# *Diagnosing the causes of the climate-change induced strengthening of the Brewer-Dobson circulation*

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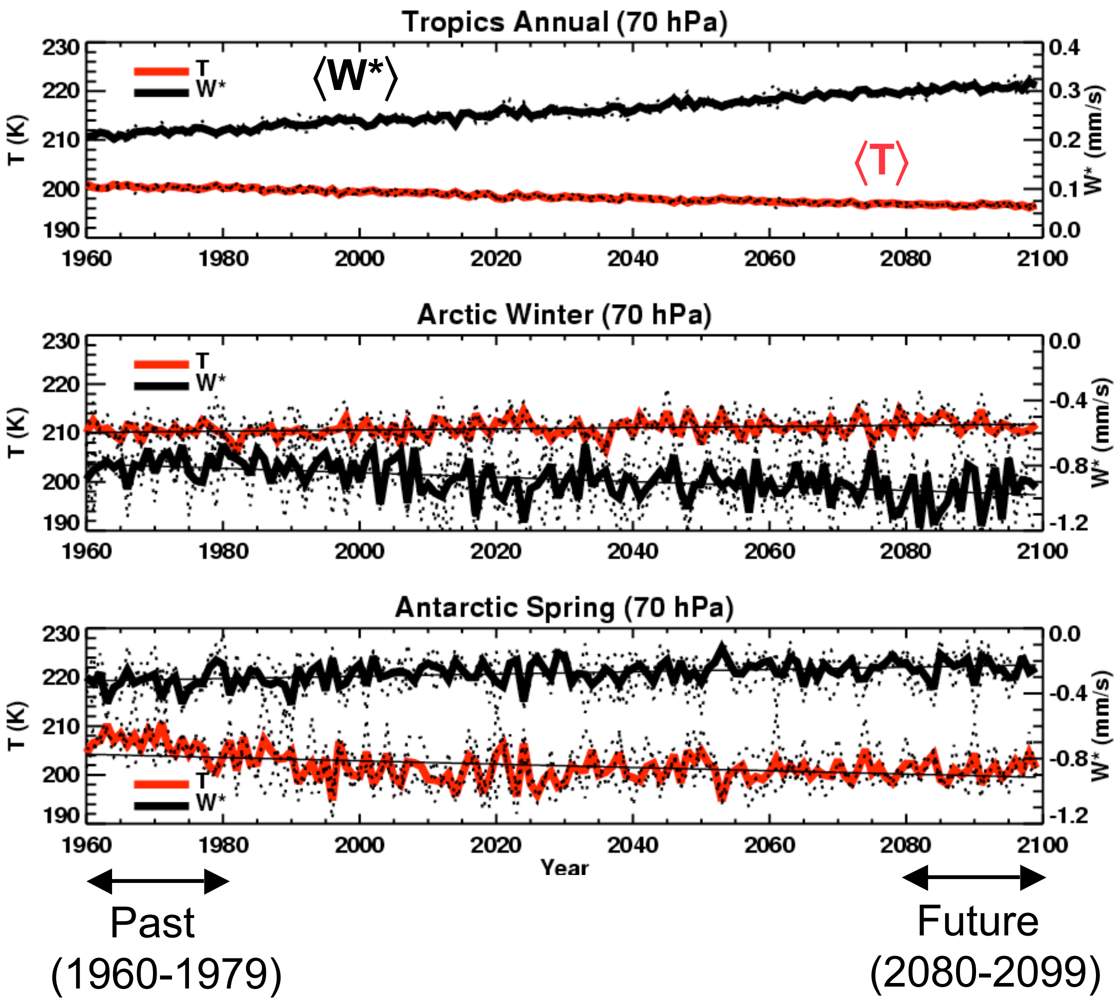
# Goals

- Quantify the roles of planetary waves, synoptic waves, and parameterized gravity waves in driving the predicted climate-change induced strengthening of the BDC.
- Investigate the connection between the high and low latitude changes in the BDC.

# Model Simulations

- Using the Canadian Middle Atmosphere Model (CMAM) - a CCM which simulates climate change and ozone depletion and recovery.
- Here we examine three 150-year (1950-2100) transient simulations using the CCMVal “REF2” scenario for changes in GHGs and ODSs.
- SSTs specified from a coupled atmosphere-ocean model.

