Stratosphere-Troposphere coupling: Mechanisms and implications for Data Assimilation

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with thanks to Matthew Wittman, Lorenzo Polvani and members of Reading Stratosphere and Climate group

June 09, 2010

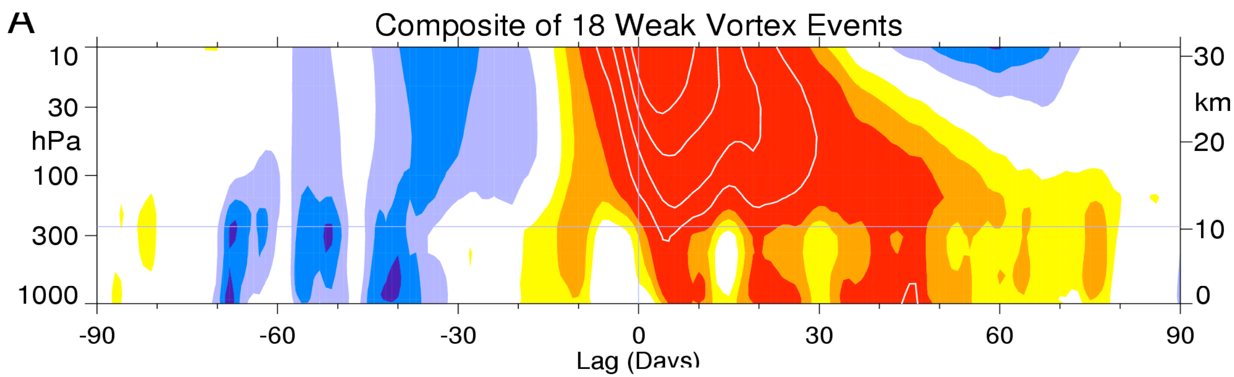
www.met.reading.ac.uk/research/stratclim/

Outline

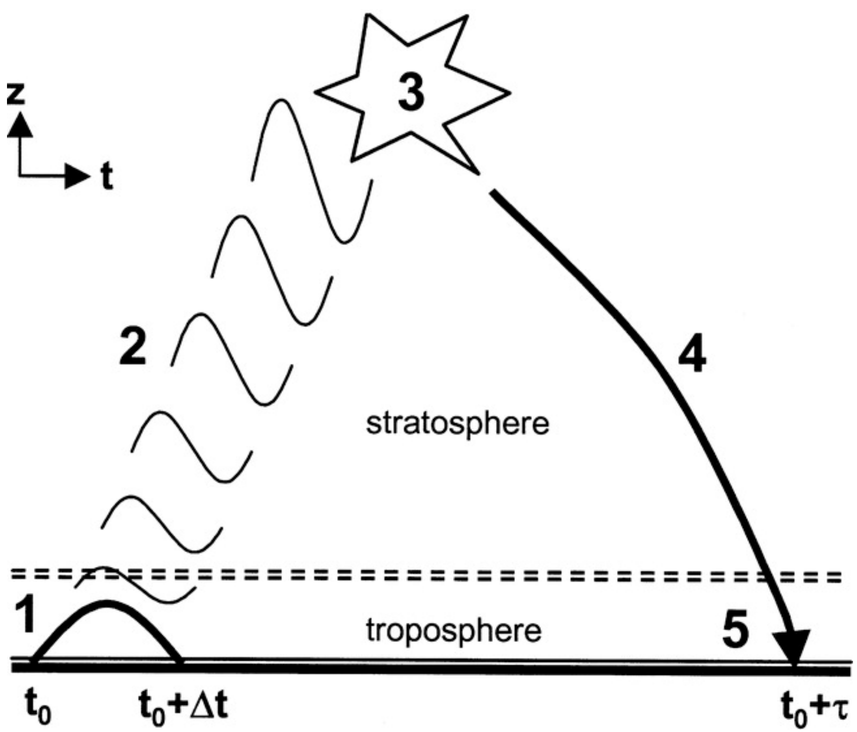
- Adam has given you a review of stratosphere-troposphere coupling.
- Clear that stratosphere important on a range of timescales and related to both natural and forced changes.
- This talk: Mechanisms for downward influence.
- Lead to discussion on consequences for DA.

Defining Stratospheric influence

Downward influence



Baldwin and Dunkerton (2001)



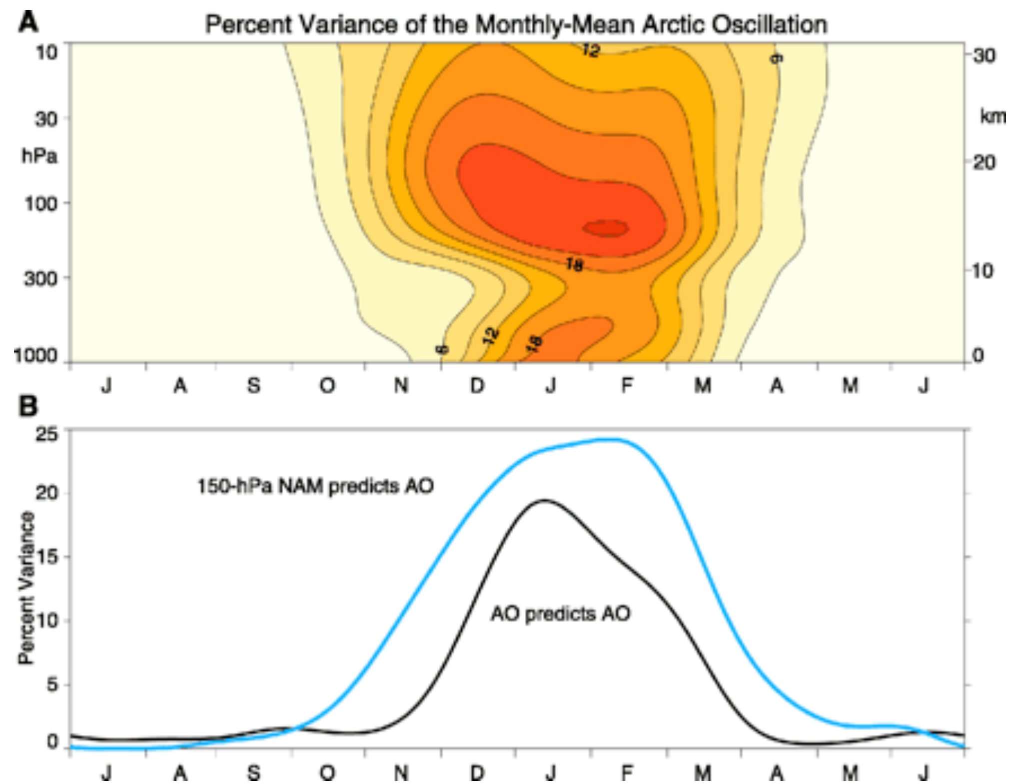
- Focus on influence on troposphere once anomaly appears in lower stratosphere
- Influence depends on 1-4

Reichler et al. (2005)

Where is the influence from?

Statistical correlations peak in the winter-time lower stratosphere ~ 150hPa
(Charlton et al. 2003, Baldwin et al. 2003)

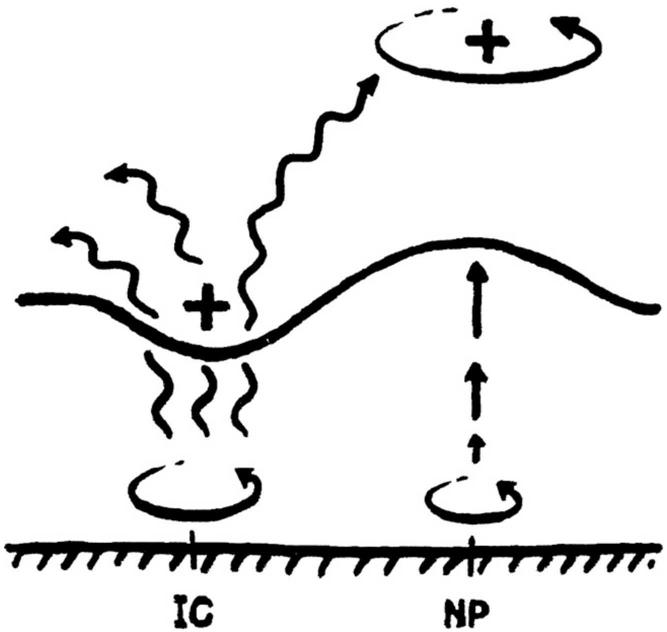
Modeling studies show this is confirmed by the response to radiative forcing
(e.g. Maycock et al. pers. comm.)

