FDEPS 2012, Lecture 5

Gravity waves and stratosphere-mesosphere coupling

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- **Flow over topography** induces high pressure on the upwind side and low pressure on the downwind side
  - Leads to a downstream force on the Earth
  - An opposite drag force on the atmosphere is implied
    - Atmospheric angular momentum covaries with the length of day due to this momentum exchange
  - But where does this drag occur?

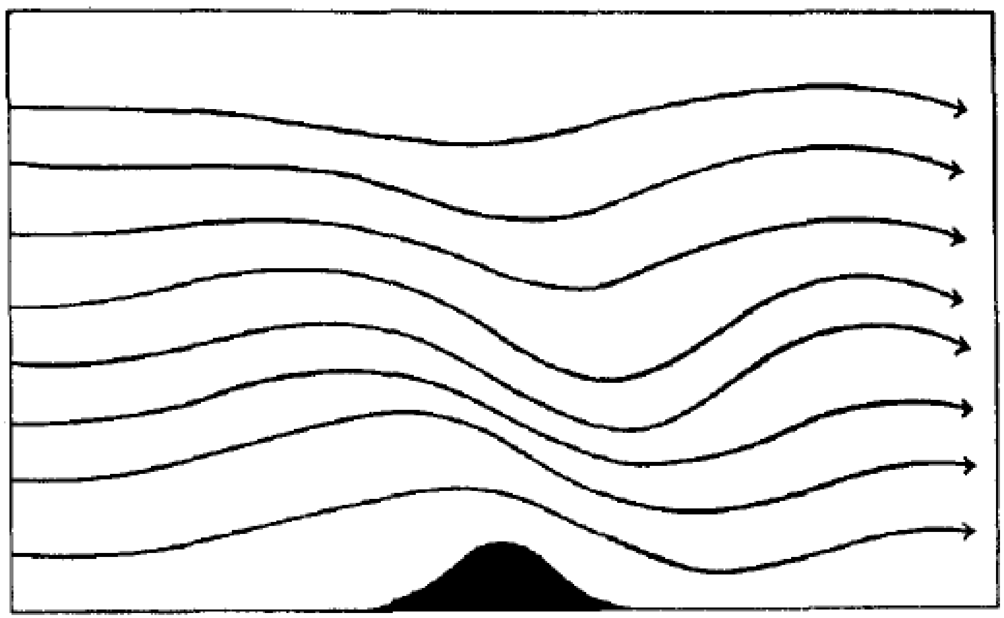


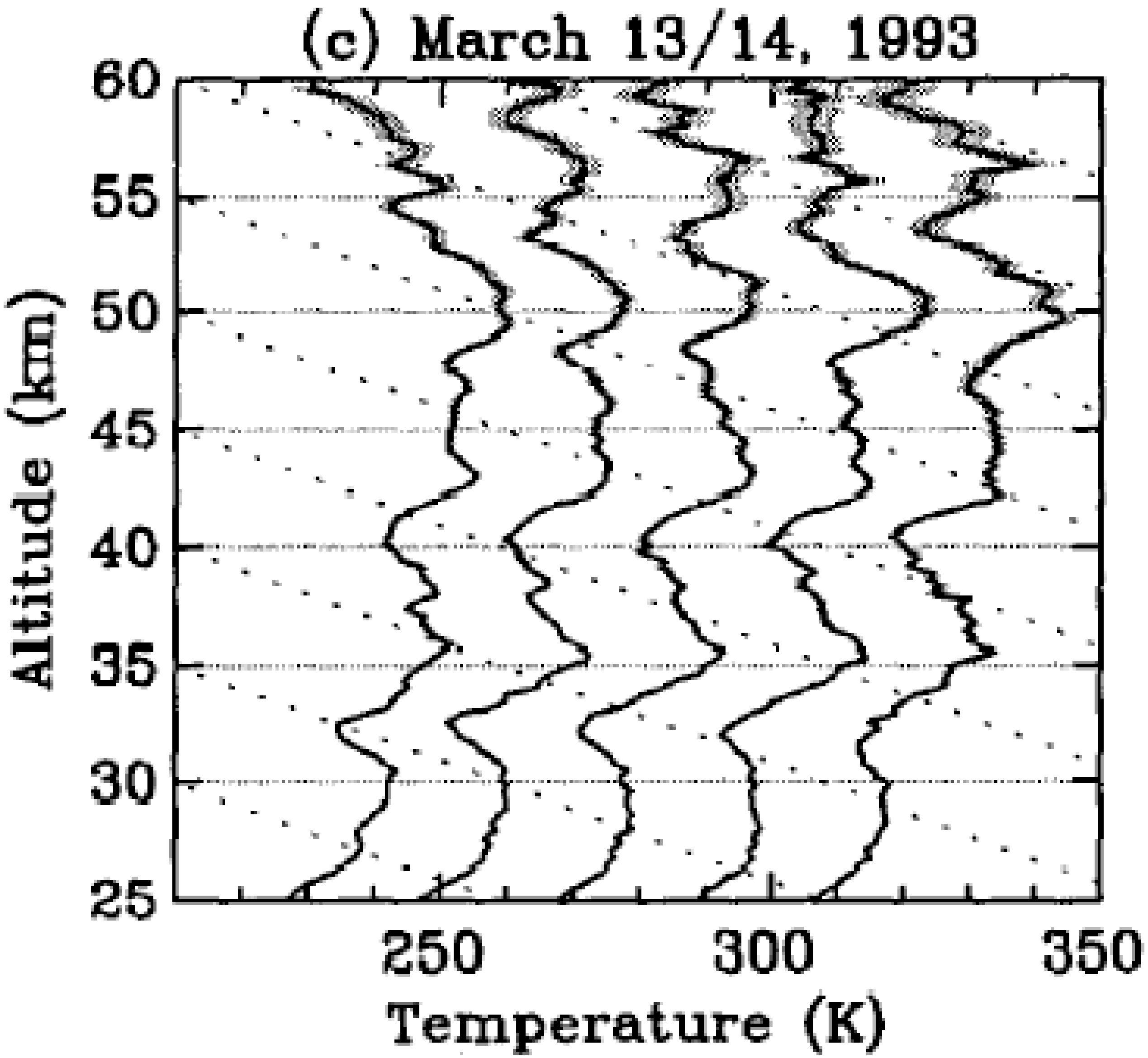
Figure 1. General character of streamlines over a ridge.

Sawyer (1958) argued the displacement of streamlines would decrease with altitude (see figure), implying momentum flux convergence at low levels

- But we know that mountains and other sources (e.g. convection) can force internal gravity waves, which can propagate to great heights
  - What happens to the momentum?

http://www.metvuw.com/

Vertical temperature profiles observed by Rayleigh lidar



Sequence of (< 30-min avg) profiles (offset by 10 K) at Eureka, Canada

Dashed lines show adiabatic lapse rate

From Whiteway & Carswell (1994 JAS)

Start with disturbance zonal momentum equation

$$\rho_0 \frac{\partial u'}{\partial t} + \rho_0 \bar{u} \frac{\partial u'}{\partial x} + \rho_0 w' \frac{\partial \bar{u}}{\partial z} = -\frac{\partial p'}{\partial x}$$

Assume $u' \propto \exp[ik(x - ct)]$, $\frac{\partial u'}{\partial t} = -c \frac{\partial u'}{\partial x}$

Then

$$\rho_0 (\bar{u} - c) \frac{\partial u'}{\partial x} + \rho_0 w' \frac{\partial \bar{u}}{\partial z} + \frac{\partial p'}{\partial x} = 0$$

$$\Leftrightarrow \frac{\partial}{\partial x} [\rho_0 (\bar{u} - c) u' + p'] = -\rho_0 w' \frac{\partial \bar{u}}{\partial z}$$

$$\Leftrightarrow \overline{[\cdots] \frac{\partial}{\partial x} [\cdots]} = 0 = -\rho_0 \frac{\partial \bar{u}}{\partial z} [\rho_0 (\bar{u} - c) \overline{u' w'} + \overline{p' w'}]$$

Therefore $\overline{p'w'} = -\rho_0(\bar{u} - c)\overline{u'w'}$

But $\overline{p'w'} > 0$ for upward propagating GWs, hence

$$\mathrm{sgn}(c - \bar{u}) = \mathrm{sgn}(\overline{u'w'})$$

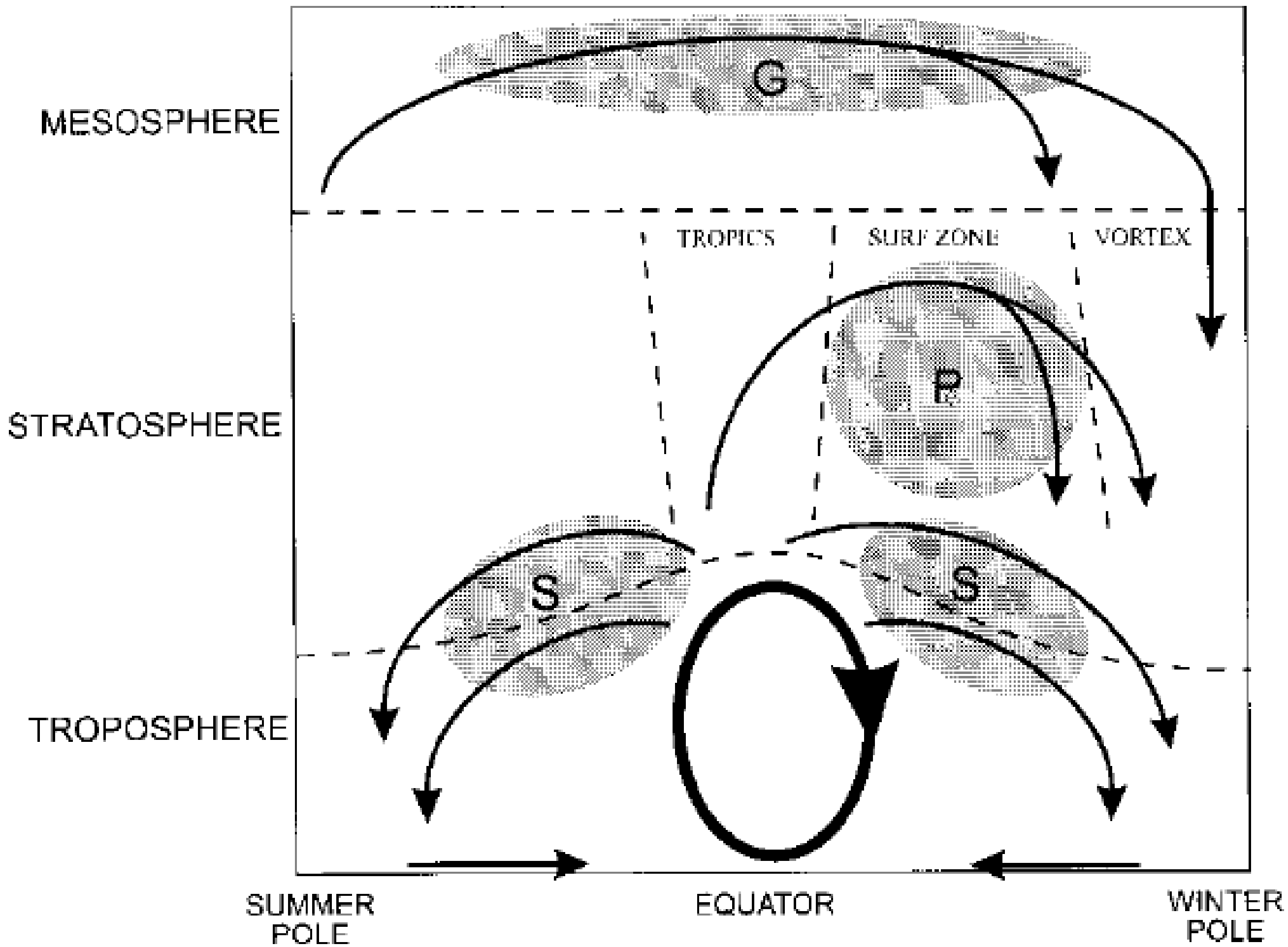
and

$c > \bar{u} \Rightarrow$ positive momentum forcing

$c < \bar{u} \Rightarrow$ negative momentum forcing

- In both cases the waves act to drag the flow towards their phase speed where they dissipate
  - This is not always a “drag”; it can be an acceleration
- In the absence of transience and dissipation, there is no momentum flux convergence and $\overline{\rho_0 u'w'}$ is constant with height
  - This is the *Eliassen-Palm theorem (1961)*

- **In the mesosphere**, gravity-wave drag is important for driving the meridional overturning circulation



Plumb (2002 JMSJ)

- **Downward control:** in the steady limit, the TEM vertical velocity (related to diabatic vertical velocity) is

$$\overline{w}^{*} = -\frac{1}{a\,\rho\cos\phi}\frac{\partial}{\partial\phi}\int_{z}^{\infty}\frac{\rho F\cos\phi}{2\Omega\sin\phi}dz$$

