The role of planetary waves in dynamical coupling between stratosphere and troposphere

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(PHH work reported here includes collaborations with Peter Hitchcock, Stephen Hardiman and others)

DAMTP **CC*f*CS**

The troposphere affects the stratosphere

Upward propagation of waves (large-scale planetary waves, but also gravity waves).

Simple theory (Charney Drazin)

Numerical experiments (`mechanistic' models and troposphere-stratosphere general circulation models)

Observational indicators (summer-winter differences, interhemispheric differences)

Wave Activity

Wave Activity Conservation Relation

$$\frac{\partial}{\partial t}\left\{\frac{1}{2}\frac{\overline{q'^2}}{\bar{q}_y}\right\} + \frac{\partial}{\partial y}\left\{-\overline{u'v'}\right\} + \frac{1}{\rho_0}\frac{\partial}{\partial z}\left\{\rho_0\frac{f_0\overline{v'\theta'}}{\bar{\theta}_z}\right\} = \frac{\overline{v'\mathcal{D}'}}{\bar{q}_y}$$

wave activity = ‘wave stuff’

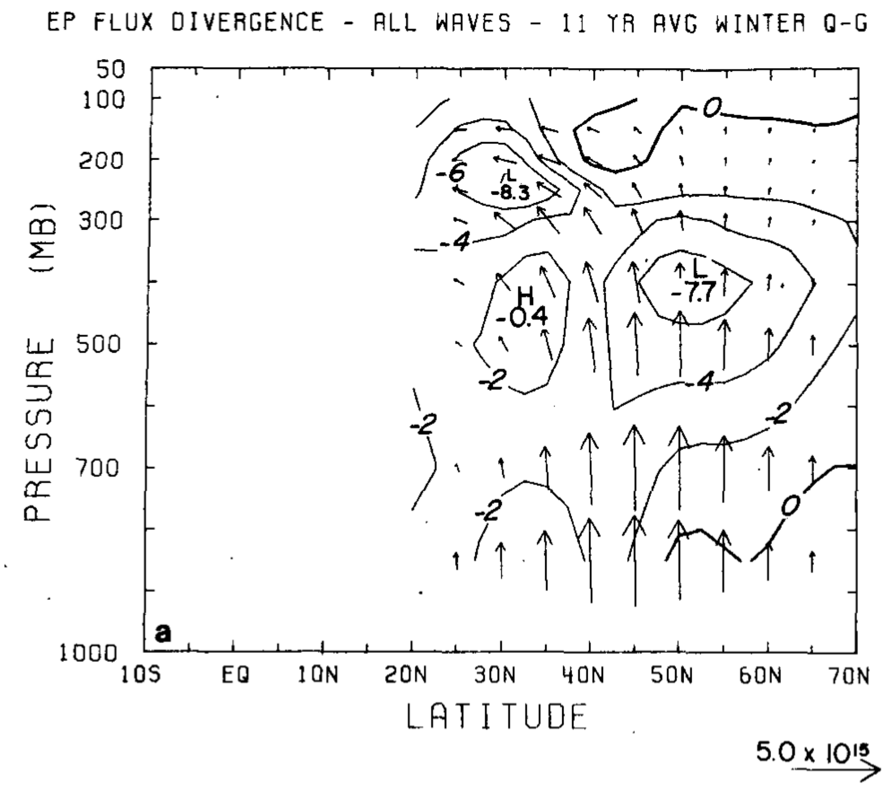
‘Eliassen-Palm flux’

$$\mathbf{F} = (F^{(y)}, F^{(z)})$$

$$\frac{\partial \mathcal{A}}{\partial t} + \frac{\partial F^{(y)}}{\partial y} + \frac{\partial F^{(z)}}{\partial z} = \mathcal{D}_{\mathcal{A}}$$