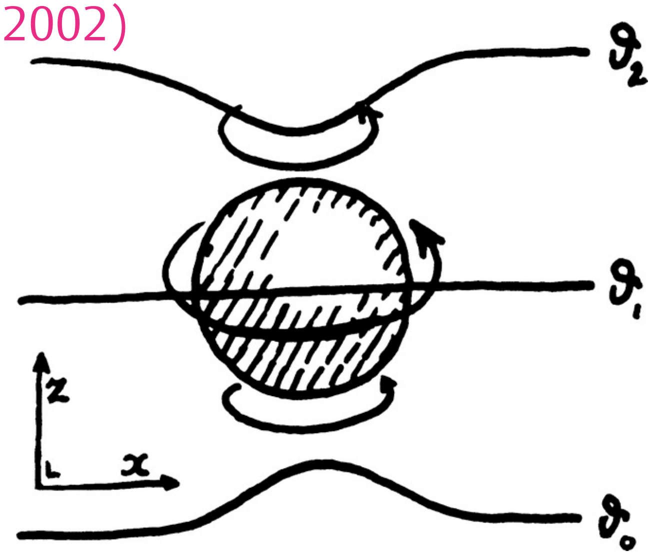


Direct response

Stratospheric PV anomalies

Ambaum and Hoskins (2002)





$$P = \frac{f + \xi}{\sigma} \qquad \sigma = -\frac{1}{g}\frac{\partial p}{\partial \theta}$$

For Bu = 1 10% change in stratospheric PV results in 5% change in tropopause height

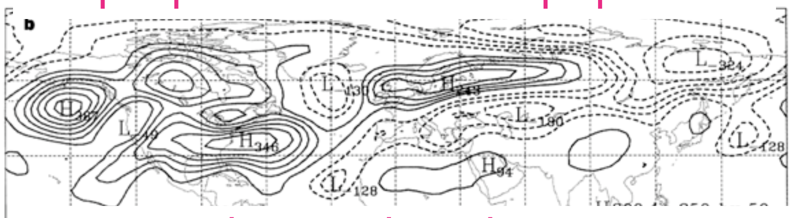
$$\frac{\Delta P}{P} \approx -(1 + Bu)\frac{\Delta p_{\mathrm{tpp}}}{p_{\mathrm{tpp}}}$$

For tropopause temp. 210K equivalent to a 300m change in tropopause height

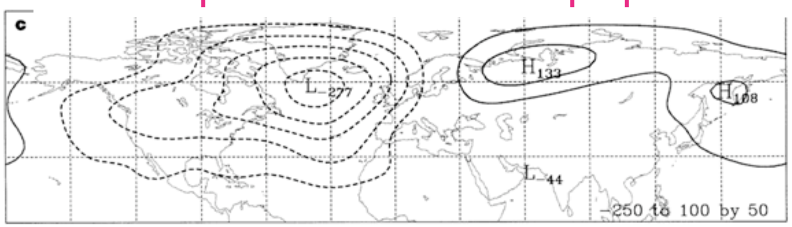
Tropopause changes

Observed tropopause Z'

Troposphere induced tropopause Z'



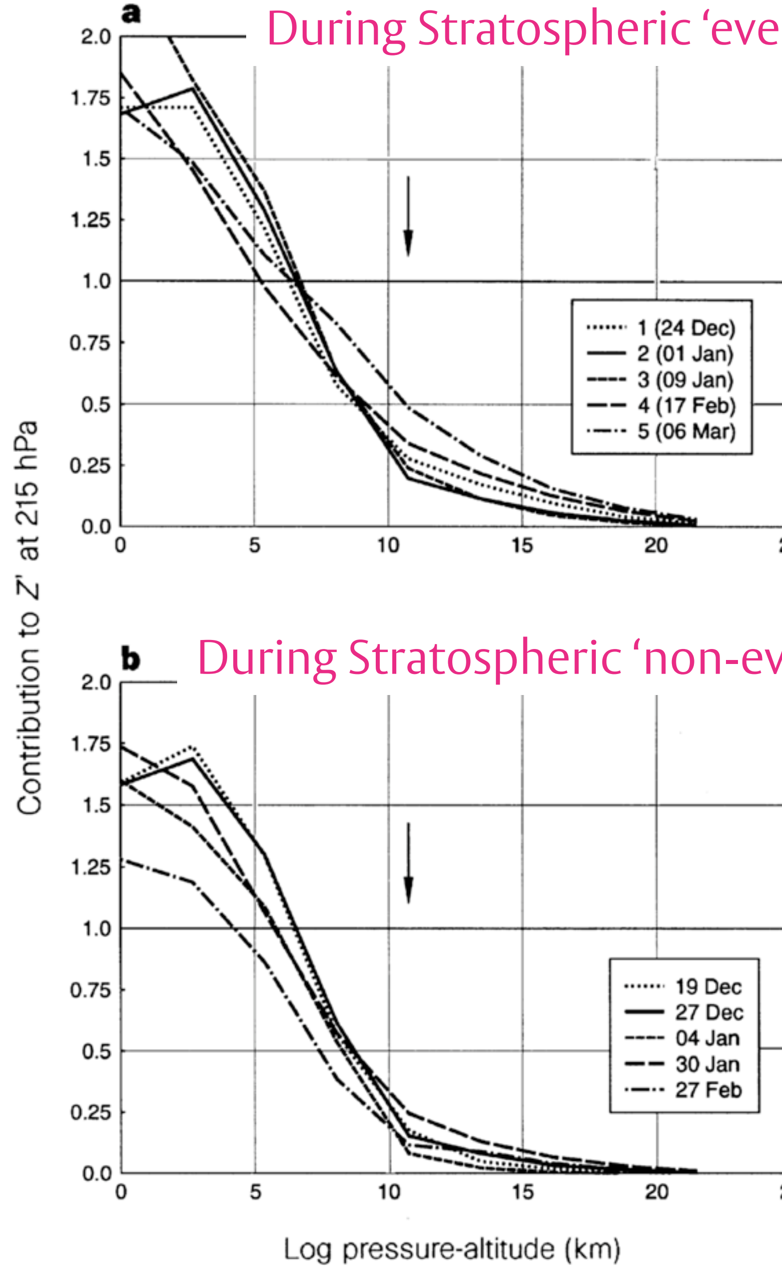
Stratosphere induced tropopause Z'



- Pattern of influence on troposphere large-scale and out of phase with observed response
- Possible eddy-feedback within troposphere (Chen and Robinson, 2004)

During Stratospheric 'events'

During Stratospheric 'non-events'



Hartley et al. (1998)

Planetary wave reflection

Reflection of planetary waves

- In a series of papers Judith Perlwitz and Nili Harnik have investigated the possibility of planetary wave reflection in the stratosphere (Perlwitz and Harnik (2003) Harnik and Perlwitz (2004), Shaw et al. (2010), Shaw and Perlwitz (2010)
- Key theoretical idea: negative zonal wind shear in the upper stratosphere (2-10hPa) is consistent with a reversed (negative) potential vorticity gradient and provides a reflecting surface for planetary waves.
- Impact on troposphere related to interference of reflected wave-packets with tropospheric planetary waves (both stationary and transient)
- Key challenge is diagnosing reflection in models in data.