# Simulated trends in temperature & residual vertical velocity in lower stratosphere



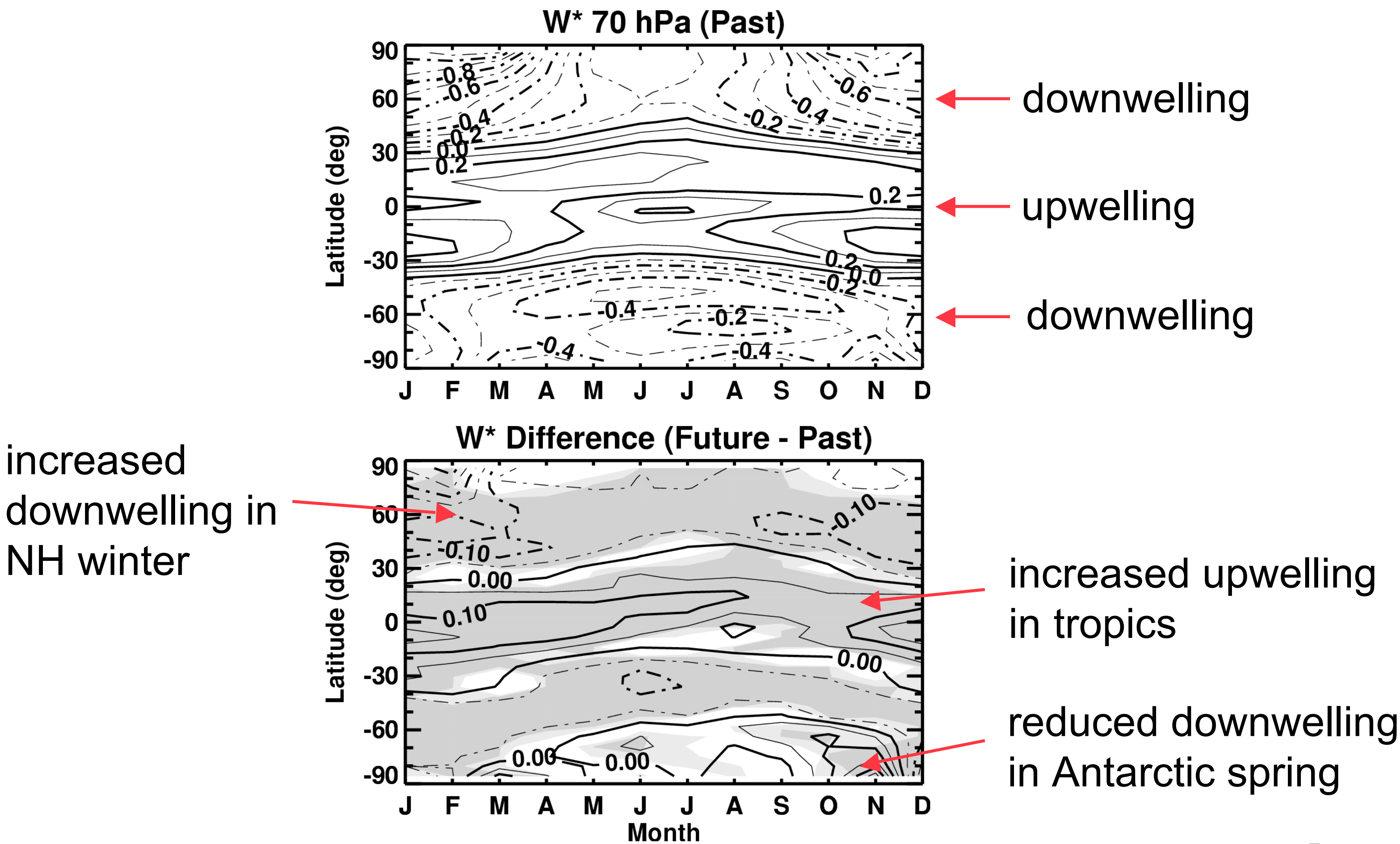

thick curves = ensemble average
dotted curves = three individual simulations

**Tropics:** cooling and increasing upwelling.

**Arctic winter:** slight warming and increasing downwelling.

**Antarctic spring:** cooling and decreasing down-welling. Note that ozone depletion causes stronger cooling in late 20th century.