density — *y*-flux — *z*-flux — dissipation

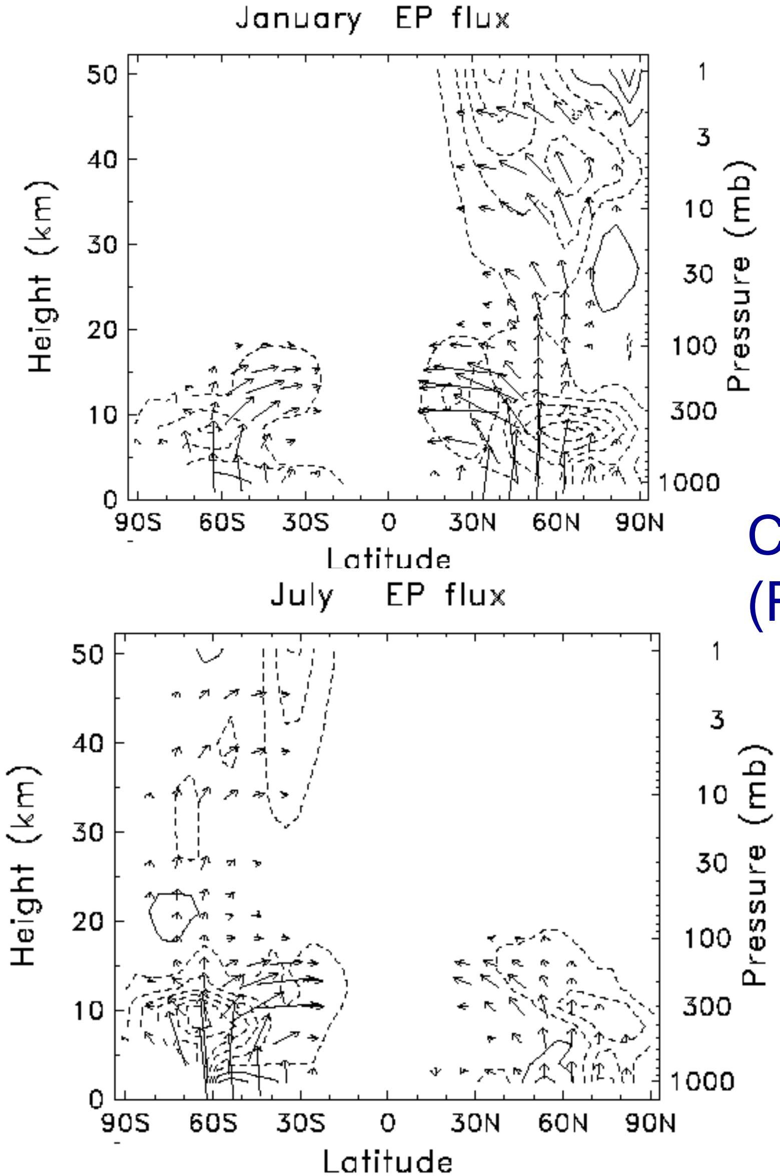
Tropospheric EP fluxes



Contributions from ‘synoptic-scale’ and ‘planetary-scale’ waves

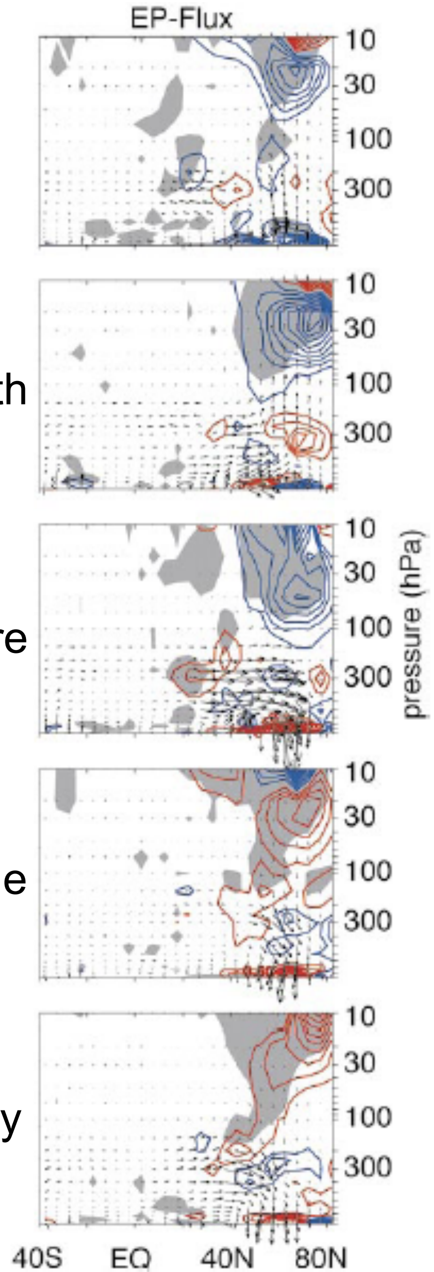
Edmon et al (1980)