- For gravity waves, this simplifies to

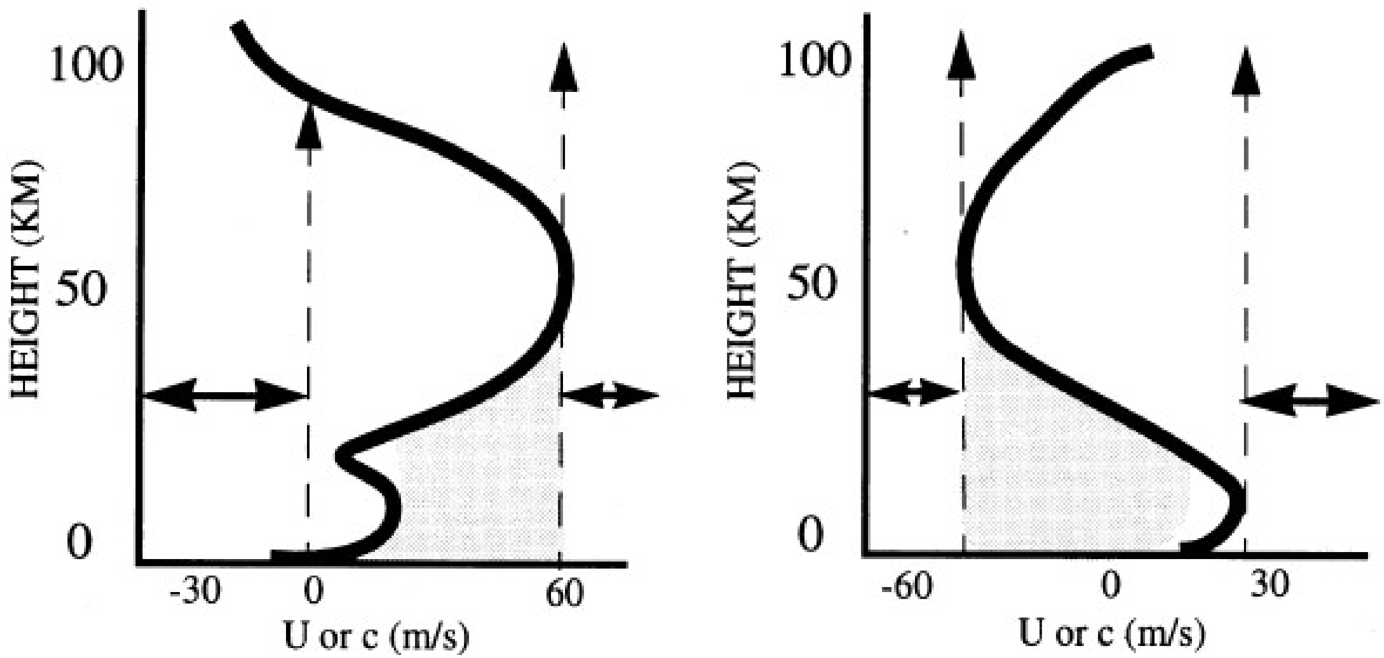
$$\overline{w}^{*} = -\frac{1}{a\cos\phi}\frac{\partial}{\partial\phi}\left(\frac{\cos\phi\,\overline{u'w'}}{2\Omega\sin\phi}\right)$$

or integrated over the (north) polar cap,

$$\int_{\phi}^{\pi/2}\overline{w}^{*}a\cos\phi\,d\phi = \frac{\cos\phi\,\overline{u'w'}}{2\Omega\sin\phi}$$

- Positive momentum flux drives polar upwelling, negative momentum flux drives polar downwelling

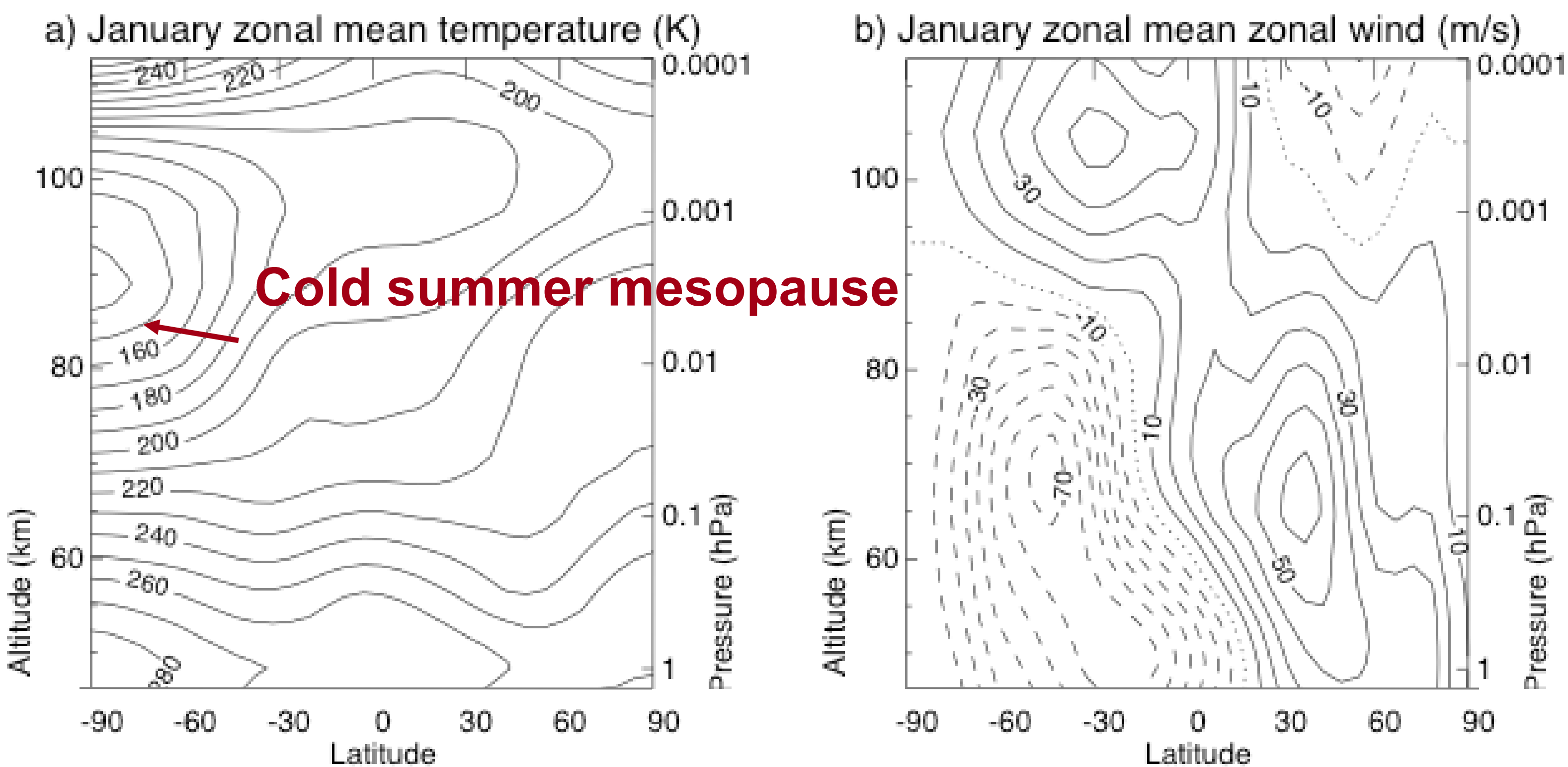
- The seasonal variation in stratospheric winds controls the spectrum of gravity waves reaching the mesosphere (where they reach large amplitudes and break)
  - Gravity waves are dissipated at critical levels (c=U)
- The result is a negative torque in the winter hemisphere, and a positive torque in the summer hemisphere



Gravity waves drag the zonal flow towards their phase speed (Eliassen & Palm 1961)

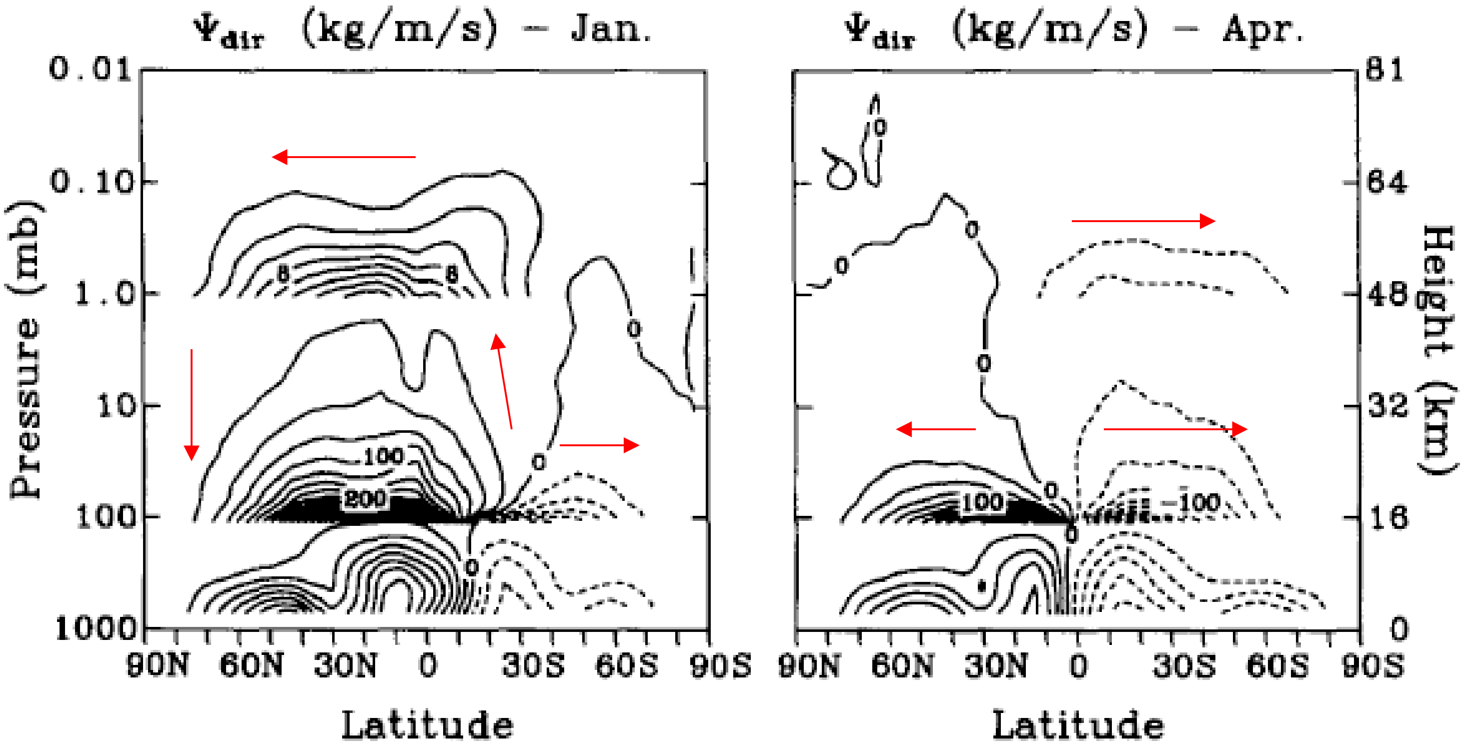
McLandress (1998 JASTP)

- The gravity-wave drag is so strong that it reverses the winter-to-summer-pole temperature gradient in the upper mesosphere
  - Summer mesopause is the coldest region on Earth!
  - Reversal of winds above implies the gravity-wave induced torques are acting to accelerate the flow



Shepherd (2003 Chem. Rev.)

