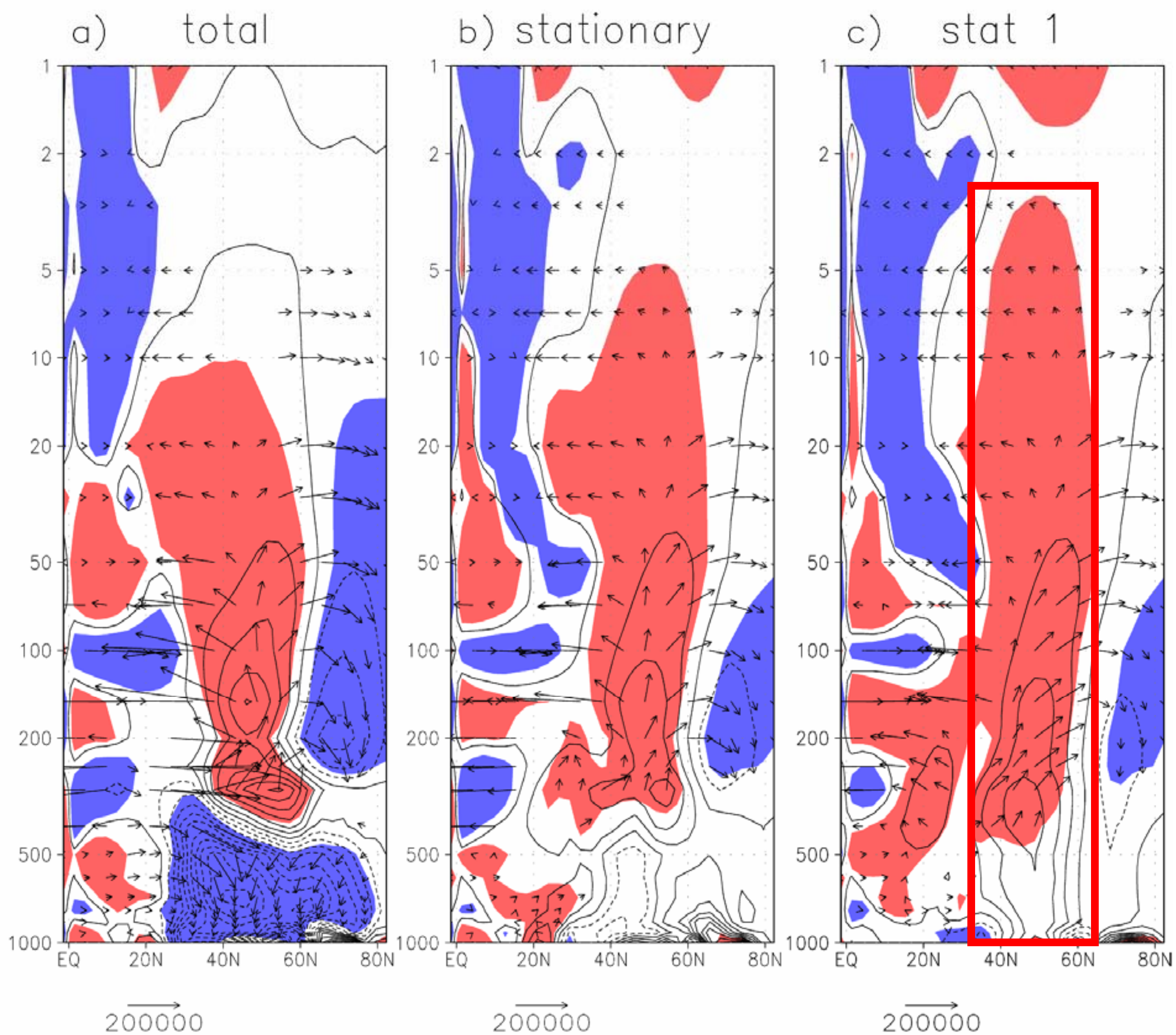



Difference in Eliassen-Palm (EP) flux vectors, 2×$CO_2$ – control:

Shading indicates 95% significant changes in upward component EP flux

Total stratospheric/tropospheric change pattern very similar to stationary/transient change pattern