# Changes in *w** in lower stratosphere




light and dark shading = 95% and 99% confidence levels

# “Downward control” diagnostics

- Contributions to *w** from different types of wave drag (*F*) given by:

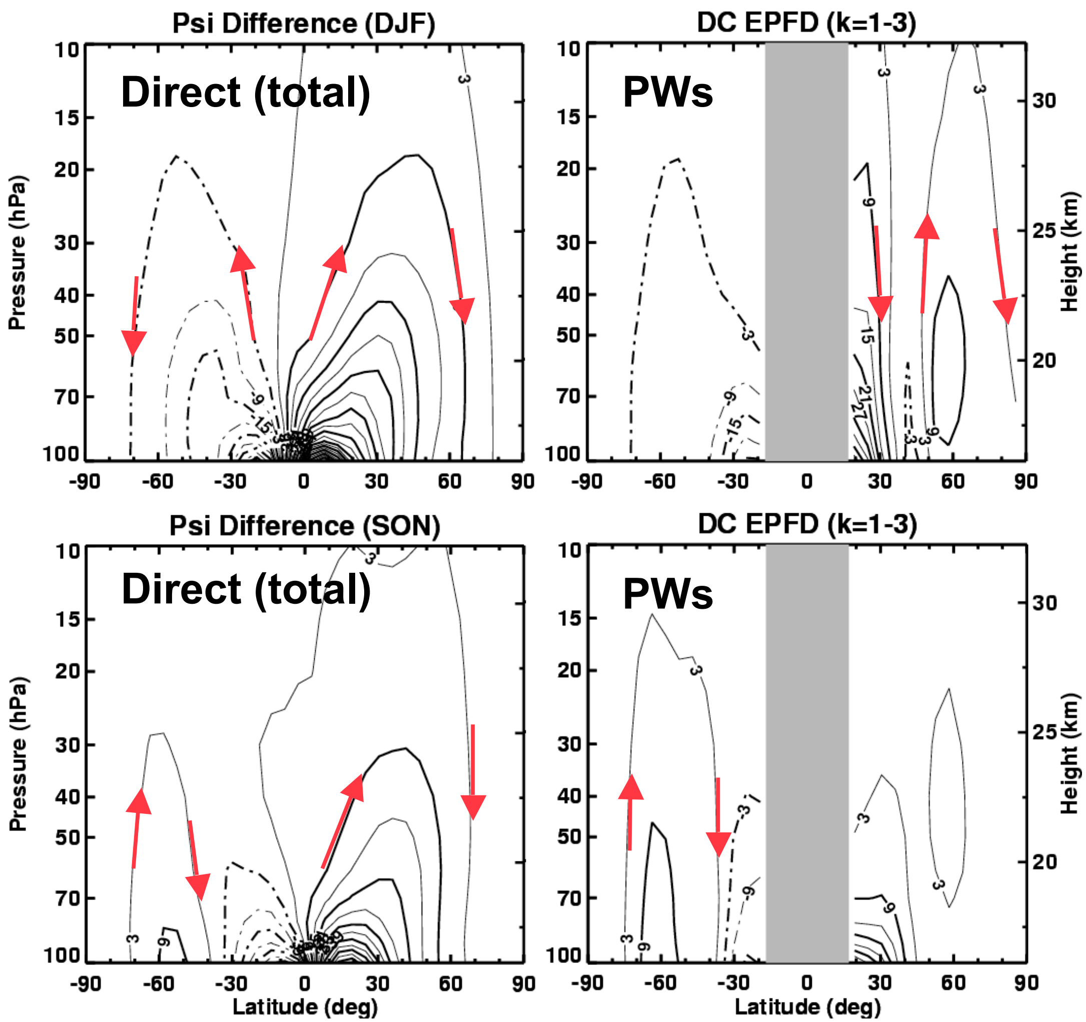
$$\bar{w}^* = \frac{-1}{a\cos\phi}\frac{\partial}{\partial\phi}\left[\frac{1}{\rho}\int_z^\infty \frac{\rho\bar{F}\cos\phi}{\hat{f}}\,dz\right]$$

- *F* includes: resolved wave drag due to planetary waves (k=1-3) and synoptic waves (k>3); parameterized orographic and nonorographic gravity wave drag.