Evidence for reflection

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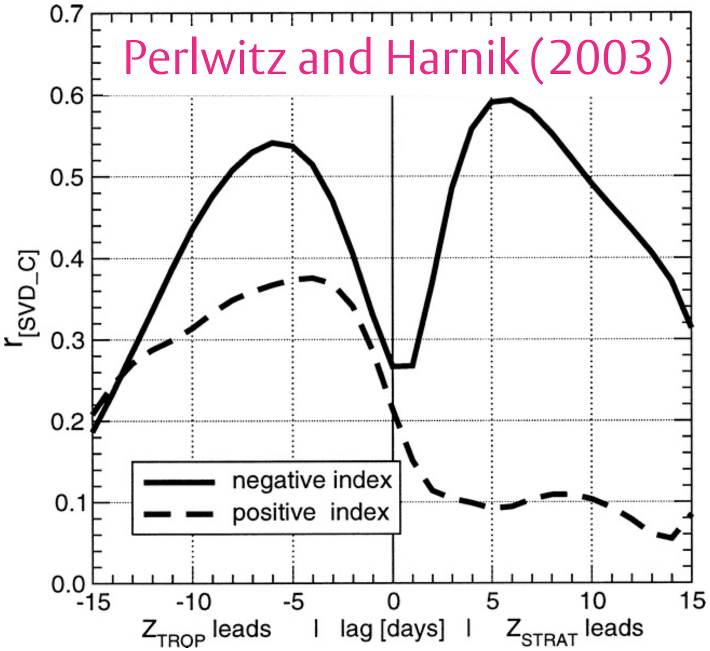
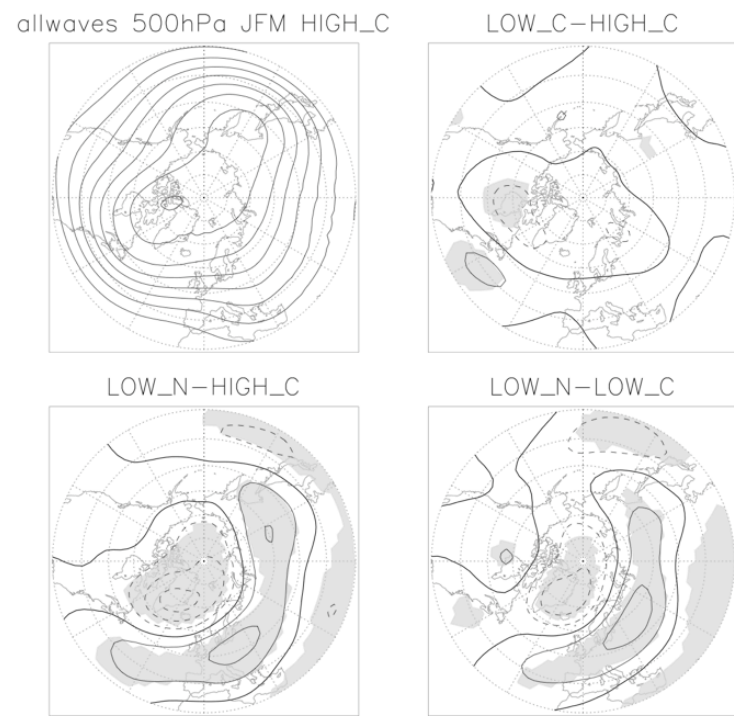


Reflection calculated by lagged singular value decomposition of wave 1 geopotential height field

Two lines show correlation between stratospheric and tropospheric SVD modes for cases with negative upper stratospheric shear and positive upper stratospheric shear.



Model formulation (top, gravity wave drag) can produce spurious reflection from lower altitudes leading to significant tropospheric biases

Shaw and Perlwitz (2010)

Tropospheric Baroclinic systems

Background

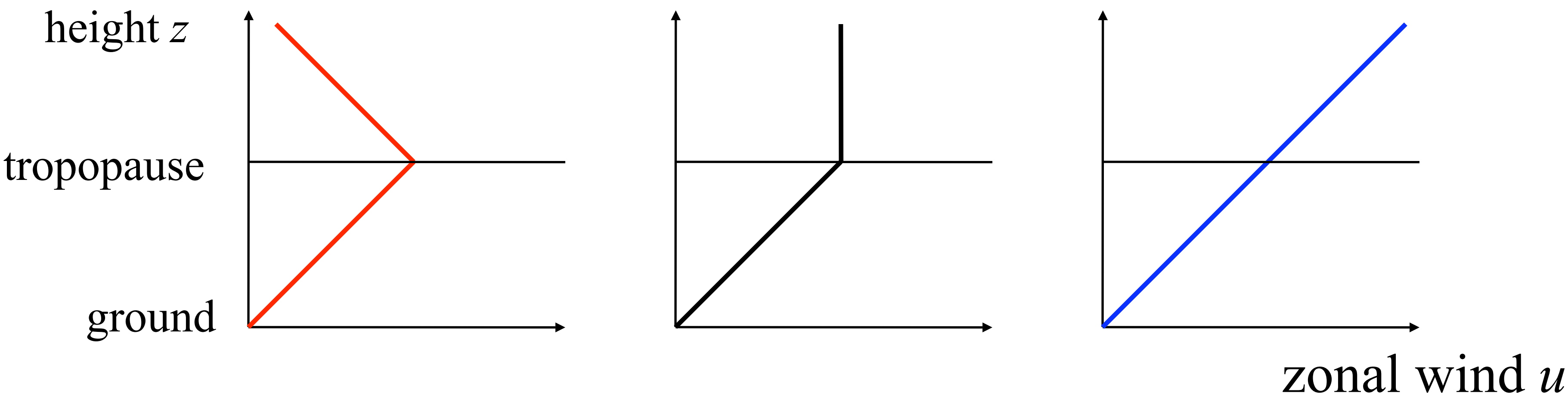
- Many recent studies have highlighted the role possibly played by tropospheric eddies.

  (Polvani and Kushner (2002), Haigh et al. (2005) Charlton et al. (2004), Wittman et al. (2004), Song and Robinson (2004))

- In this section, experiments which assess how this might occur and how large the effect is are discussed.

Modified Eady Problem

$$\frac{\partial u}{\partial z} < 0 \qquad \frac{\partial u}{\partial z} = 0 \qquad \frac{\partial u}{\partial z} > 0$$

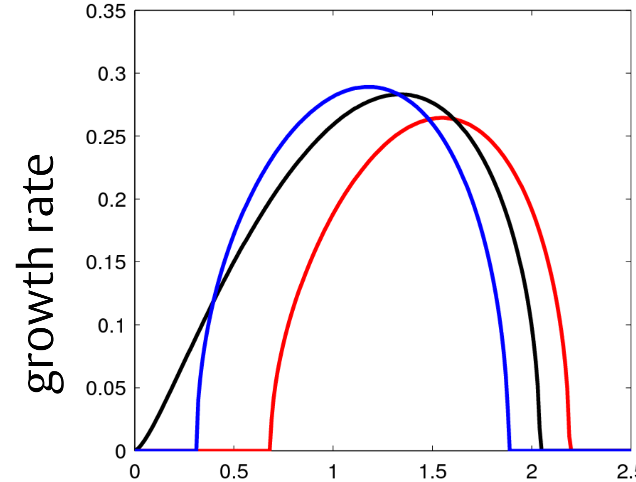


- Two-layer, open top domain
- Variable stratospheric shear – 3 cases shown
- $N_s^2 = 4\,N_t^2$ (Realistic Brunt-Väisälä frequency ratio)