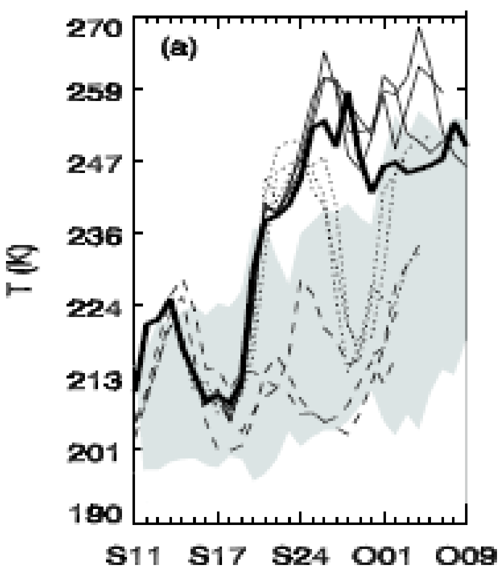
- Wave-induced torques drive a middle atmosphere circulation with a strong seasonal dependence
  – Mainly from Rossby waves in the stratosphere — the ‘Brewer-Dobson circulation’ (BDC)
  – Mainly from gravity waves in the mesosphere



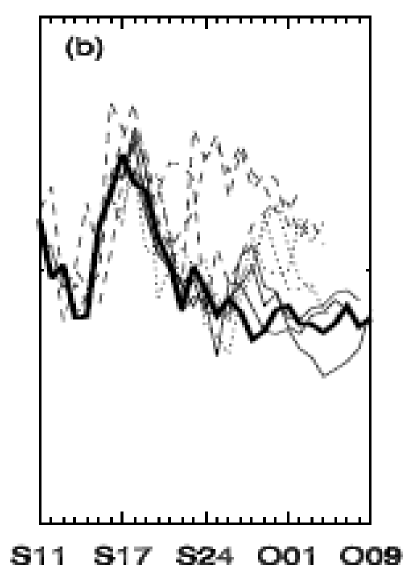
CMAM results from Beagley et al. (1997 Atmos.-Ocean)

- The same gravity-wave filtering mechanism operates on shorter timescales too
- **Stratospheric Sudden Warmings** act to cool the polar mesosphere (Holton 1983 JAS), seen here in the CMAM-DAS response to the 2002 Antarctic SSW
  - Forecast ensemble shows response is deterministic

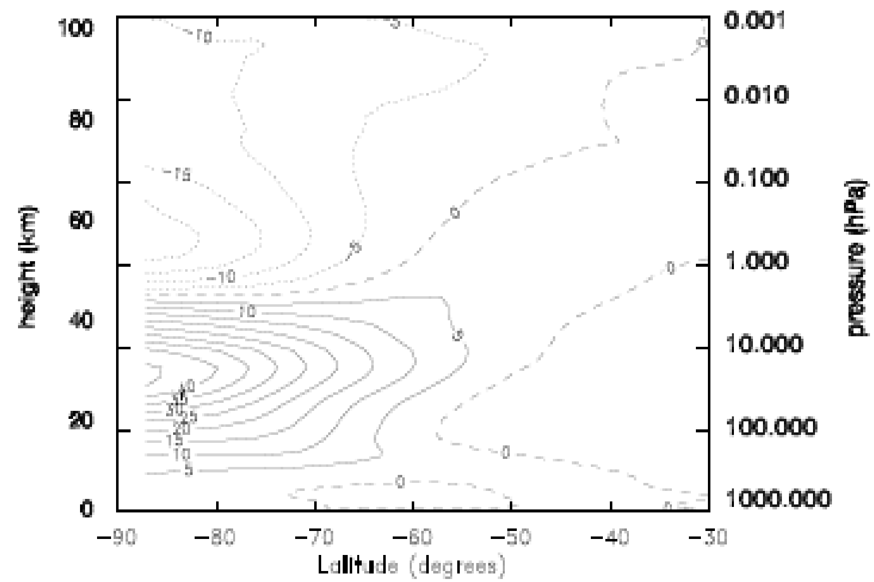
10 hPa SP T



0.1 hPa SP T

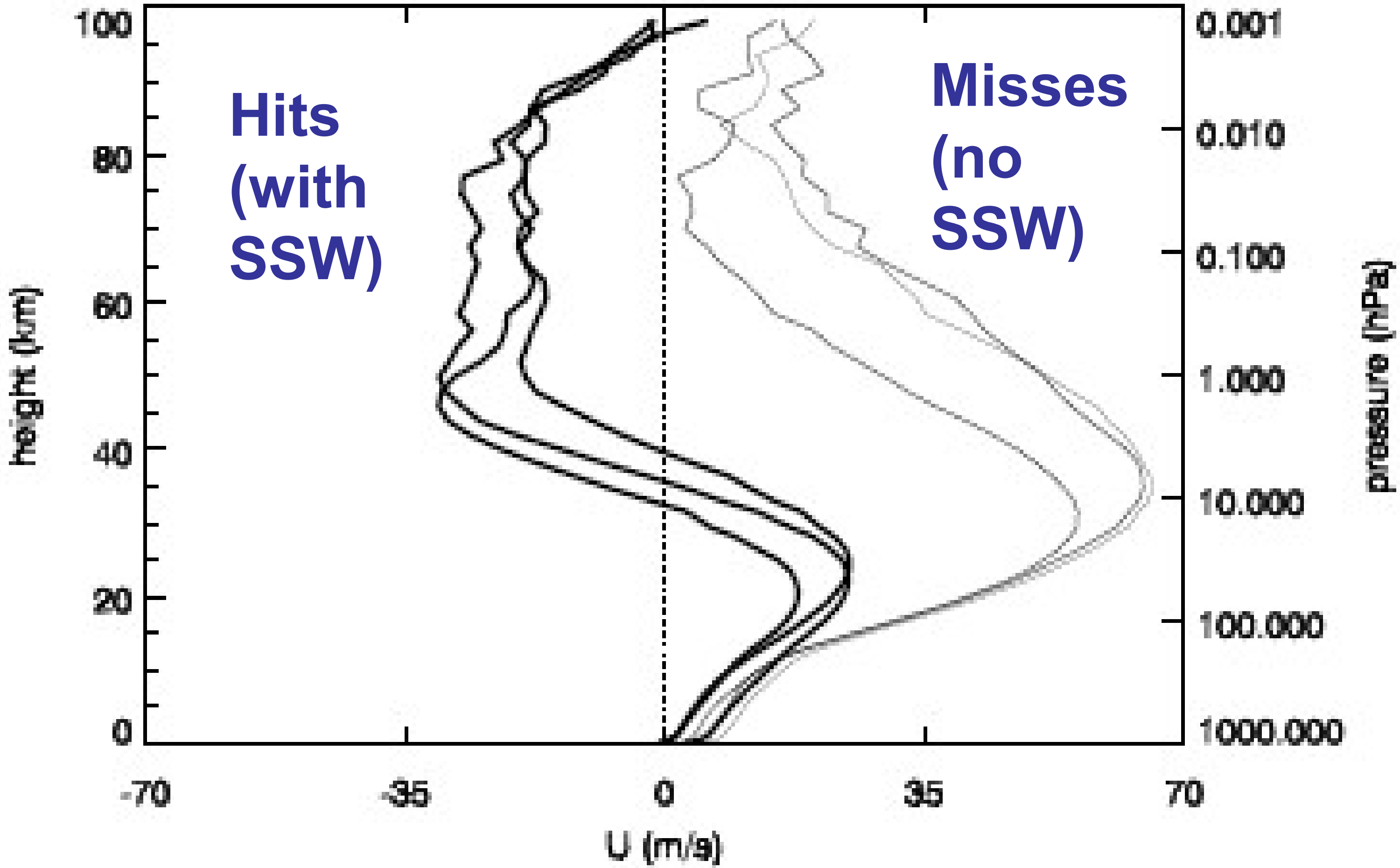


T (hits - misses)

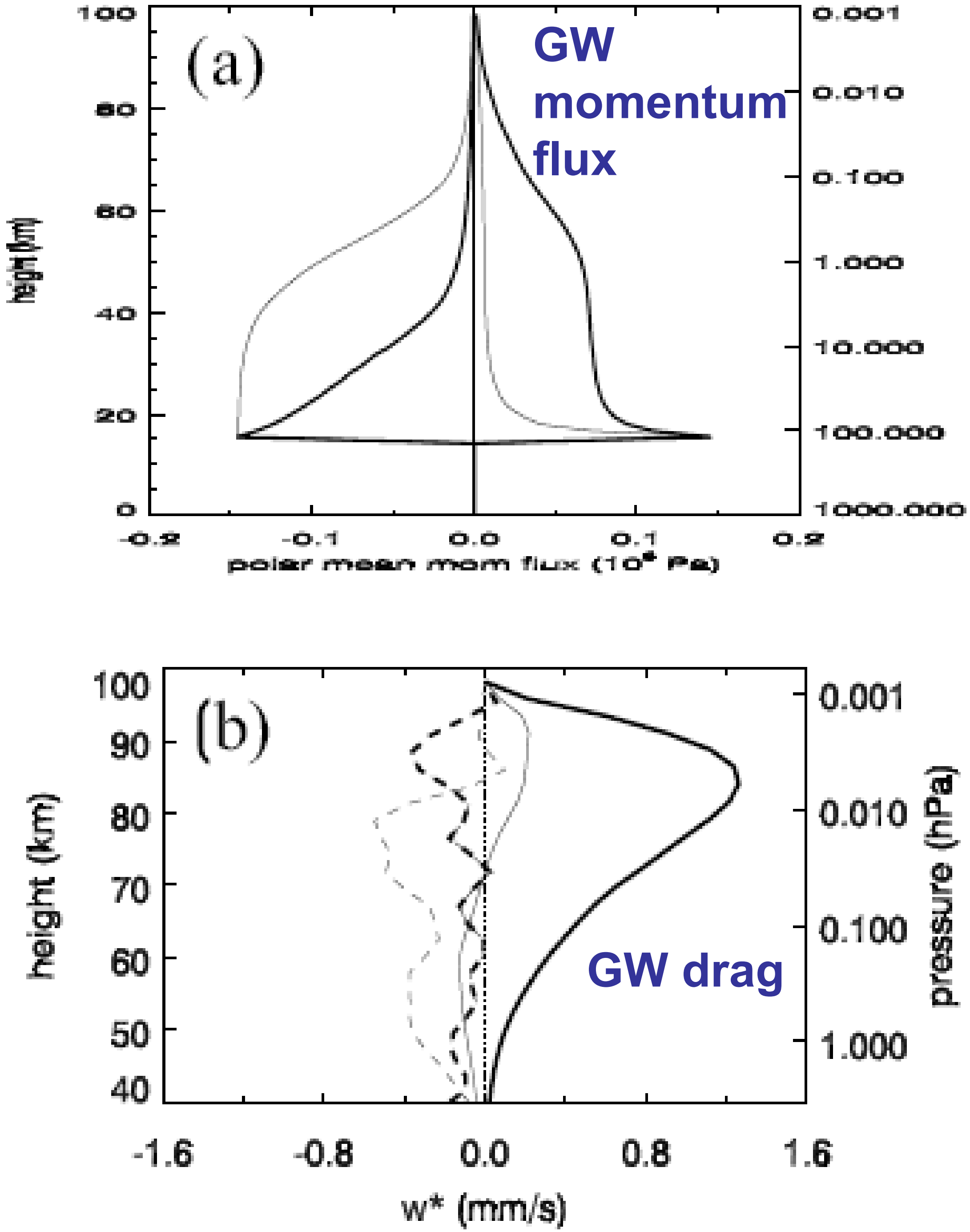


Ren, Polavarapu & Shepherd (2008 GRL)

- The SSW is associated with a huge change in the zonal winds, shown here at 60°S



Ren et al. (2008 GRL)

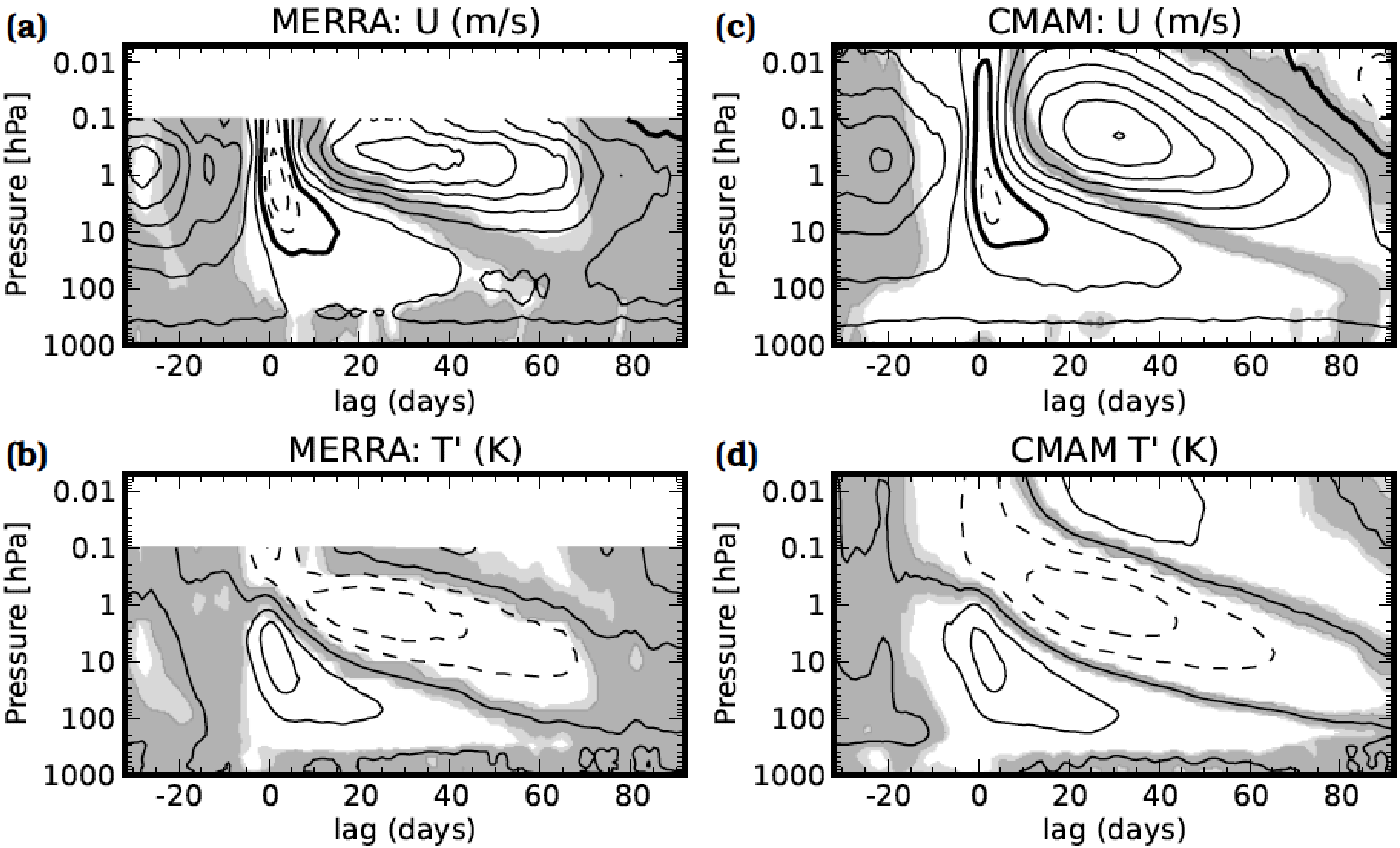


The dramatic zonal wind changes associated with the SSW alter the filtering of the gravity-wave (GW) spectrum, leading to a positive GWD anomaly (hence cooling) in the polar mesosphere