# Impact of planetary wave drag

$\Delta\Psi$ (DJF)

$\Delta\Psi$ (SON)

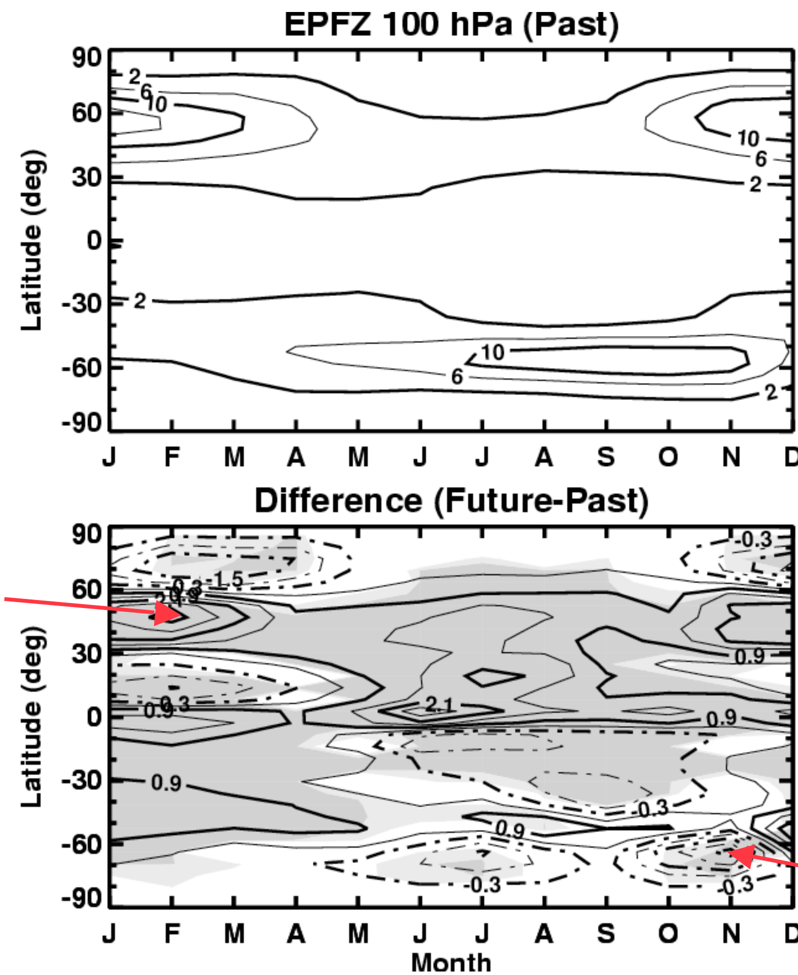



**NH winter:** PWs drive increased downwelling in Arctic and down-welling in subtropics.

**Antarctic spring:** PWs drive reduced downwelling.

$$\bar{v}^* = \frac{-1}{\rho \cos\phi}\frac{\partial \Psi}{\partial z} \qquad \bar{w}^* = \frac{1}{\rho\, a \cos\phi}\frac{\partial \Psi}{\partial \phi} \qquad \Psi(\phi, z) = -\int_z^{\infty} \frac{\rho \bar{F} \cos\phi}{\hat{f}}\, dz$$