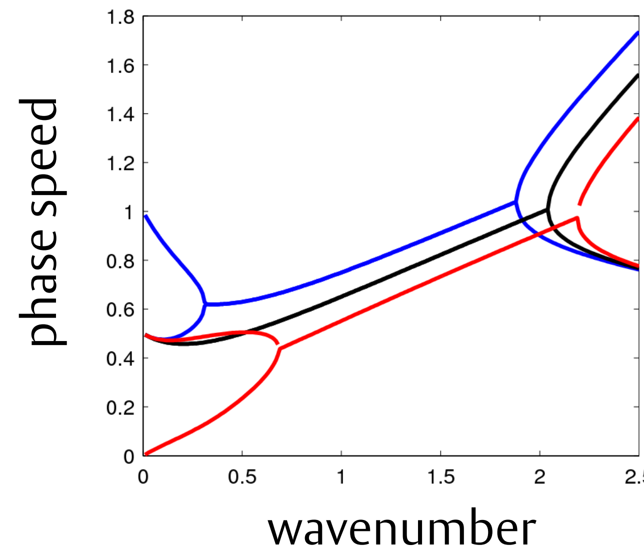
Wittman et al. (2007)

1-D results

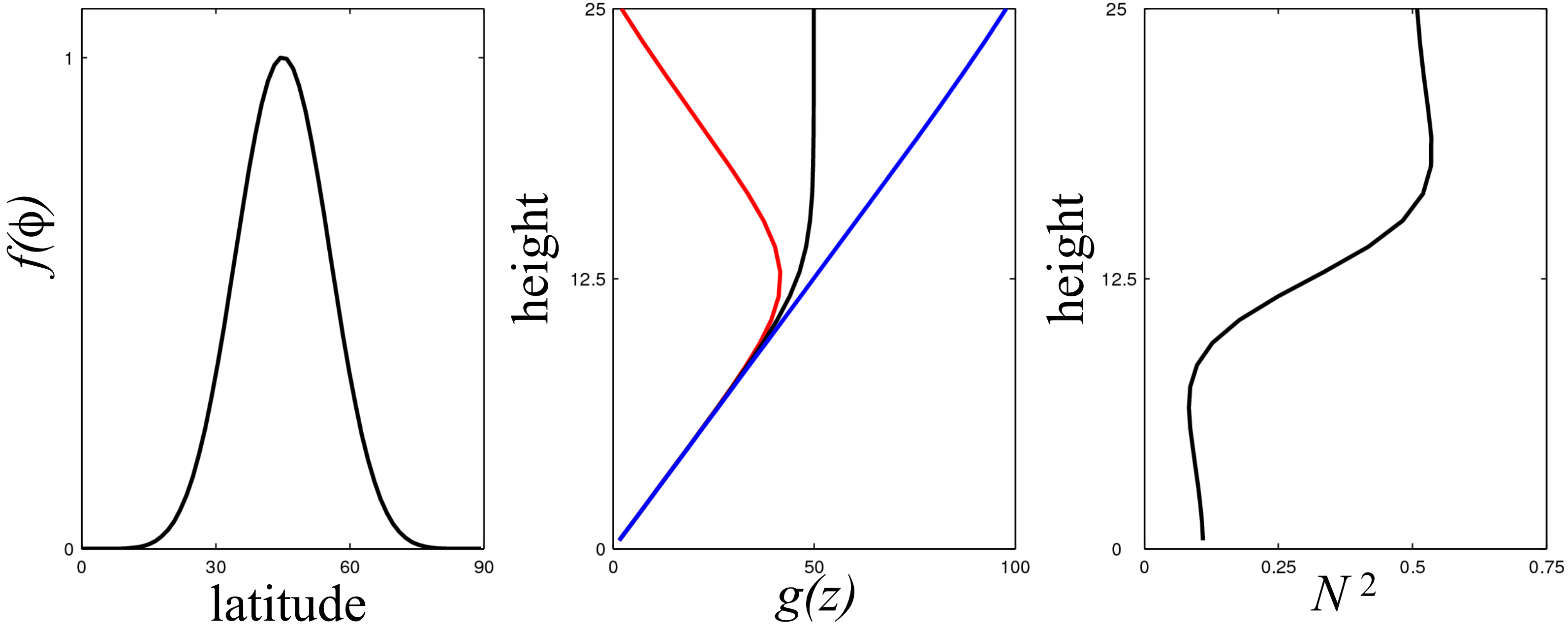
- Low wavenumbers: growth rates increase with shear
- High wavenumbers: growth rates decrease with shear



- Phase speed increases with increasing shear

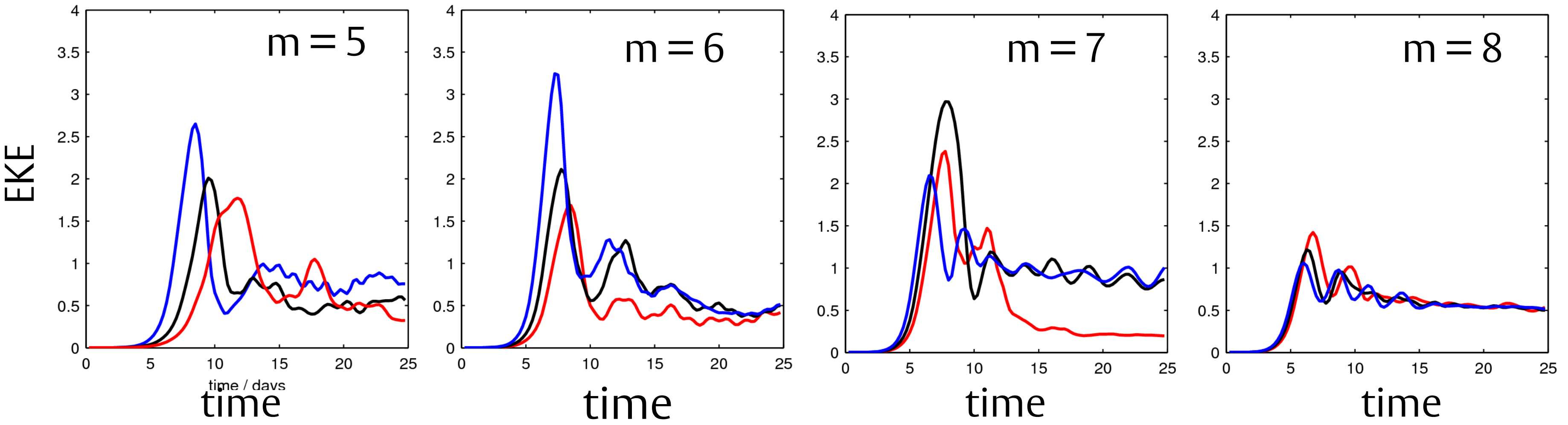


Linear 3-D Primitive Equations



- Basic state $u = f(\varphi)\, g(z)$
- $\partial u/\partial z$ and N^2 as in 1-D model
- Obtain normal modes by solving an Initial Value Problem

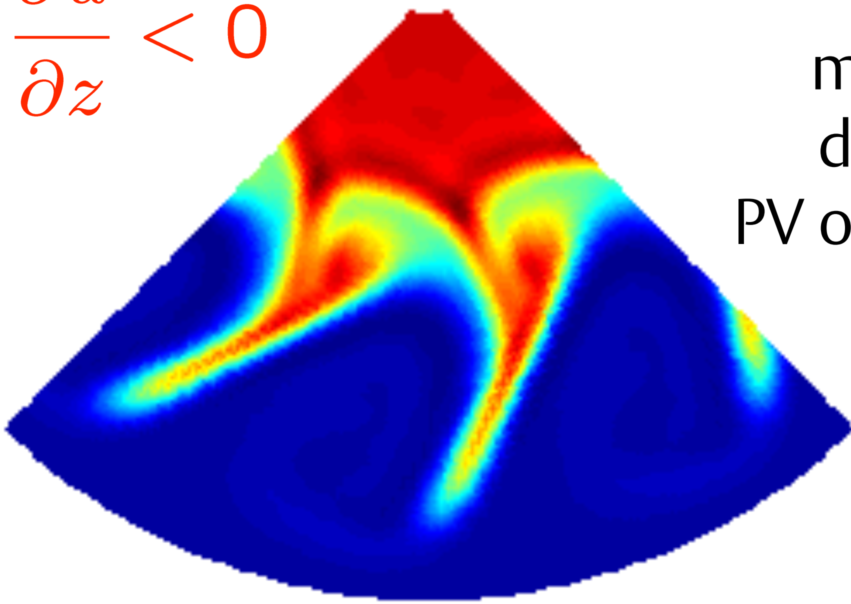
Lifecycles



- Growth rates as expected from linear calculation
- Saturation amplitude dependent on shear
- Transition from LC1 to LC2 at $m = 7$?