Thick=hits
Thin=misses

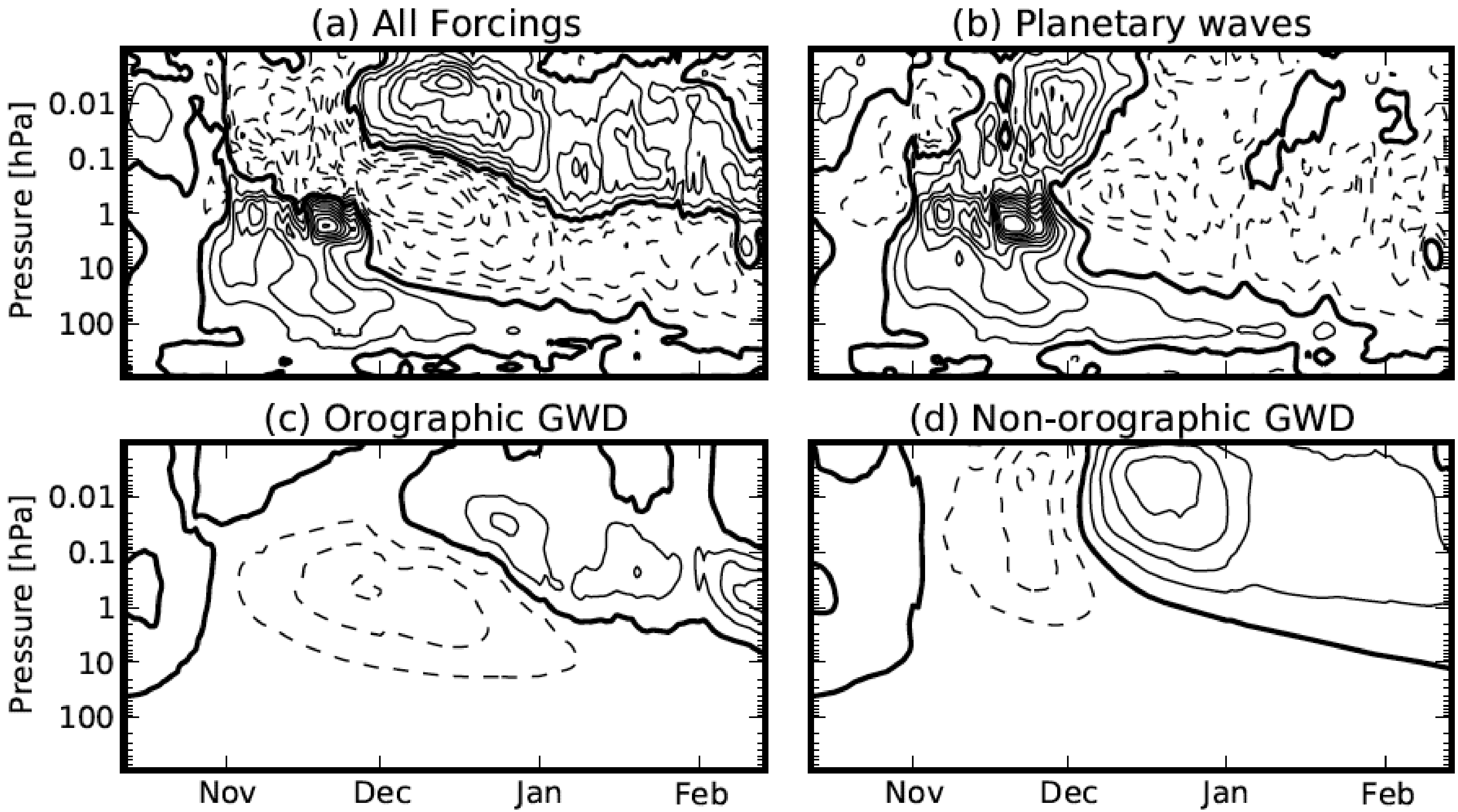
Ren et al. (2008 GRL)

- The mesospheric response to extended recoveries from NH SSWs in the free-running CMAM seems quite realistic



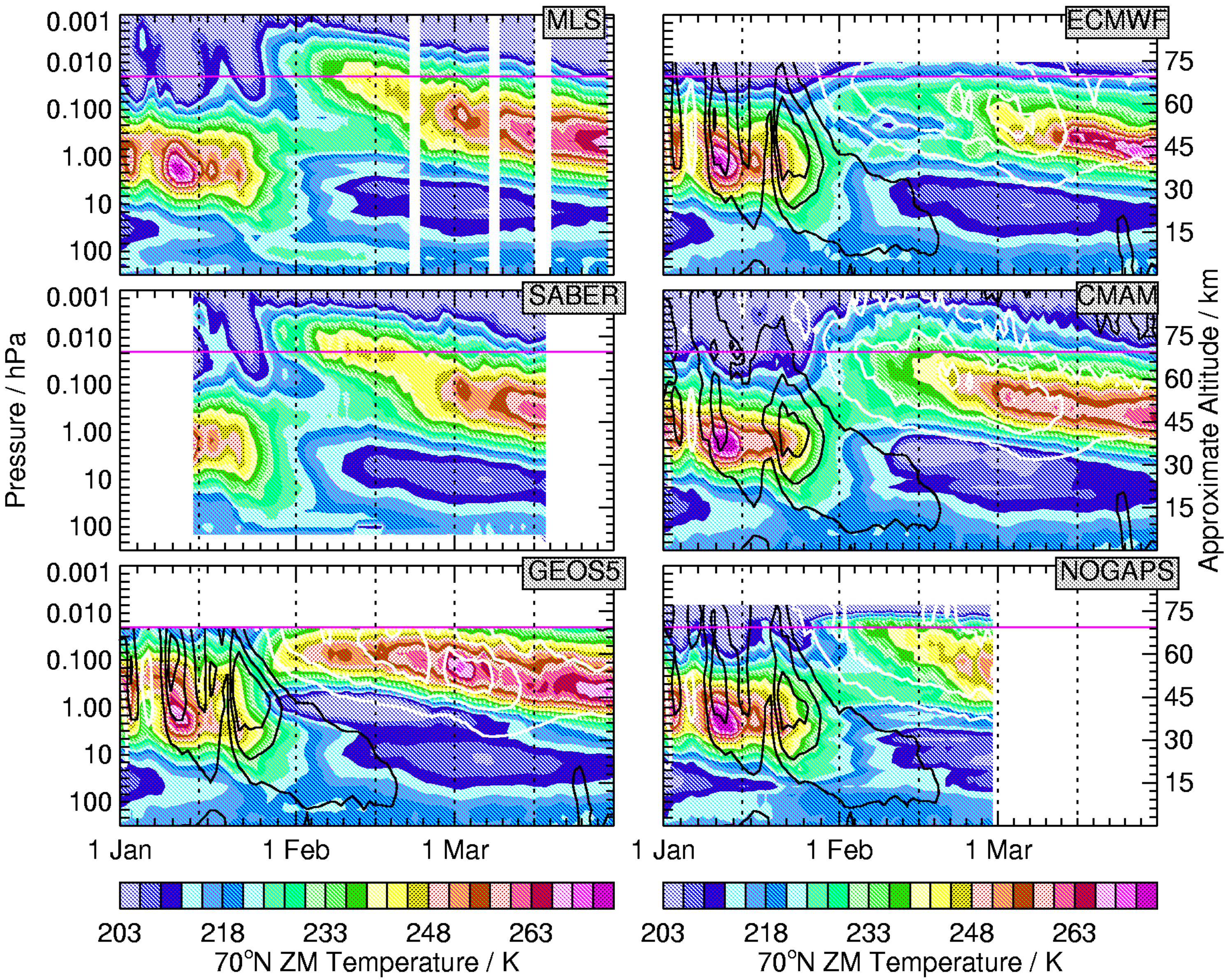
Hitchcock & Shepherd (JAS, in press)

- Evolution of CMAM polar-cap temperature anomalies can be attributed to different wave forcings via Eliassen adjustment



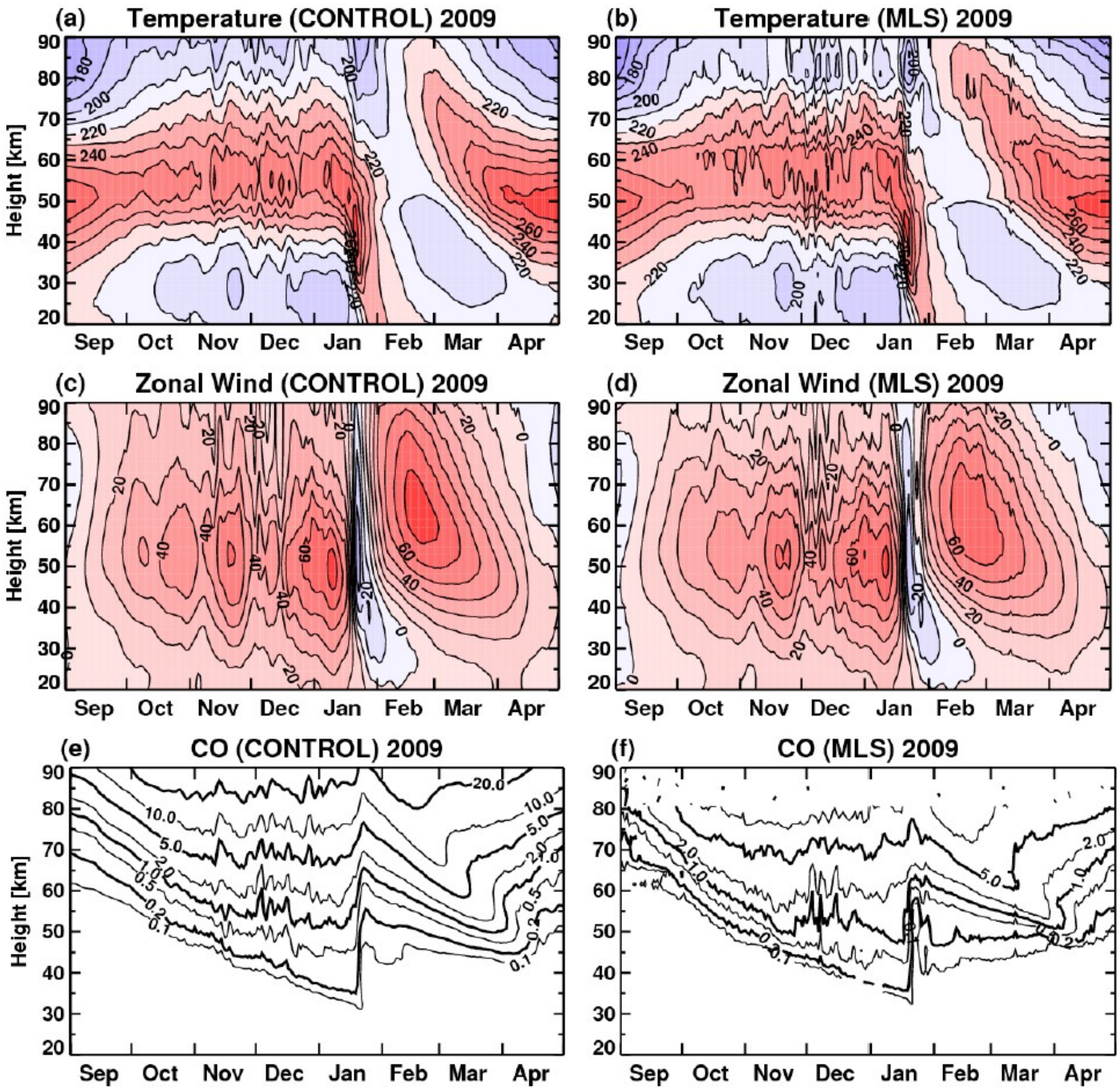
Hitchcock & Shepherd (JAS, in press)