# Vertical component of EP flux in upper troposphere




**increased $F_Z$ in NH mid latitudes in winter**

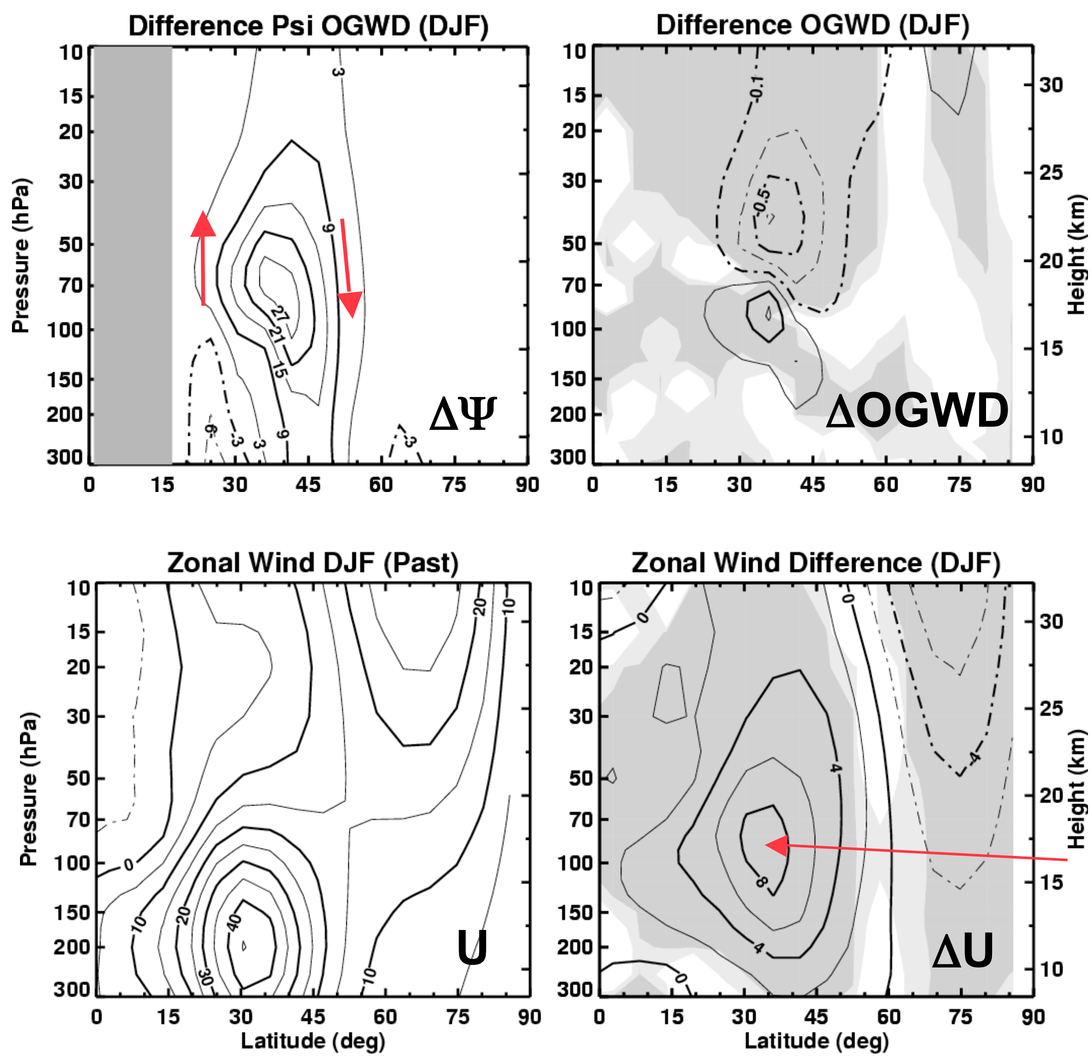
**reduced $F_Z$ in Antarctic spring (and winter)**

## Other comments:

- stationary PWs account for most of changes in $F_z$.
- averaging $F_z$ over latitude (e.g. Newman et al. 2001) may mask climate-change signal.

# Impact of orographic GWD

Changes in OGWD drive increased upwelling in subtropics, downwelling in mid latitudes.