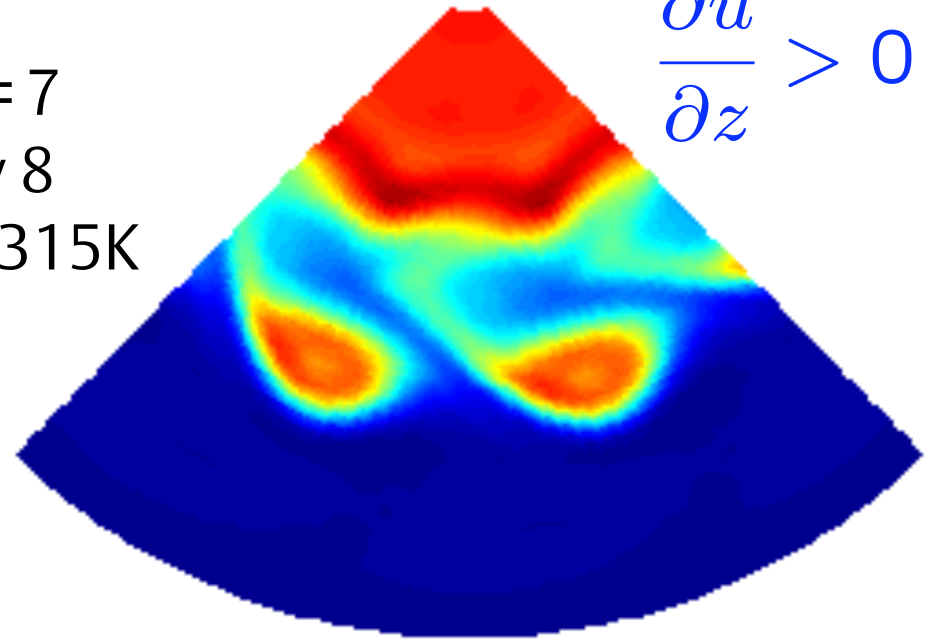
LC1 / LC2 transition

$$\frac{\partial u}{\partial z} < 0$$



m = 7
day 8
PV on 315K

$$\frac{\partial u}{\partial z} > 0$$

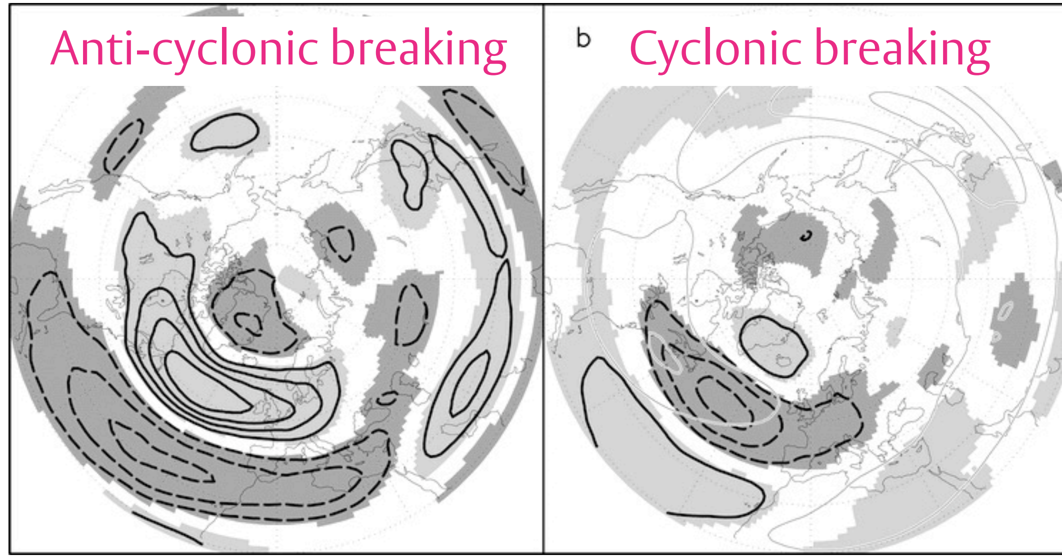


- Anti-cyclonic wave breaking towards the equator – LC1
- Cyclonic wave breaking towards the pole, persistent PV anomalies – LC2

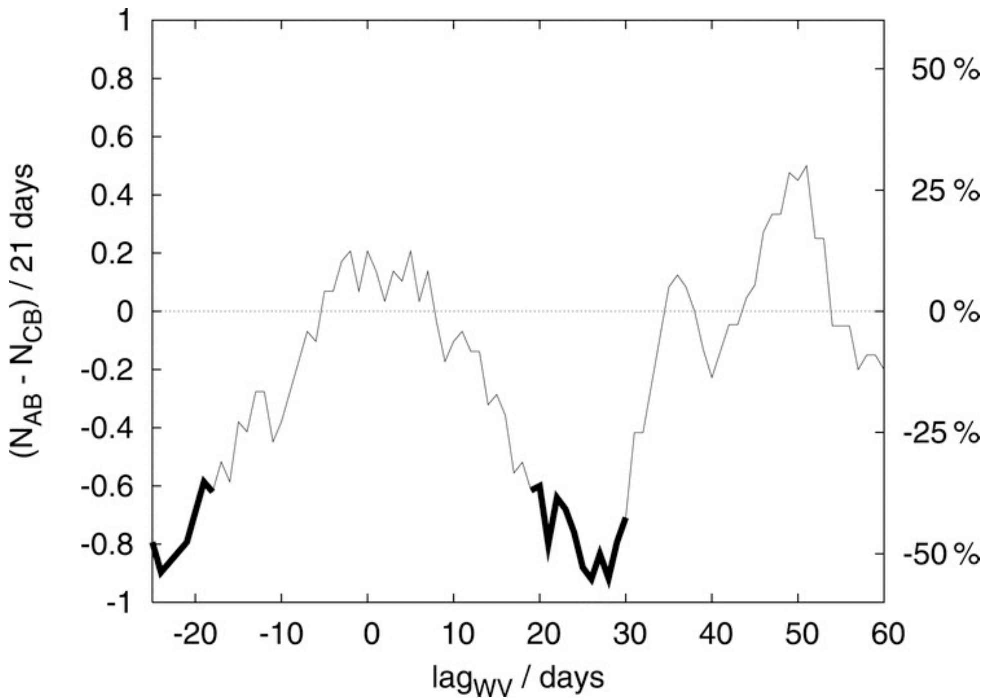
ERA-40 composites

Significant zonal wind anomalies in Atlantic sector following different types of wave-breaking in ERA-40