The 2006 SSW in observations and models



CMAM-DAS did not assimilate mesospheric observations, yet does better than the two operational systems

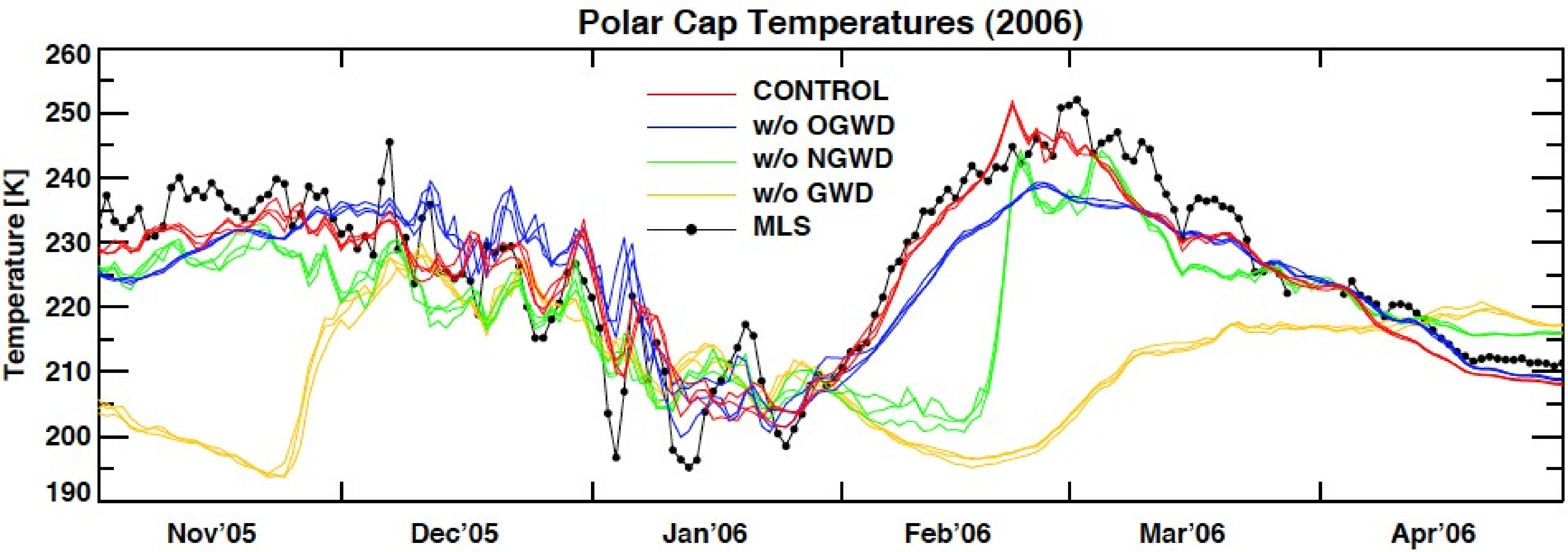
Figure courtesy of Gloria Manney, NASA JPL



- When CMAM is nudged to reanalyses in the stratosphere, the mesosphere reproduces the observations very well
- Information propagates upward through wave fluxes

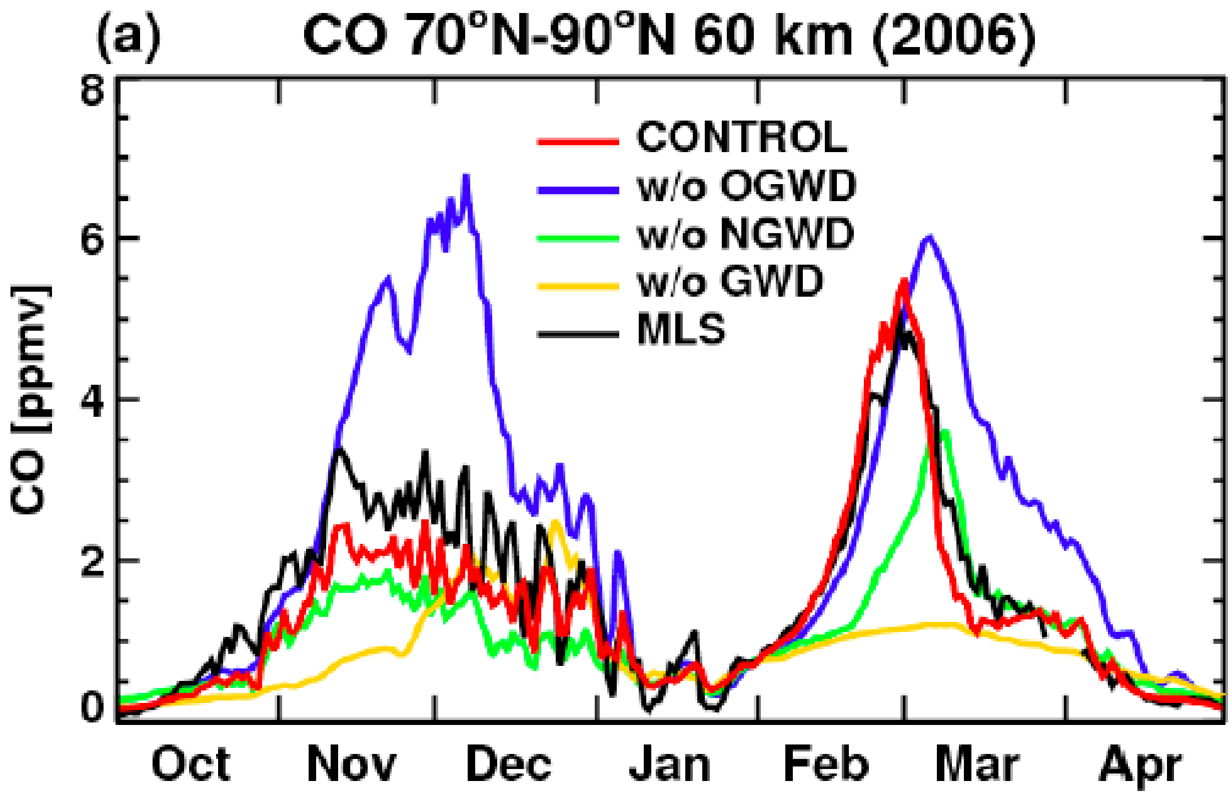
McLandress et al. (JAS, submitted)

- Removing either the orographic and/or the non-orographic gravity-wave drag changes temperatures at 0.05 hPa (70 km) during the extended recovery phase
  - There is a nonlinear coupling between orographic and non-orographic gravity-wave drag



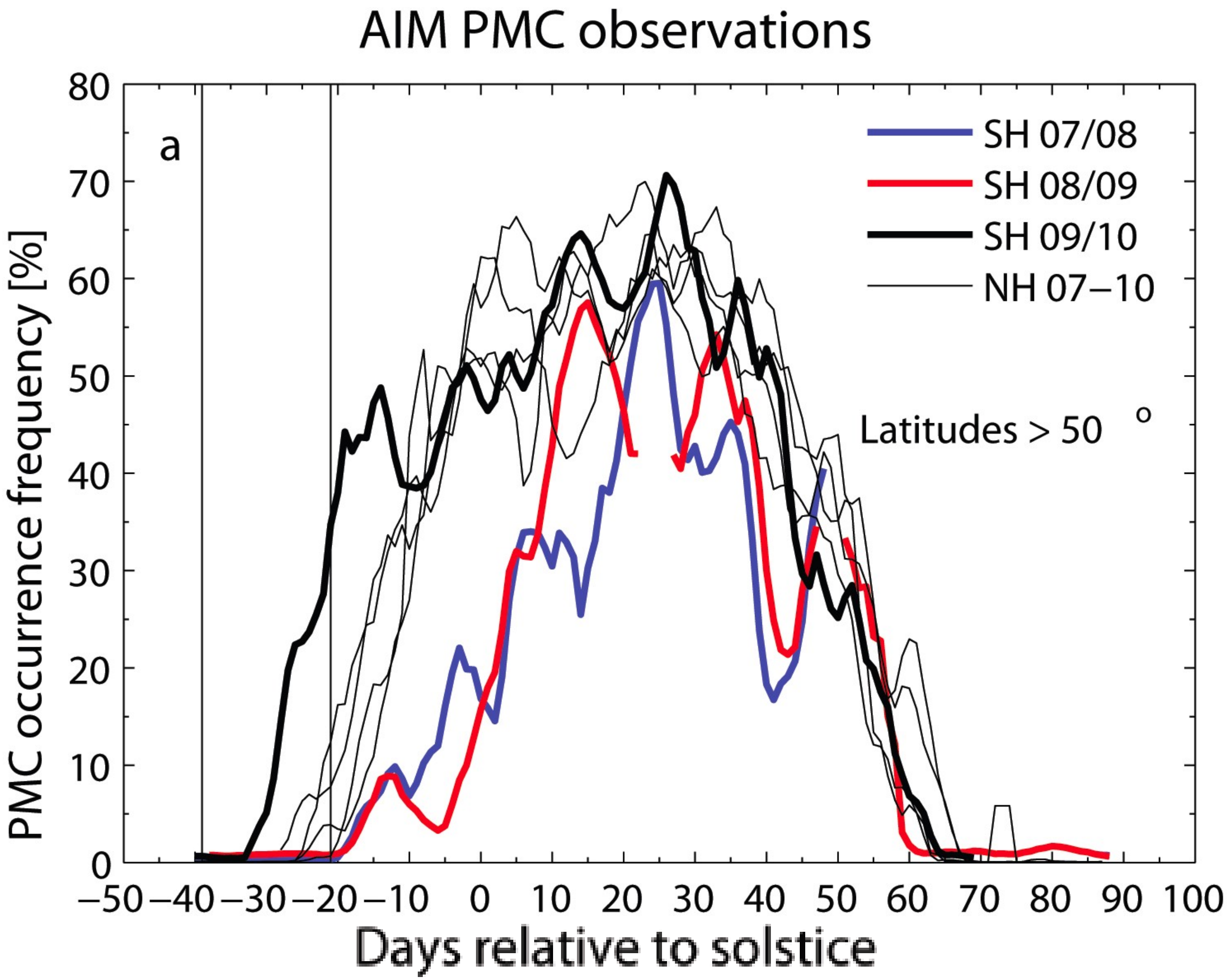
McLandress et al. (JAS, submitted)

- Outside the period of the SSW, orographic GWD is responsible for limiting the upper stratospheric winds and thus limiting the polar descent induced by non-orographic GWD, which acts to bring down high values of CO