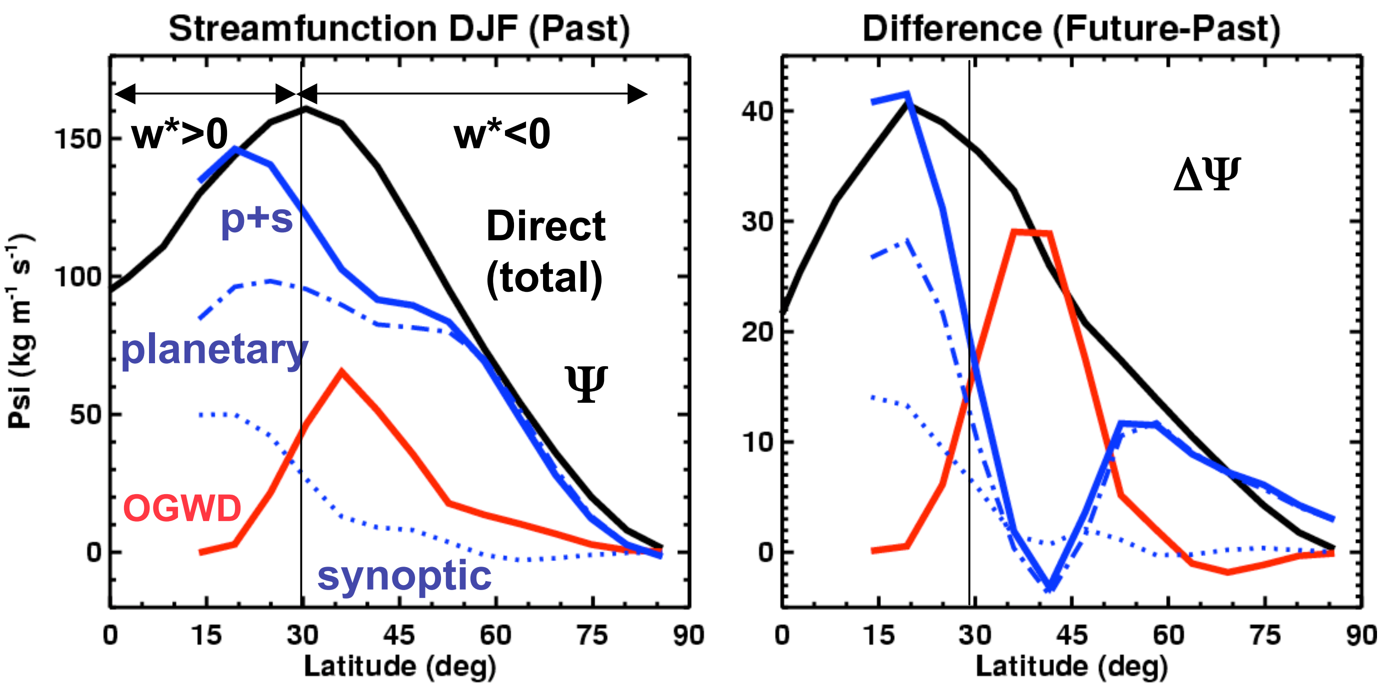

Dipole pattern of ΔOGWD indicates upward shift in (negative) OGWD maximum.

Upward shift in OGWD results from climate-change induced increase in SWJ in lower stratosphere.

# Net downward mass flux

$$F_{nh}^{\downarrow} = -2\pi a^2 \rho \int_{\phi_{nh}}^{90} \bar{w}^* \cos\phi \, d\phi$$

⇒ Gives net mass exchange between stratosphere and troposphere.



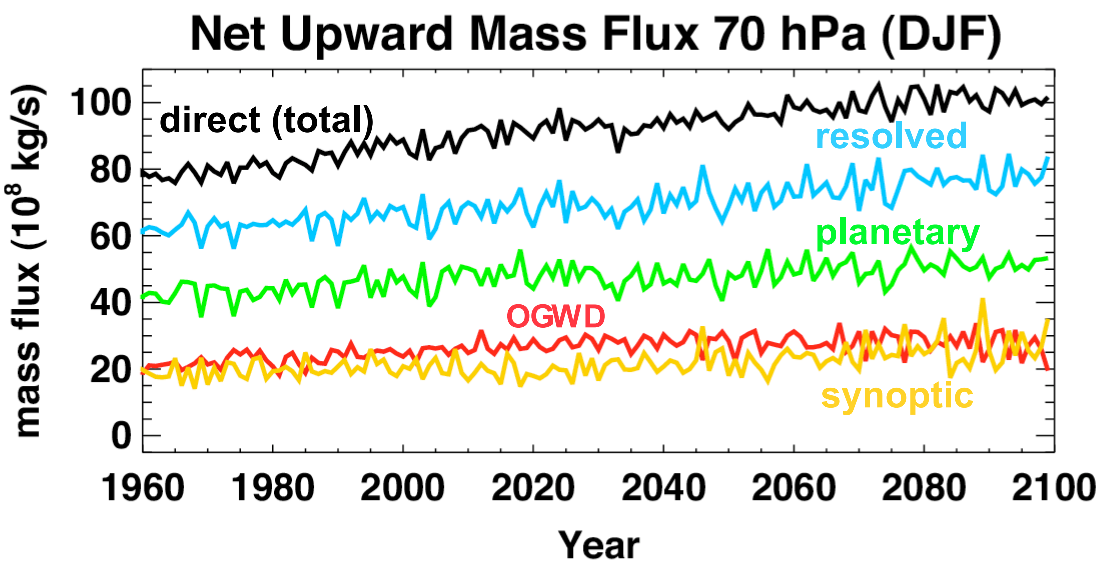

- $\Delta$ mass flux proportional to $\Delta\Psi$ evaluated at latitude $\varphi_{NH}$.
- $\Delta$ mass flux sensitive to $\varphi_{NH}$ due to rapid latitudinal variation of $\Delta\Psi$ in sub-tropics.