300hPa zonal wind anomalies

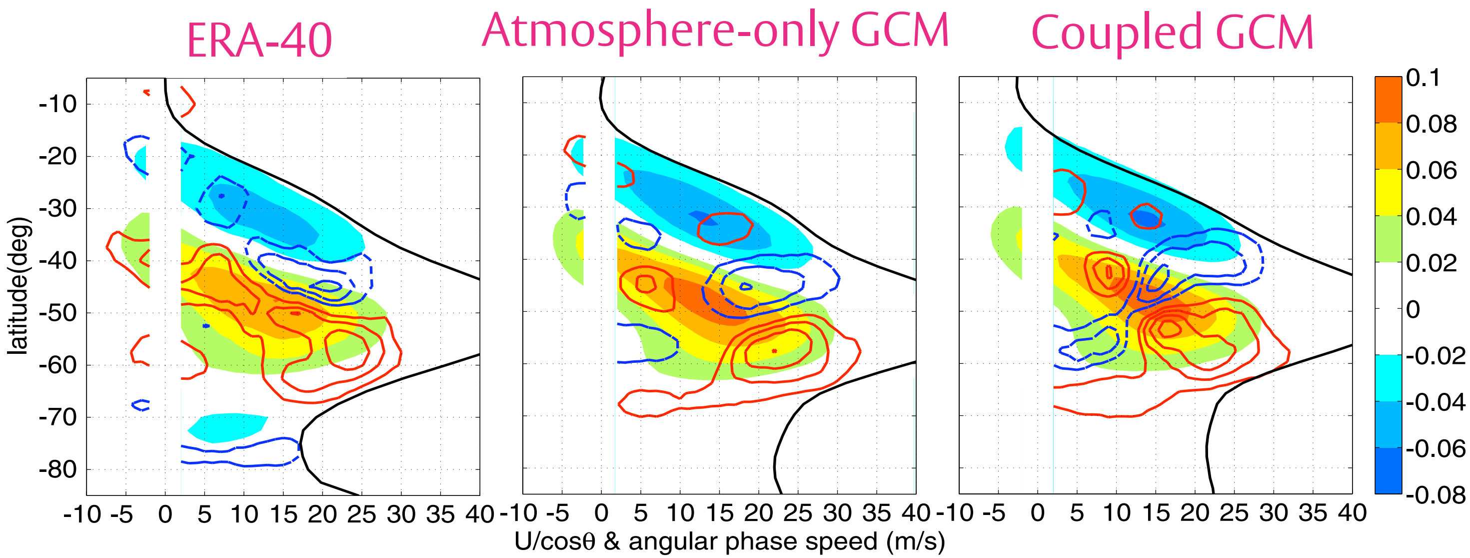


Kunz et al. (2007)



Significant increase in cyclonic breaking events (50%) following weak stratospheric vortex events

Phase speed spectra



Chen and Held (2007)

Colours - eddy momentum flux convergence
Contours - trend
Black line - climatological zonal wind

Observed poleward trend in southern hemisphere jet linked to increasing phase speed of eddies transporting momentum

An alternative explanation

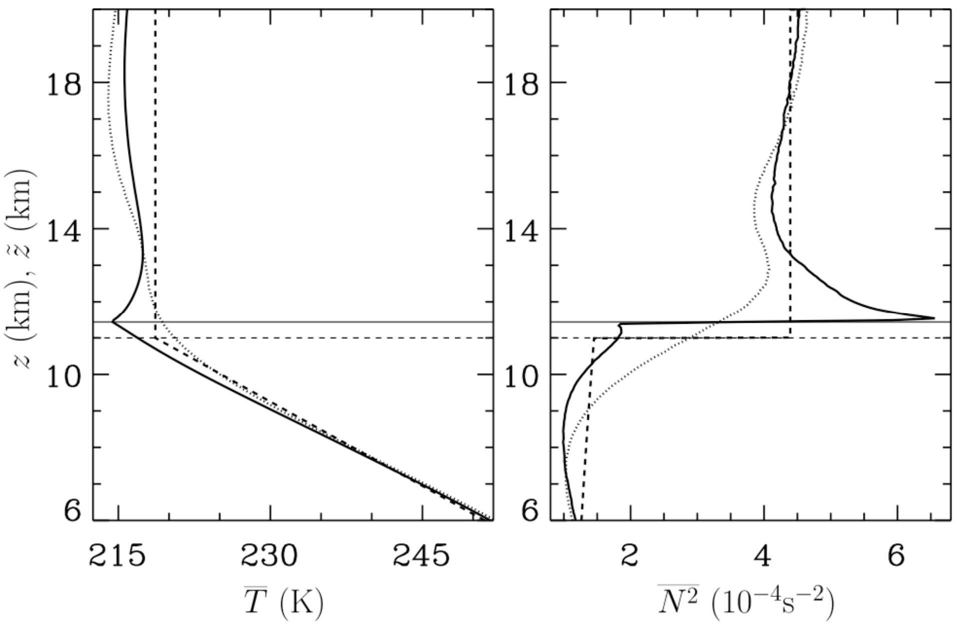
- Simpson et al. (2009) perform spin-up experiments with an idealised GCM looking at the response to many different stratospheric forcings.
- Also observe changes to jet position associated with change in momentum flux convergence.
- Suggest changes to eddies are related to changes in refractive index near tropopause

Summary of mechanisms

- Several competing mechanisms proposed for link between the stratosphere and troposphere.
- Hard to rule out any mechanisms, since all seem to be of significant size and valid.
- In practical terms, the tropospheric eddy-driven jet will clearly be important, even if other mechanisms are also present.
- Particularly true when considering location, size and scale of impact.
- Direct adjustment response to stratospheric PV likely well captured by all models, other mechanisms somewhat.

Implications for Data Assimilation

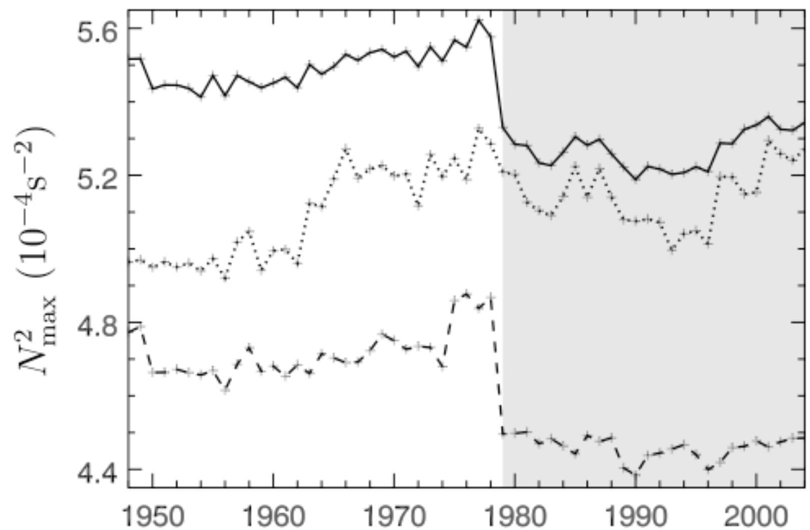
Fine-scale tropopause structure



Birner (2006)

- Recent focus on highly complex structure near extra-tropical tropopause
- Potentially crucial for all three mechanisms

Given coarse observations and model grids, can fine-scales structure near the tropopause by properly assimilated?



Birner et al. (2006)

Dependence on full atmospheric structure

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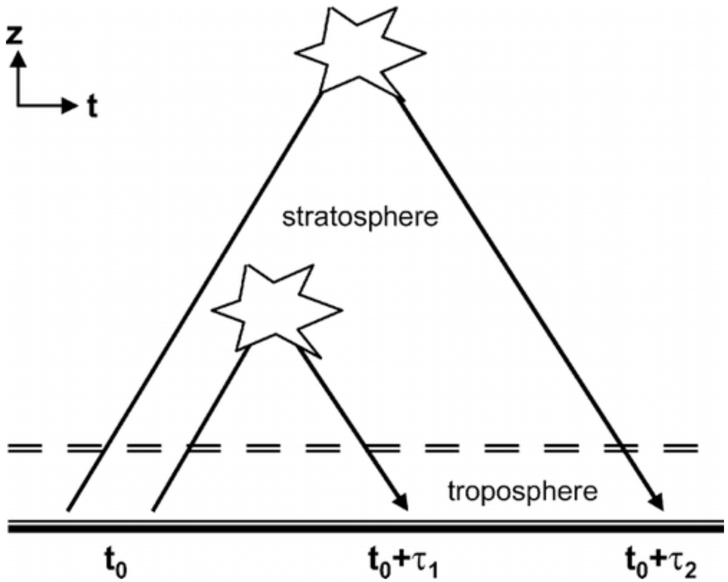