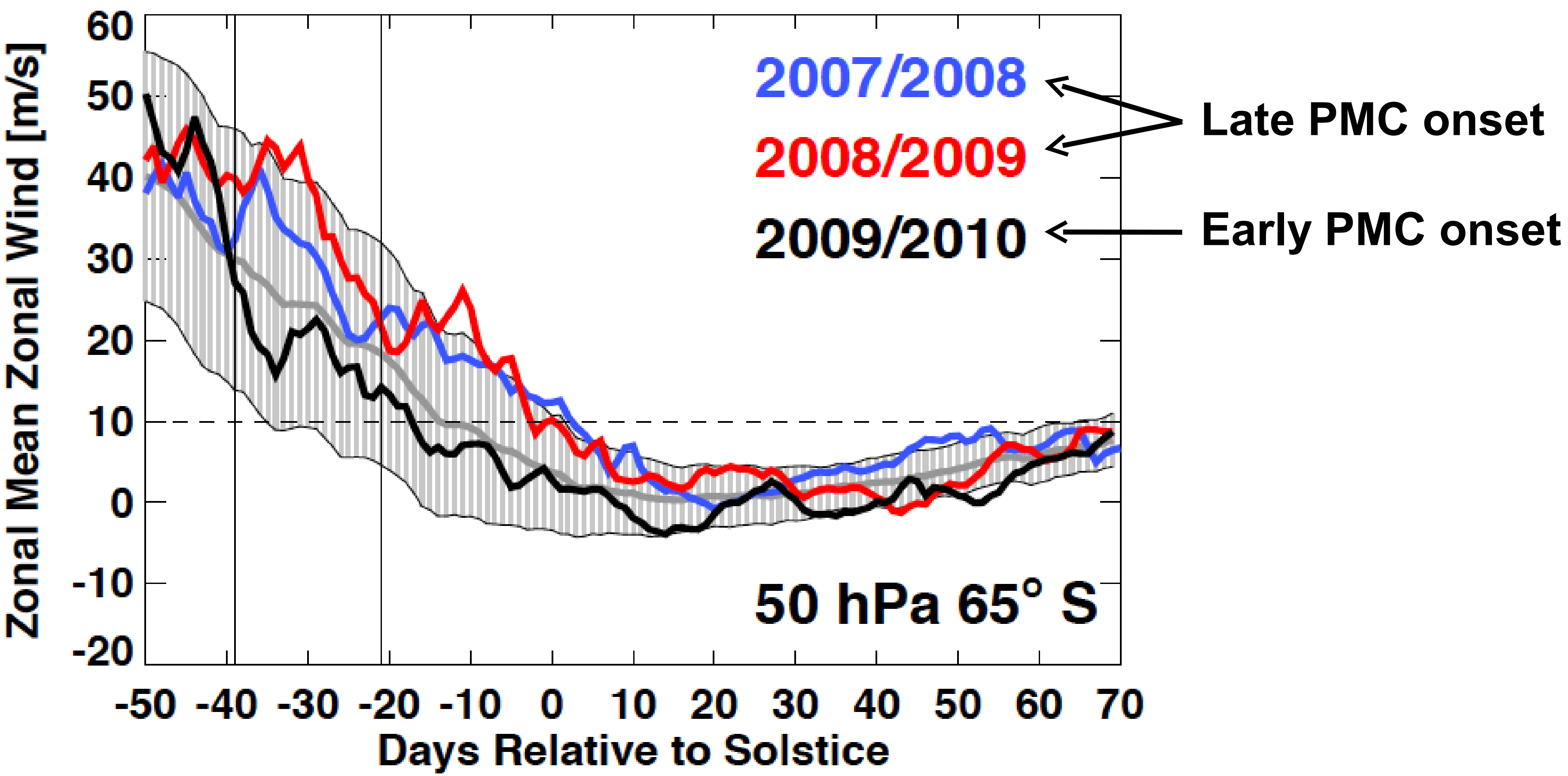
McLandress et al. (JAS, submitted)

- The very low **summer mesopause** temperatures lead to the formation of Polar Mesospheric Clouds (PMCs)
- The onset of the PMC season is highly variable in the SH, much less so in the NH



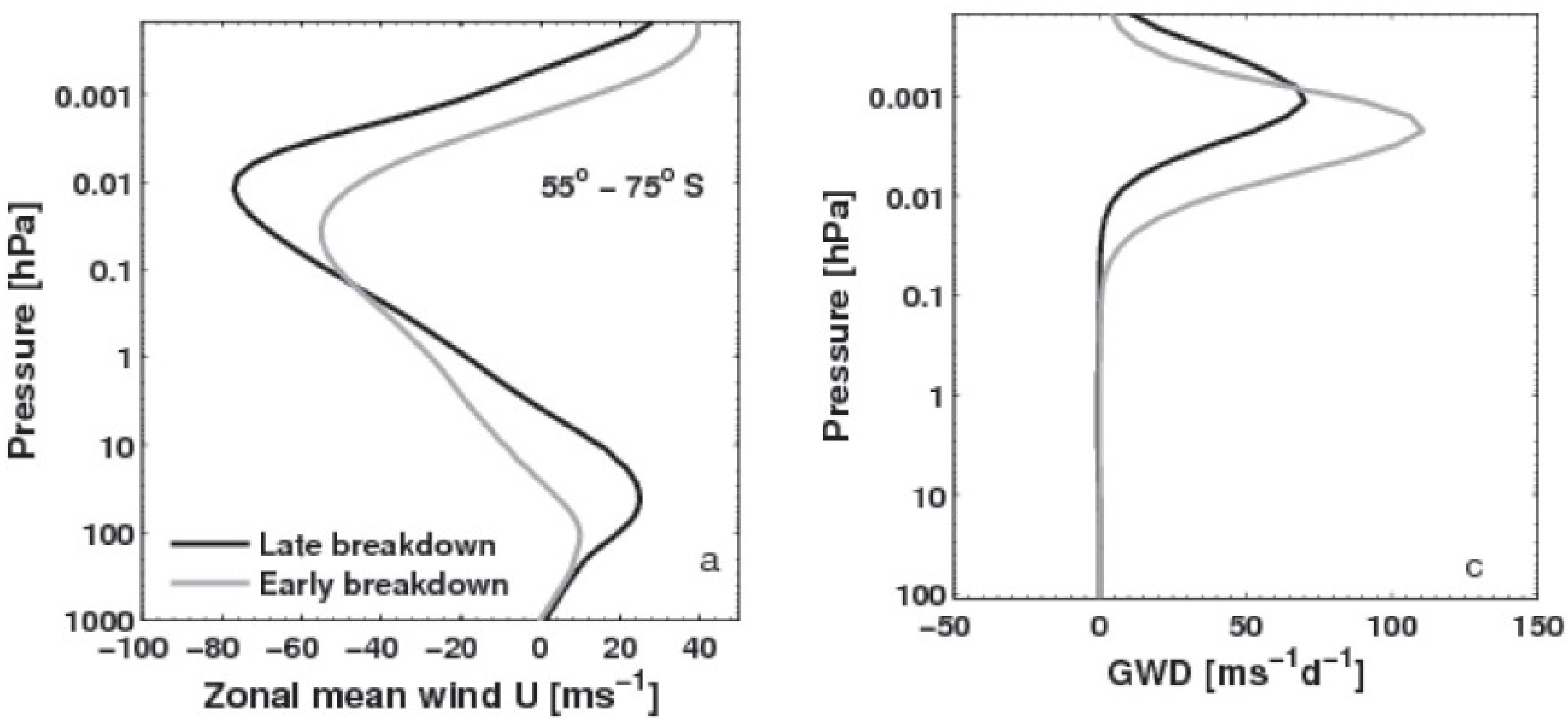
Karlsson et al. (2011 JGR)

- This behaviour is due to the lateness of the SH polar vortex breakdown, which provides a source of variability in SH mesopause temperatures in early summer through the same gravity-wave filtering mechanism

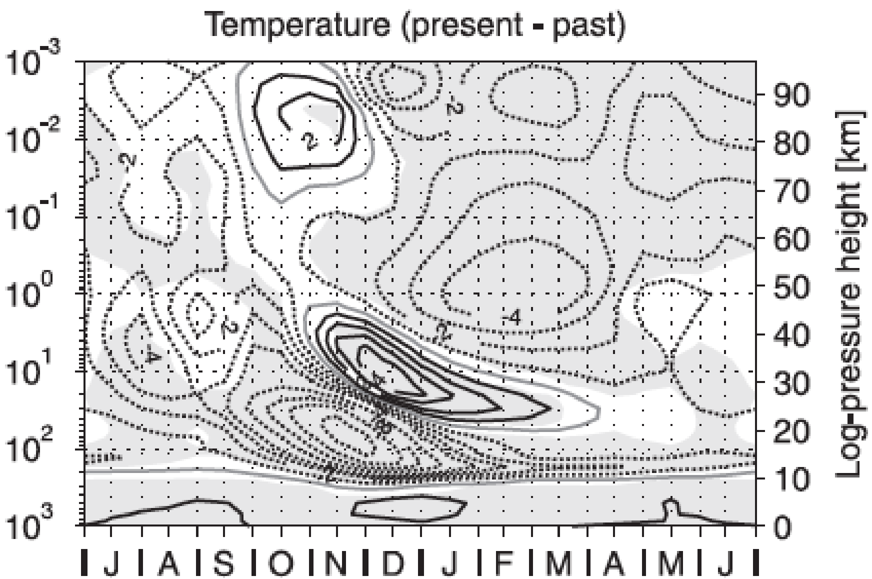


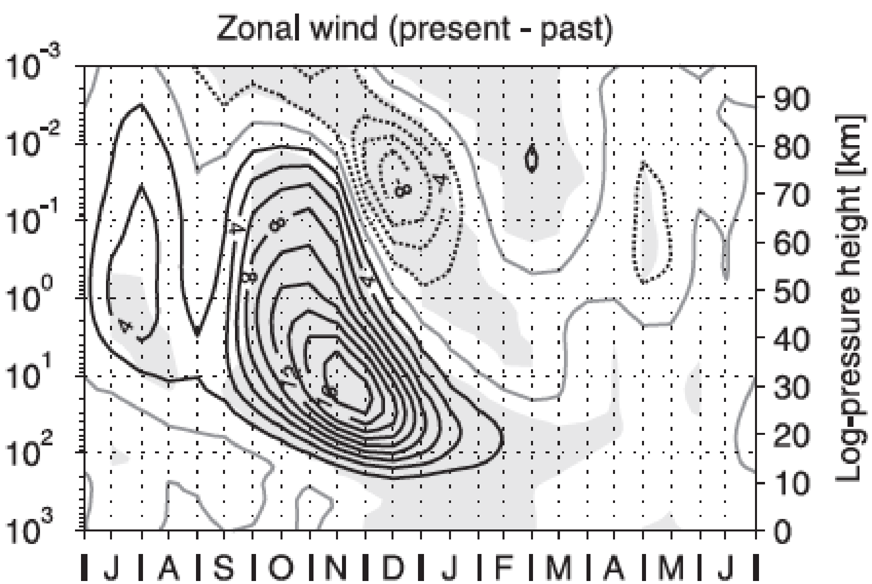
Karlsson et al. (2011 JGR)

- Late vortex breakdowns filter more eastward-propagating gravity waves
  - Reduces positive torque in upper mesosphere
  - Reduces polar upwelling and cooling
  - Delays onset of PMCs



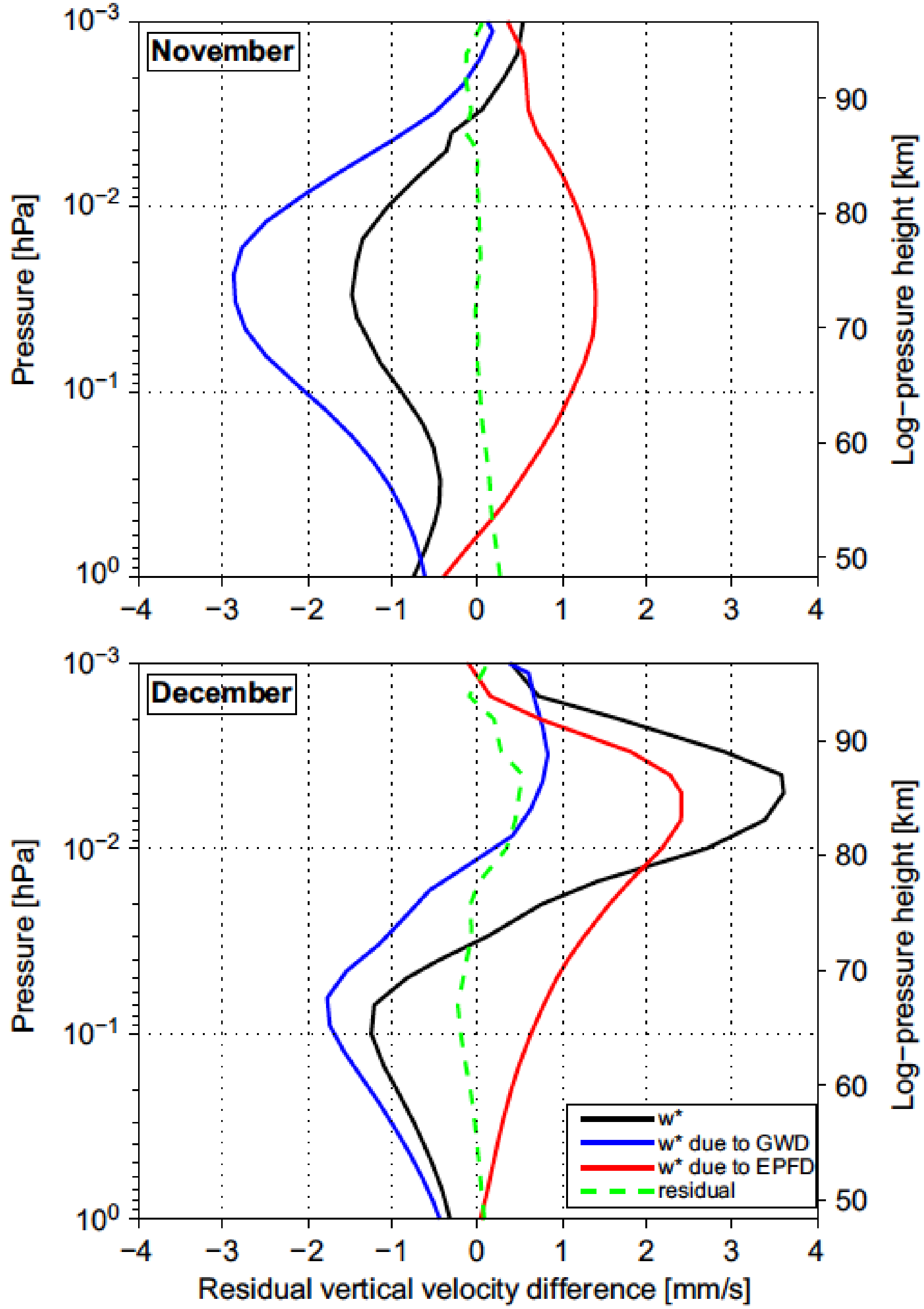
Karlsson et al. (2011 JGR)