Stratospheric EP fluxes



Climatology
(Randel 1992)

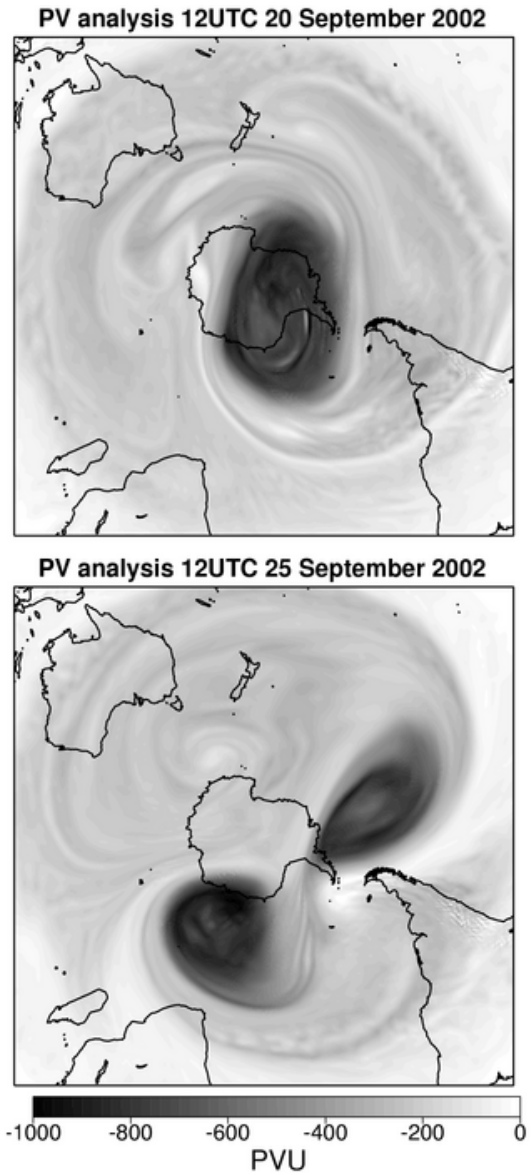
Life-cycle of a sudden warming (Limpavusan et al 2004)



Sudden stratospheric warmings

major perturbation of winter-time stratospheric circulation -- research focus in 1970s and 1980s.

We still cannot point to circulation anomalies in the troposphere and identify them as the `cause' of a dynamical perturbation in the stratosphere.