70 hPa

$$\bar{w}^* = \frac{1}{\rho \, a \cos\phi} \frac{\partial \Psi}{\partial \phi}$$

# Net upward mass flux

(net upward mass flux = sum of net downward mass fluxes)




**140-year linear trends**

| | | Resolved Wave Drag | | | Gravity Wave Drag | |
|---|---|---|---|---|---|---|
| Season | Direct | $k$=1-32 | $k$=1-3 | $k$=4-32 | oro | nonoro |
| DJF | 18.3 (0.6) | 12.3 (0.8) | 6.7 (0.7) | 5.6 (0.5) | 4.9 (0.6) | -0.2 (0.0) |
| MAM | 12.7 (0.3) | 6.5 (0.5) | 3.5 (0.4) | 3.0 (0.3) | 7.2 (0.4) | -0.4 (0.0) |
| JJA | 9.1 (0.4) | 7.3 (0.6) | 5.5 (0.5) | 1.8 (0.3) | 1.0 (0.3) | -0.4 (0.0) |
| SON | 8.6 (0.6) | 2.8 (0.7) | 1.9 (0.6) | 0.9 (0.3) | 4.6 (0.3) | 0.0 (0.0) |
| Annual | 12.2 (0.2) | 7.2 (0.3) | 4.4 (0.2) | 2.8 (0.2) | 4.5 (0.2) | -0.2 (0.0) |

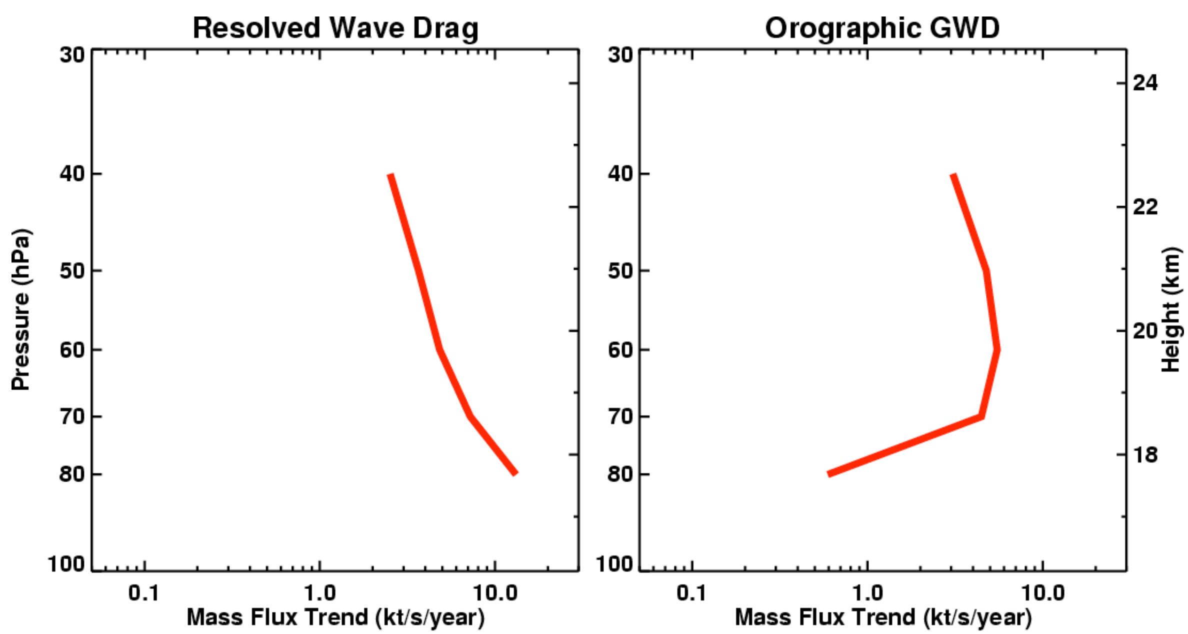
## DJF trend:

- planetary waves: ~37%
- synoptic waves: ~31%
- OGWD: ~27%

## Annual mean trend:

- planetary waves: ~35%
- synoptic waves: ~25%
- OGWD: ~35%
- note: NH DJF is ~25% of annual trend.