- The ozone hole has led to a delay in SH vortex breakdown by about 3 weeks (bottom)
- The previous reasoning based on gravity-wave filtering would imply a warming of the upper mesosphere in late spring
- CMAM simulations of the ozone hole show this effect (top), but also a widespread mesospheric cooling during summer

Lossow, McLandress, Jonsson & Shepherd (2012 JASTP)

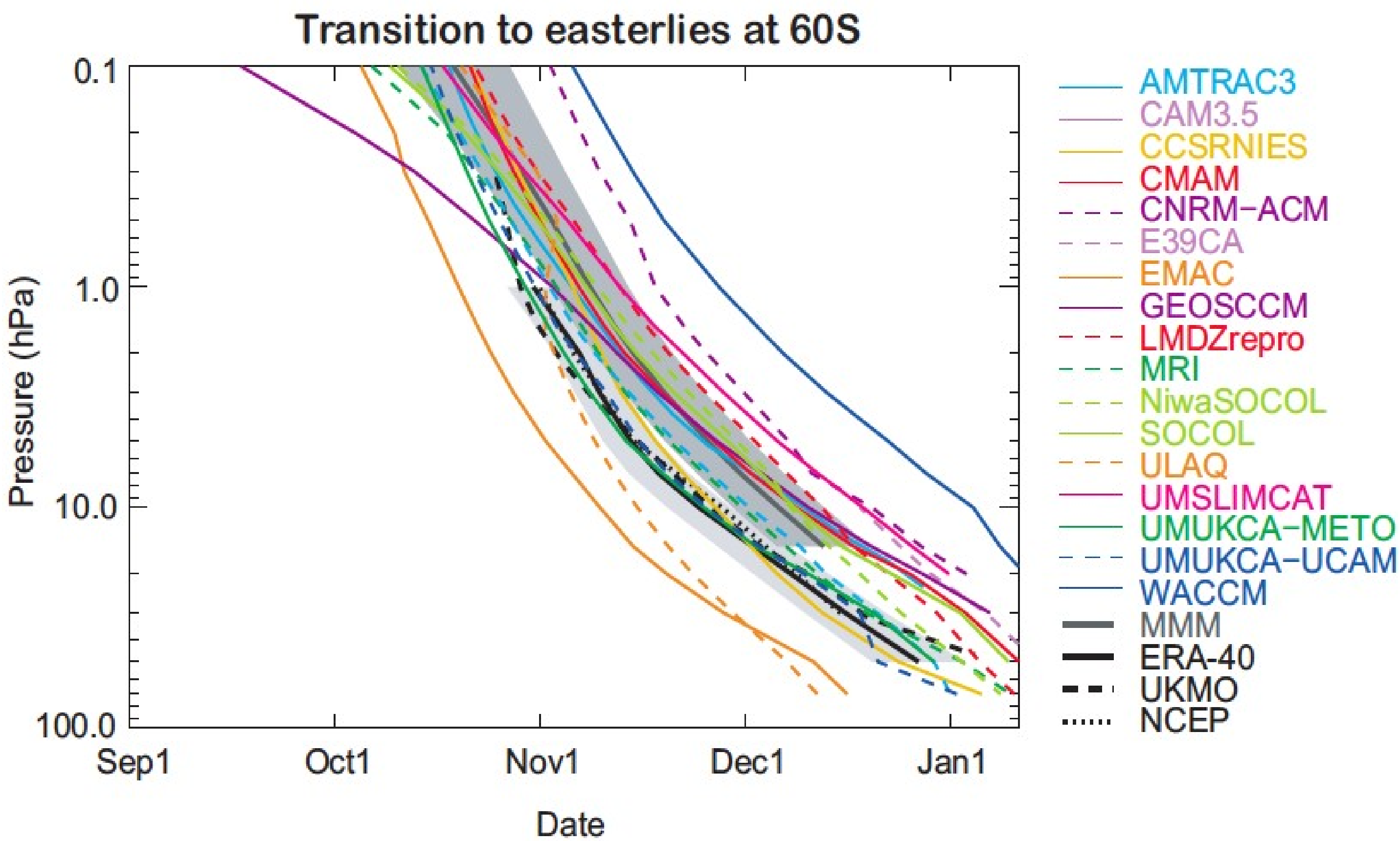


- Analysis shows that the TEM vertical velocity (w bar star) induced by resolved wave drag (red) acts generally against that induced by GWD (blue), and completely dominates the upper mesosphere response in early summer (bottom)
- Arises from in-situ baroclinic instability

Lossow, McLandress, Jonsson & Shepherd (2012 JASTP)

However, climate models tend to have a **systematic bias** towards a too-late Antarctic vortex breakup

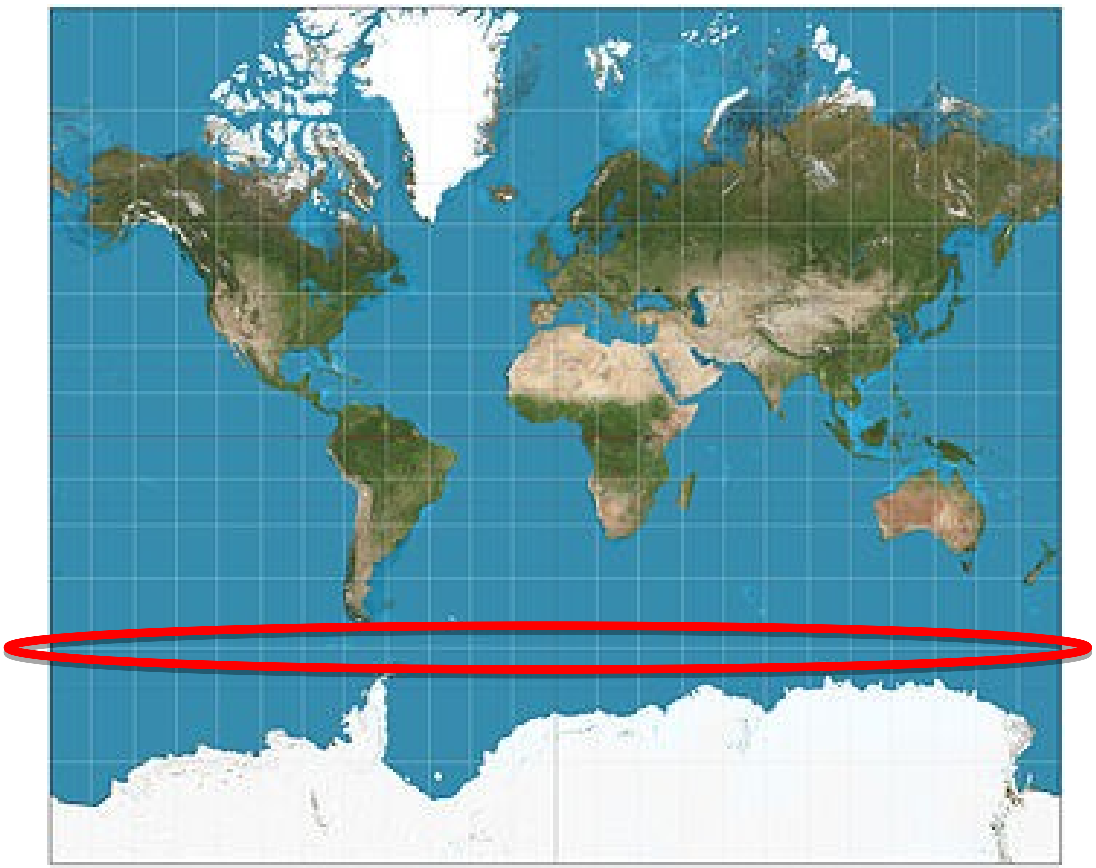
– This would affect the timing of stratosphere-mesosphere coupling relative to the PMC season

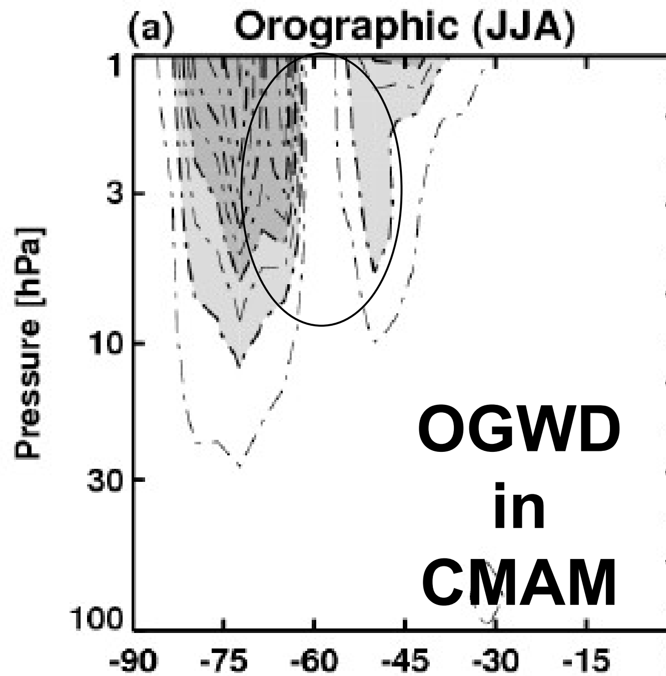


Butchart et al. (2011 JGR)

The SH jet has a maximum around 60°S

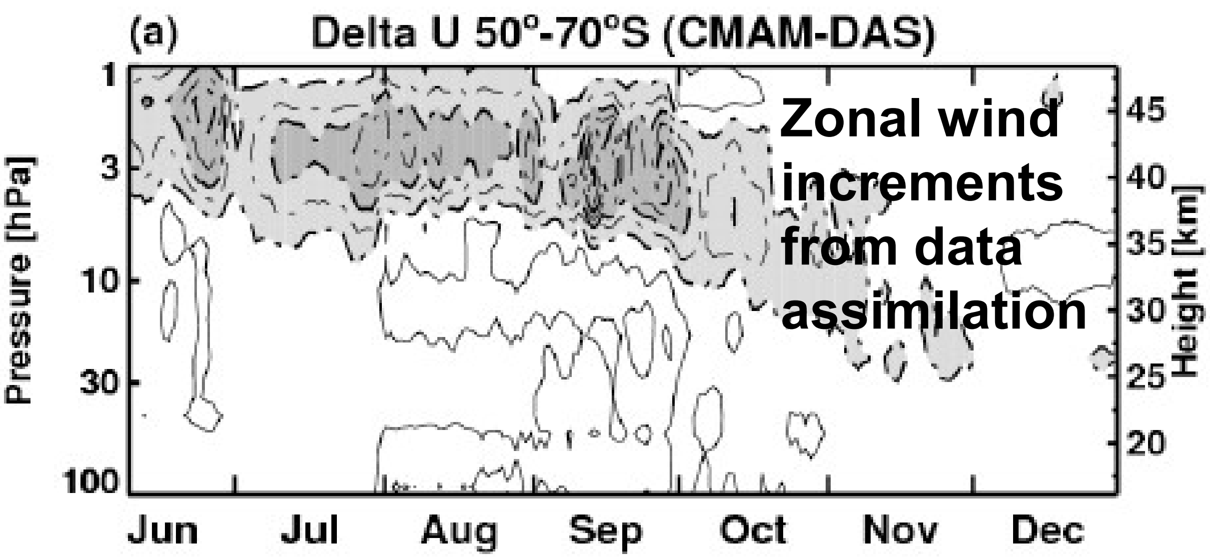
- At this latitude band, the surface is represented entirely as ocean in the models, hence no orographic GWD!