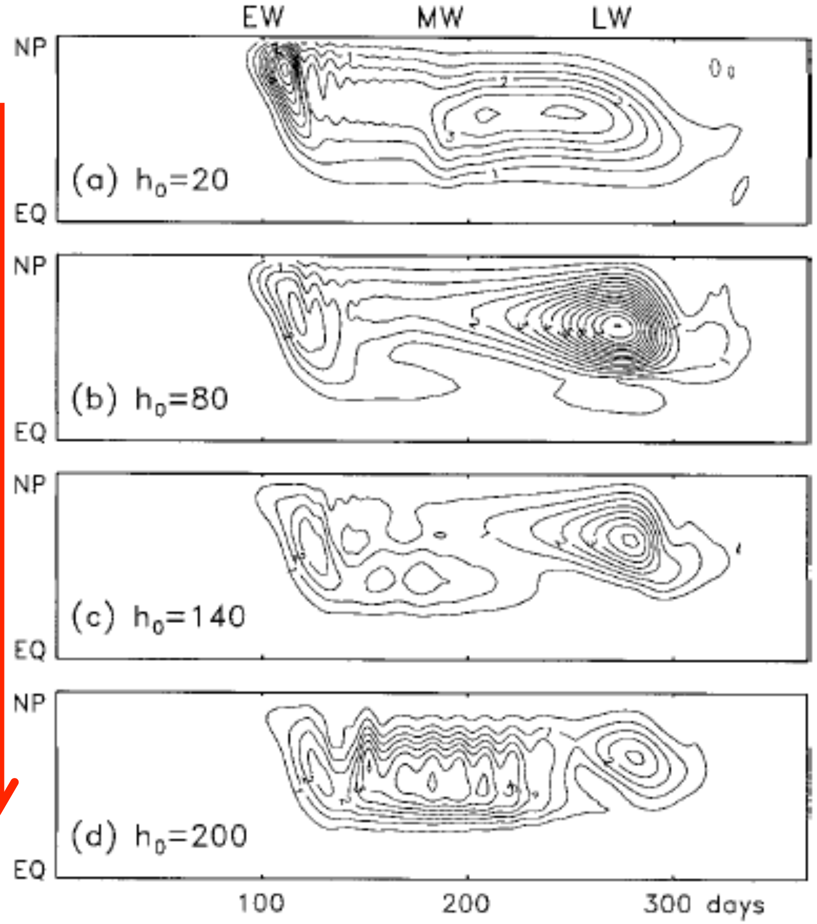


(Simmons et al 2005)

Effects of two-way interaction between waves and mean flow

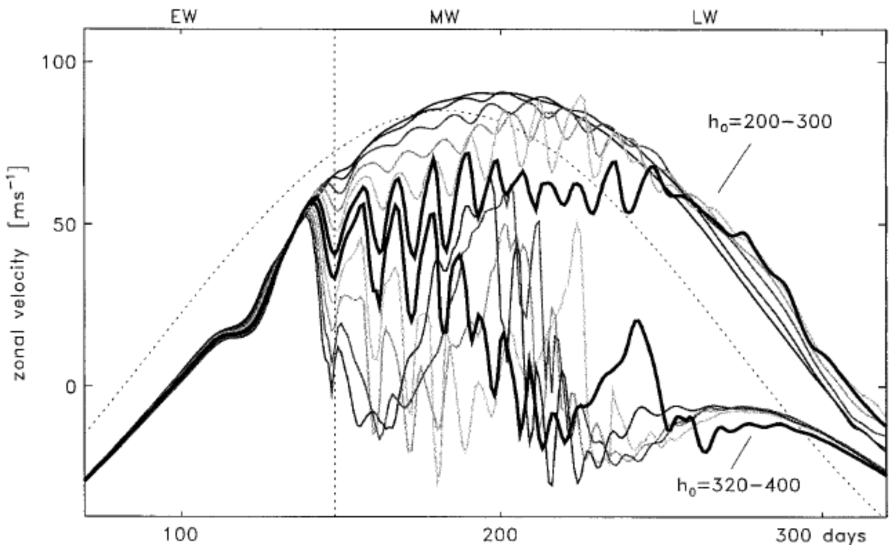
wave amplitude at 38km

increasing wave forcing



Seasonal cycle in a simple stratosphere-only model (Scott and H 2002)

mean wind at 38km



Does the one-way view of troposphere affecting stratosphere make sense?

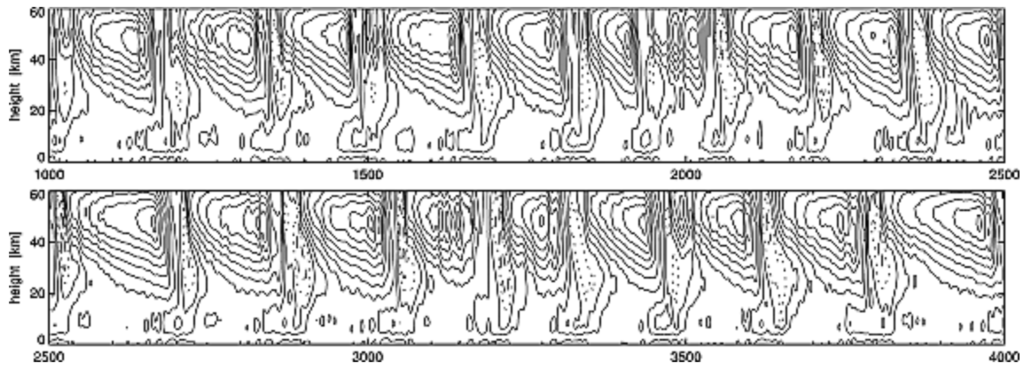
Non-local dynamics: On timescales of a few days dynamics is non-local in horizontal and in vertical (particularly in extratropics). Therefore changes in lower stratosphere inevitably affect upper troposphere and vice versa.