# Change in BDC in $2\times CO_2$ climate




**$2\times CO_2$ – control components $H_{100}$:**

**Total** +1.8 K m/s

**Stationary** +2.0 K m/s

**Stat wave1** +1.7 K m/s

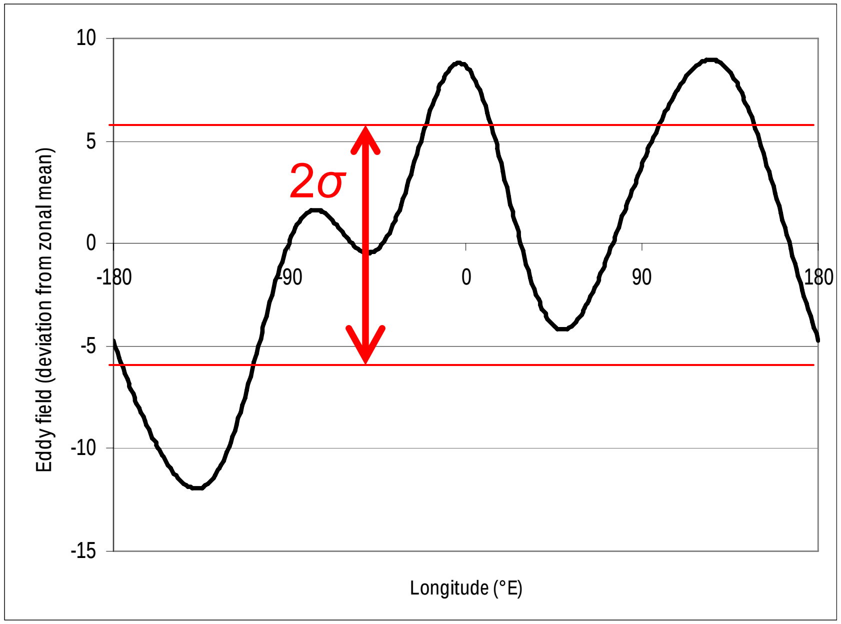
(all >95% signif.)

**Vertically coherent increase $F_z$ stationary wave 1, also in troposphere** (not significant below 500 hPa)

**More generation of stationary wave 1 activity?**

# Change in BDC

- Finally…
  Can we understand the increased wave driving of the BDC at 100 hPa in terms of the following relation?




$$[v^*T^*] = r_{v,T}\sigma_v\sigma_T$$

Zonal covariance between *v* and *T*

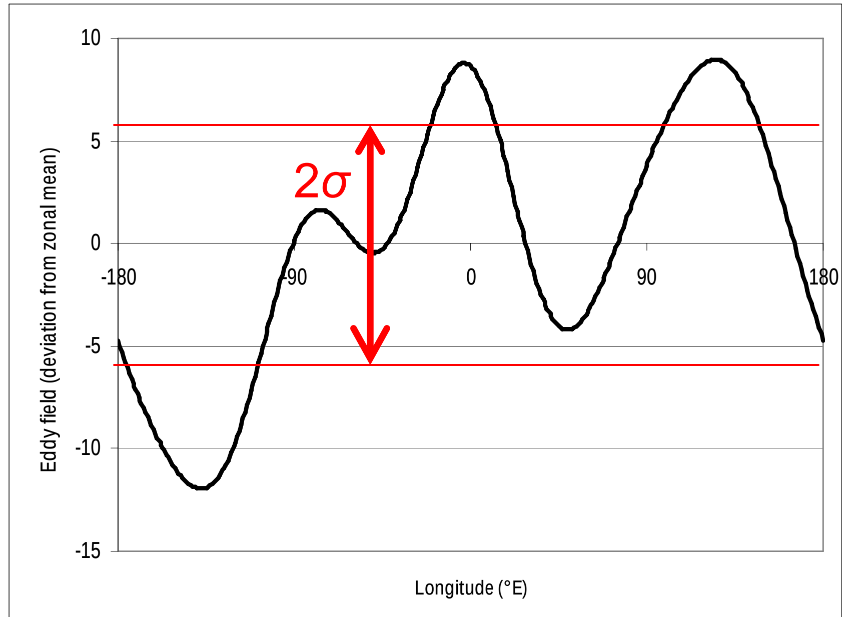
Zonal correlation coefficient between *v* and *T* *'wave efficiency'*

Zonal stdev *v*

Zonal stdev *T*

# Change in BDC

- Finally…
  Can we understand the increased wave driving of the BDC at 100 hPa in terms of the following relation?




$$[v^*T^*] = r_{v,T}\,\sigma_v\,\sigma_T$$

Increase +12% (±8%)