Reichler et al. (2005)

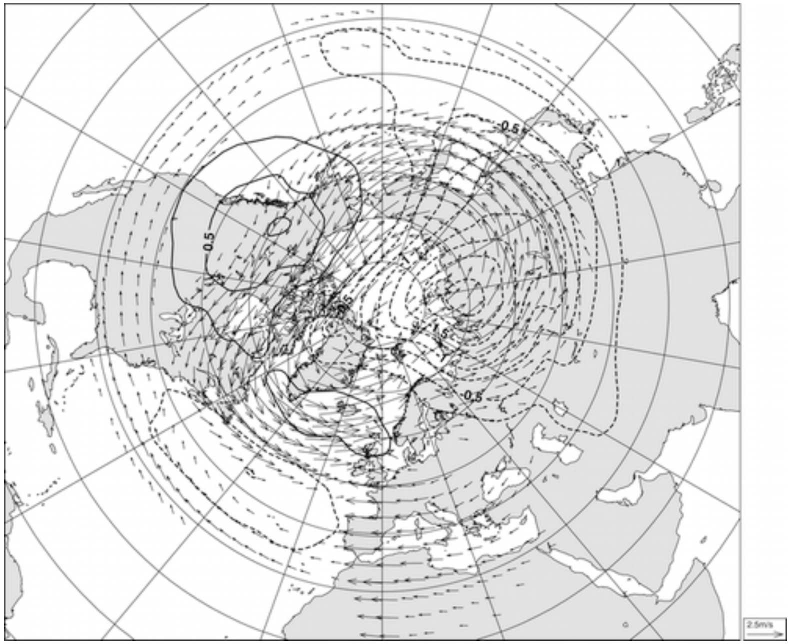
- Timescale for tropospheric impact depends on stratospheric wave mean-flow interaction
- Need to represent both planetary waves and stratospheric critical layers in the initial conditions appropriately.

Do DA systems properly initialise amplitude and phase of planetary waves and stratospheric states with appropriate wave-guide & critical layer structures?

Sensitivity analysis

Tangent-linear and adjoint models used to derive optimal perturbation patterns for the stratospheric vortex.

Also recently used to examine the sensitivity of the polar vortex to small-scale features of the tropospheric circulation (Clare Oatley, PhD Thesis)



Jung and Barkmeijer (2006)

Could DA systems be used more widely for this kind of sensitivity analysis and made more widely available?

Thanks and discussion

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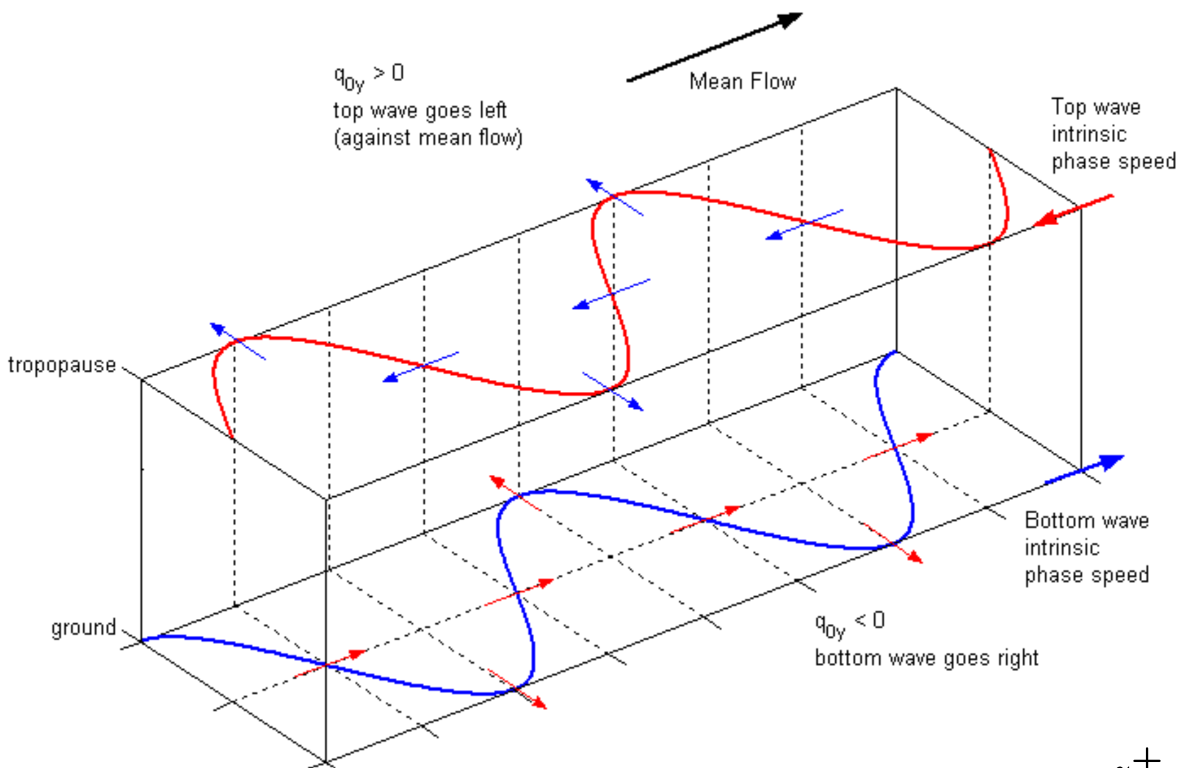
Counter-Propagating Rossby Waves I

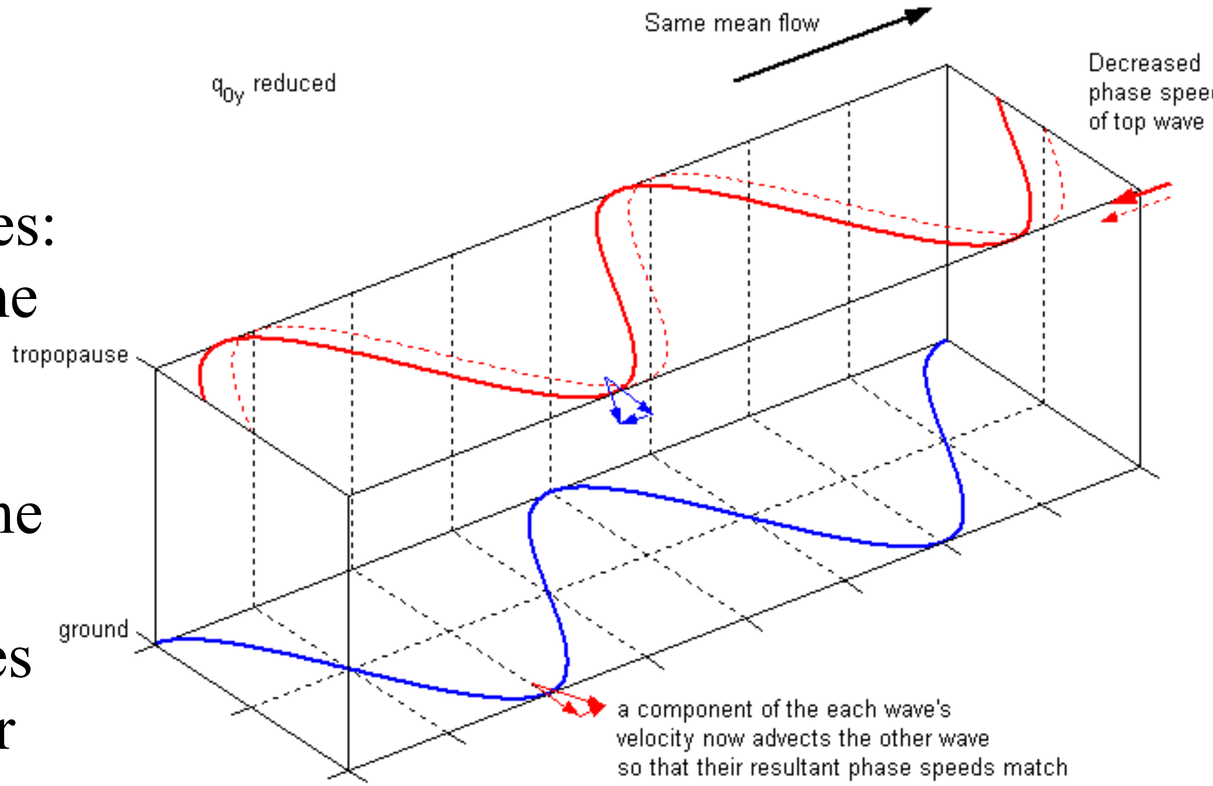
- Growth rate highest when phase speeds are equal and opposite.
- This occurs when $\partial u_s / \partial z = 0$ so that q_{0y} is equal and opposite.
- All of the velocity induced by each wave grows the other wave's PV perturbation.