Evidence from numerical simulation: Significant evidence that changes in the (middle and upper) stratosphere affect troposphere, following e.g. Boville (1984), Kodera et al (1990) and that communication is dynamical.

Stratosphere affects troposphere

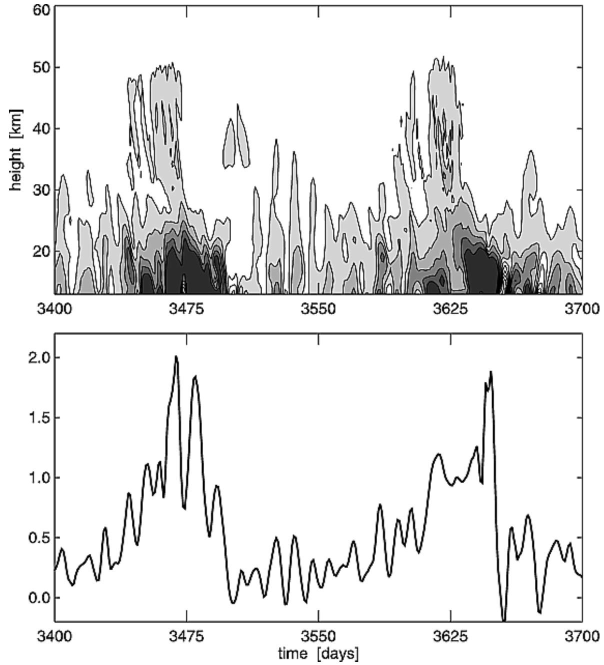