# Vertical variation of upward mass flux trends

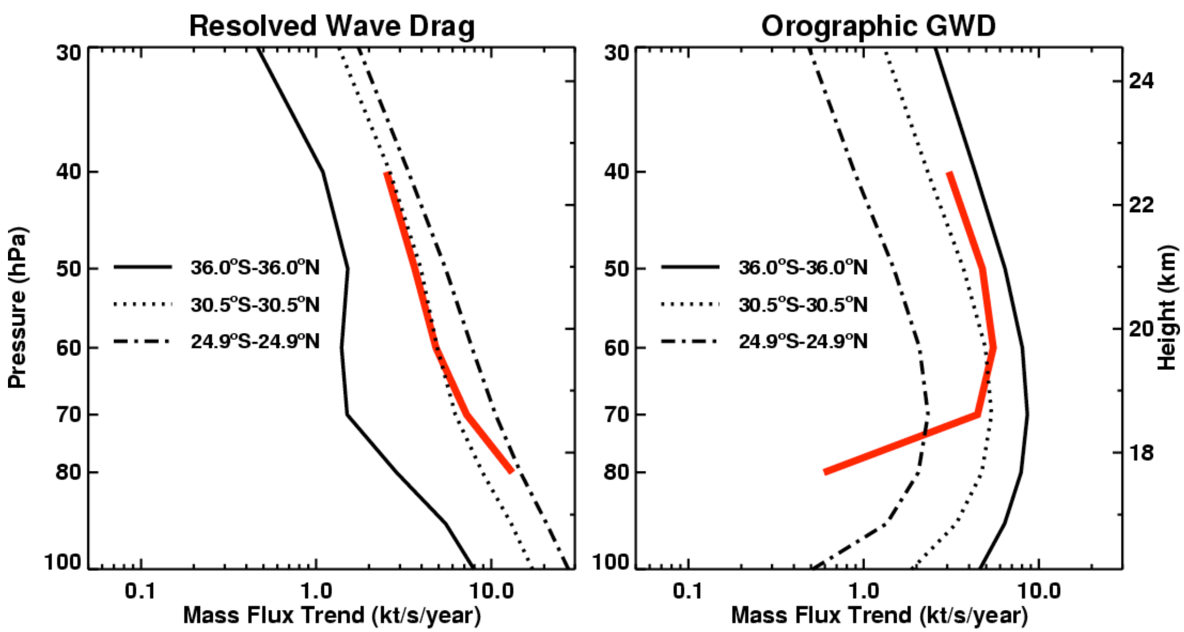



- net flux trend due to OGWD peaks at ~20 km.
- net flux trend due to resolved wave drag decreases steadily and is less than trend due to OGWD above ~20 km.

Note logarithmic x-axis.

red = net flux

# Vertical variation of upward mass flux trends




- net flux trend due to OGWD peaks at ~20 km.
- net flux trend due to resolved wave drag decreases steadily and is less than trend due to OGWD above ~20 km.
- narrowing the latitude range decreases contribution from OGWD and increases contribution from resolved waves.

Note logarithmic x-axis.

red = net flux

# Conclusions

1. Resolved wave drag and parameterized orographic gravity wave drag account for ~60% and 40%, respectively, of annual mean net upward mass flux trend at 70 hPa, with planetary wave drag accounting for ~60% of resolved wave drag trend.
   - Relative contribution of resolved and parameterized drag to mass flux trend is strongly dependent on latitude range and altitude.
2. Synoptic wave drag has strongest impact in winter NH where it accounts for nearly as much of net upward mass flux trend in lower stratosphere as planetary wave drag.
3. No straightforward connection between high and low latitude changes in BDC: increase in downwelling in Arctic in winter but decrease in Antarctic in spring.
   - High latitude changes due to changes in flux of stationary PW activity into stratosphere.

See McLandress and Shepherd, ***Simulated anthropogenic changes in the Brewer-Dobson circulation, including its extension to high latitudes***, J. Climate (under revision).