$$q_{0y} \propto \left[\frac{\partial u_t / \partial z}{N_s^2} - \frac{\partial u_s / \partial z}{N_t^2} \right]_{z^-}^{z^+}$$

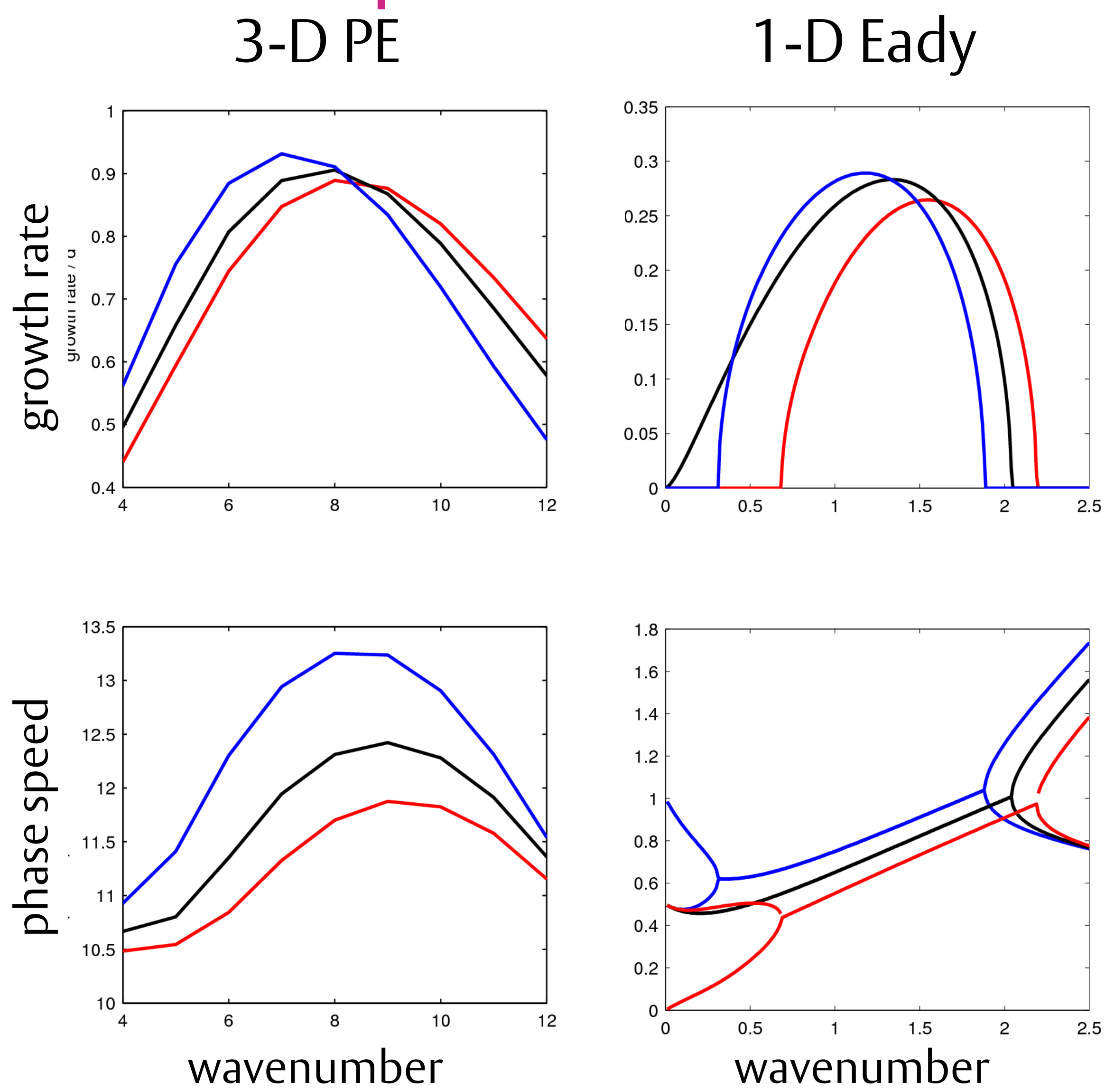
Counter-Propagating Rossby Waves II

- Changing shear changes q_{oy} at the tropopause.
- Growth rate decreases: to cohere, some of the velocity due to each wave must *advect* instead of *growing* the other.
- Phase speed increases with increasing shear

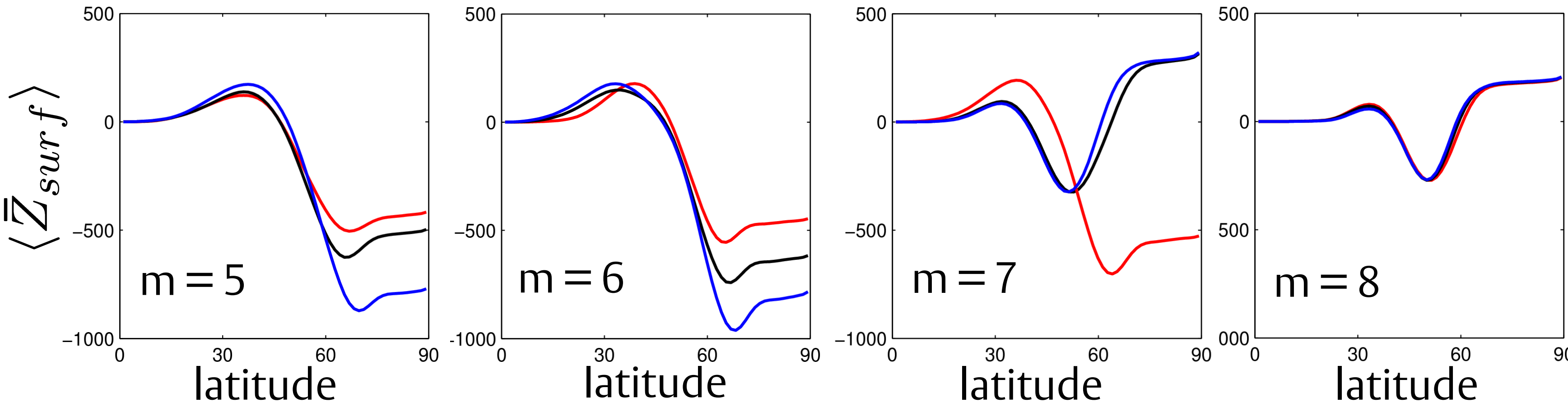


Comparison with 1-D problem

- Dependence on shear as in 1-D problem for growth rate
- and phase speed



Effect on the Annular Mode



- *m* = 5,6 (LC1): NAM signal increases with shear
- *m* = 7: LC1 / LC2 transition
- *m* ≥ 8 (LC2): no effect of shear