Scott and Polvani 2004

‘constant’ troposphere implies strong time variations in stratosphere



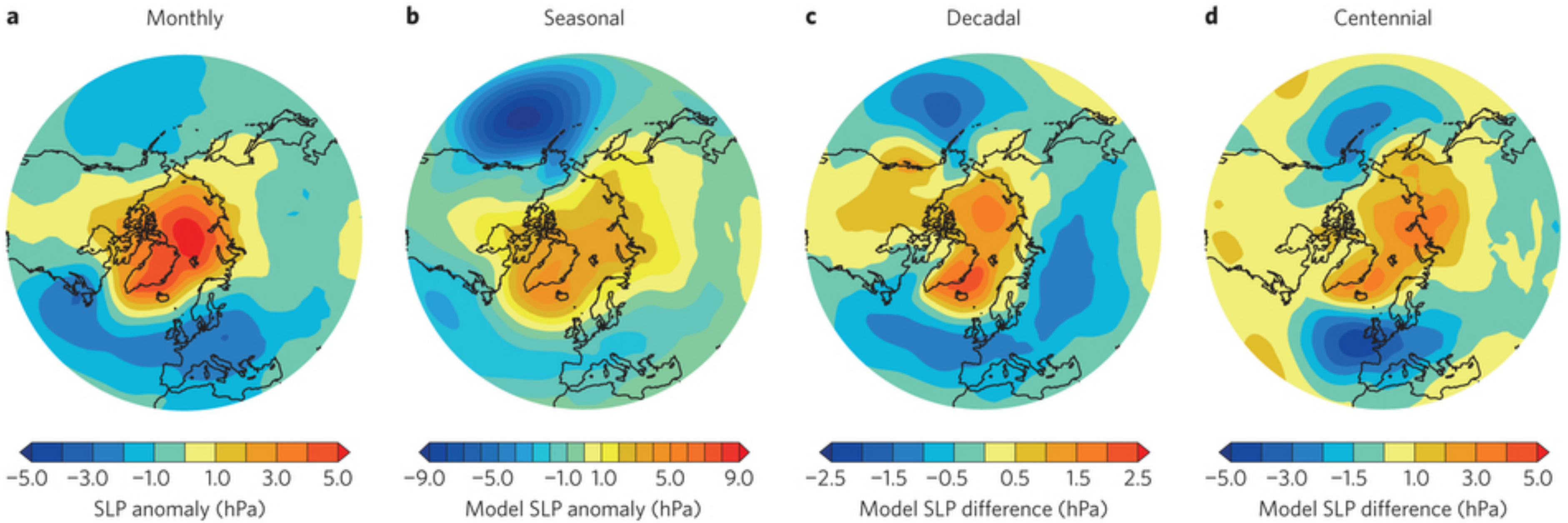
EP flux convergence in stratosphere

EP flux out of troposphere



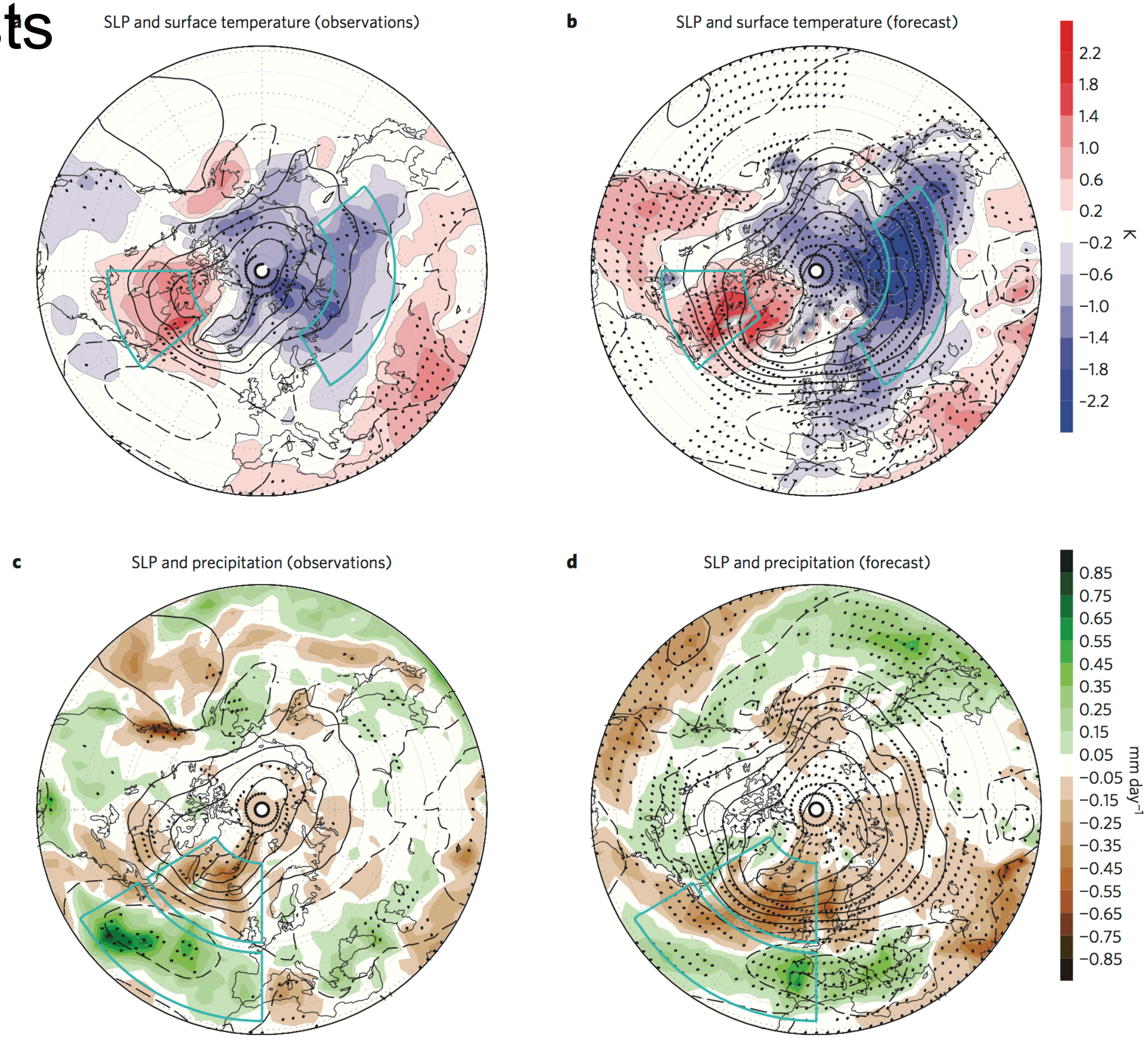
‘stratosphere determines wave flux out of troposphere’