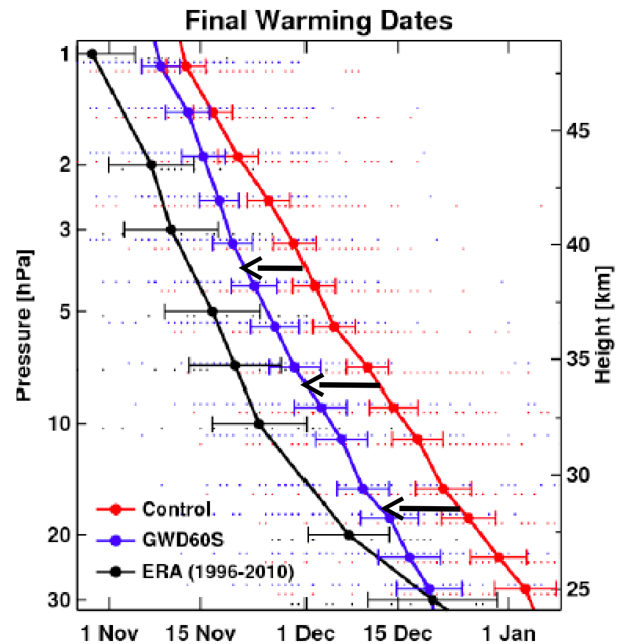




McLandress, Shepherd, Polavarapu & Beagley (2012 JAS)

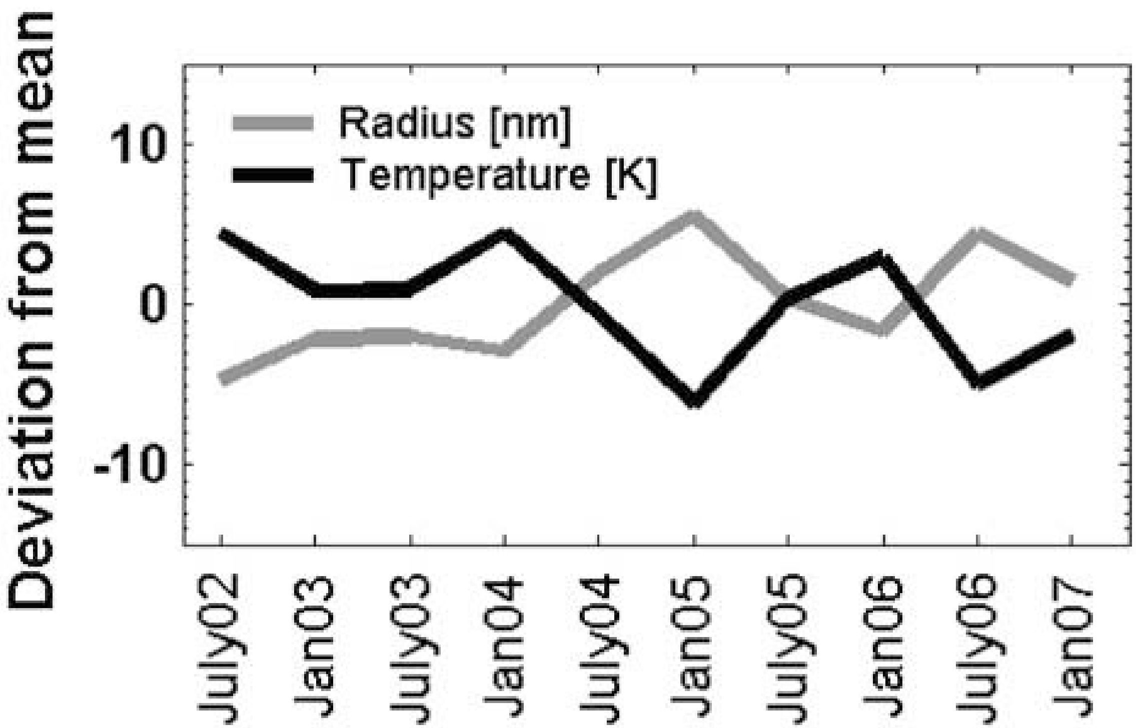
- When CMAM is run in data assimilation mode, increments imply missing drag at these latitudes, which descends from the upper stratosphere as the zero wind line descends (left)
- There is other evidence for the role of OGWD at these latitudes
- An ad hoc inclusion of extra OGWD in this latitude belt substantially reduces the zonal-wind bias in CMAM (right)



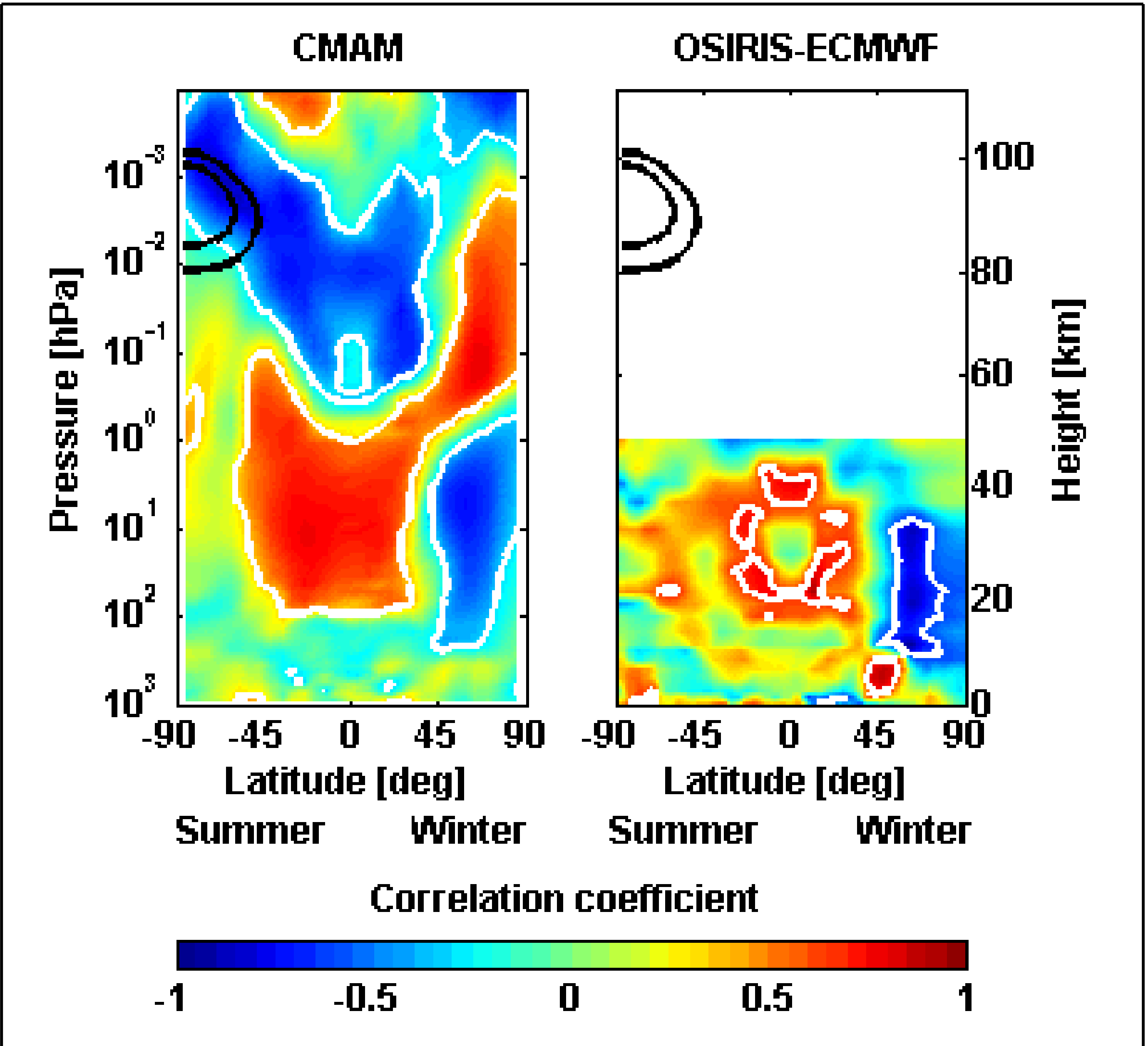


McLandress, Shepherd, Polavarapu & Beagley (2012 JAS)

- Pole-to-pole interhemispheric coupling?
  - OSIRIS observations of PMCs at the summer mesopause (after the onset period) show an apparent correlation between PMC size and temperatures in the *winter* polar lower stratosphere



Karlsson et al. (2007 GRL)

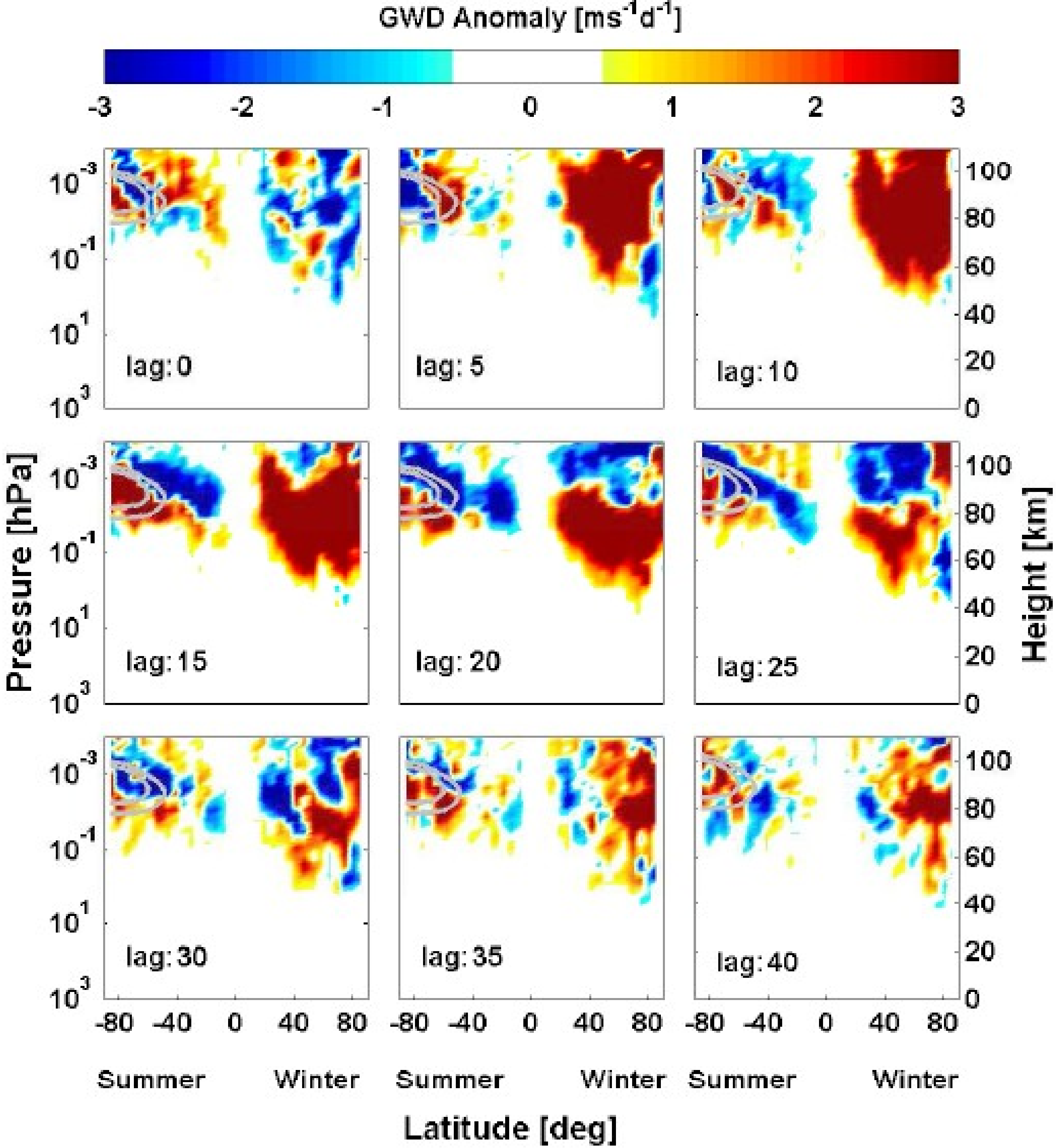


Simulations with the extended CMAM show a similar correlation pattern to the obs (associating PMC radius with low temperature)

Here the two hemispheres are combined, 19 years of model data

Black lines indicate summer mesopause

Karlsson, McLandress & Shepherd (JASTP 2009)



The inter-hemispheric coupling comes from GWD

Plots show GWD response to positive winter hemisphere EP flux anomalies in CMAM

Response is upwards and sideways

Karlsson et al. (JASTP 2009)

Summary

- Internal gravity waves can transfer momentum to great heights and exert a “drag force” (which can be positive) where they dissipate
- This drag force controls the thermal structure of the mesosphere (e.g. cold summer mesopause)
- The momentum transfer is filtered by winds in the stratosphere, providing a mechanism for stratosphere-mesosphere coupling on a variety of timescales, most prominantly in polar regions
  - Warm stratosphere implies cold mesosphere
- In this way, the behaviour of the mesosphere is “slaved” to that of the stratosphere through gravity-wave drag
- Models are able to capture this process very well

Reference 1

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