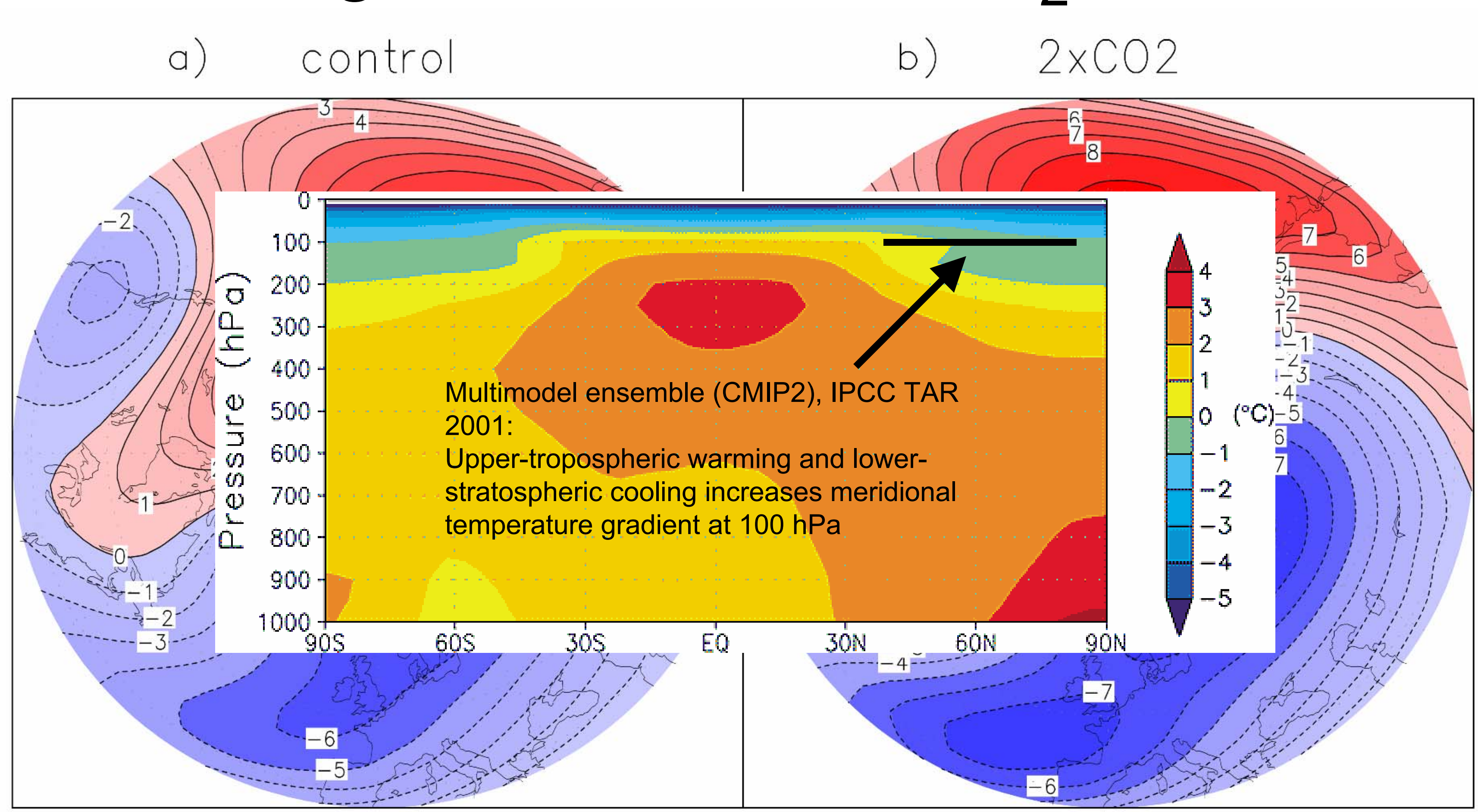
No significant change

Increase +4% (±3%)

Increase +12% (±5%)

Highly significant increase of 12%, same magnitude!
More longitudinal temperature variability at 100 hPa

# Change in BDC in 2×$CO_2$ climate




Increase in zonal temperature asymmetries likely due to increase in meridional temperature gradient (robust feature in enhanced-$CO_2$ climate experiments)

Climatological $T^*$ pattern at 100 hPa also shows increase in longitudinal variability

# Conclusions Part II

- Doubling $CO_2$ concentrations in the MA-ECHAM4 GCM yields a significant increase in $H_{100}$ of ~12%
- Transient waves account for most of the tropospheric change, stationary waves for the stratospheric change
- Stationary wave-1 increase significant and comparable to total increase → more tropospheric wave generation?
- Strenghtening of the wave driving likely associated with increased longitudinal temperature variability (due to increased north-south temperature differences at 100 hPa)

Haklander, A. J., P. C. Siegmund, M. Sigmond, and H. M. Kelder: How does the northern-winter wave driving of the Brewer-Dobson circulation increase in an enhanced-CO2 climate simulation?, *Geophys. Res. Lett.*, **35**, L07702, doi:10.1029/2007GL033054, 2008.

# Thank you!