Tropospheric response to stratosphere on different timescales



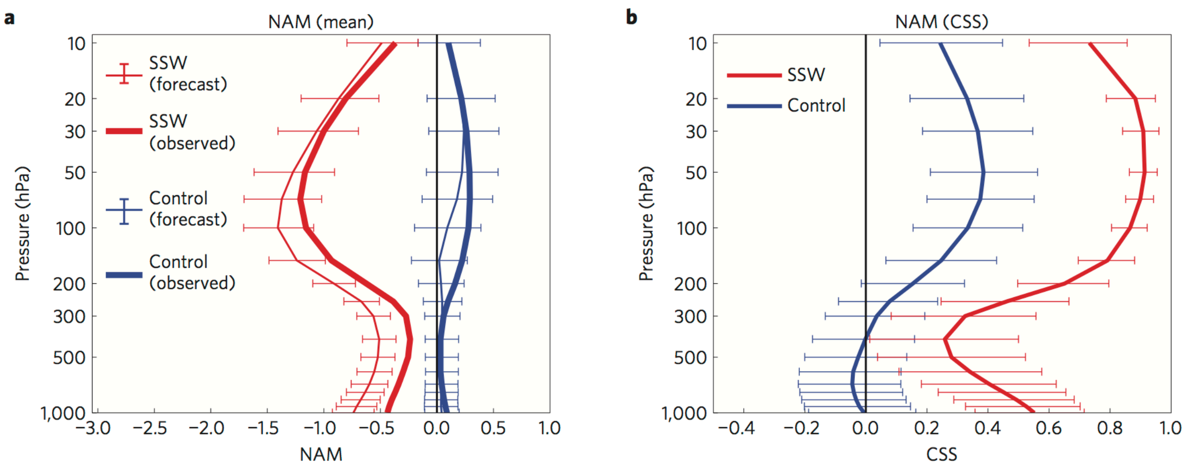
Kidston et al (2015)

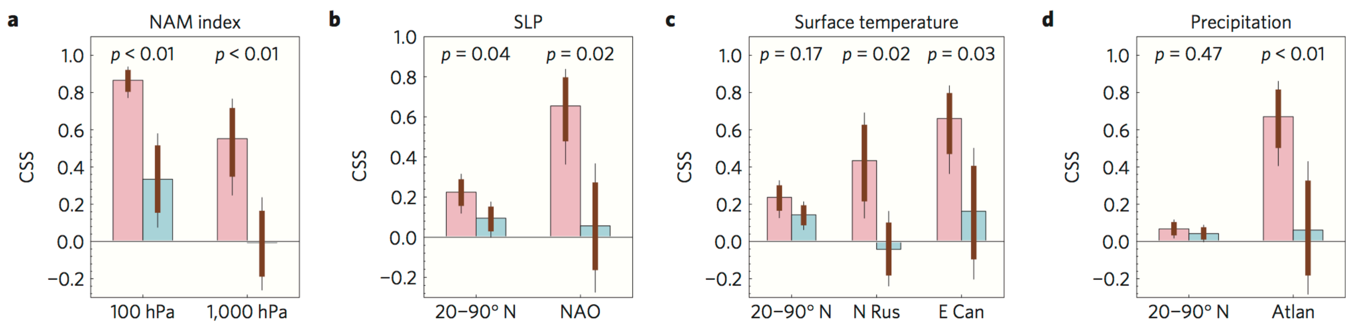
Observations/forecasts following SSWs



Sigmond et al (2013)

Measures of forecast skill

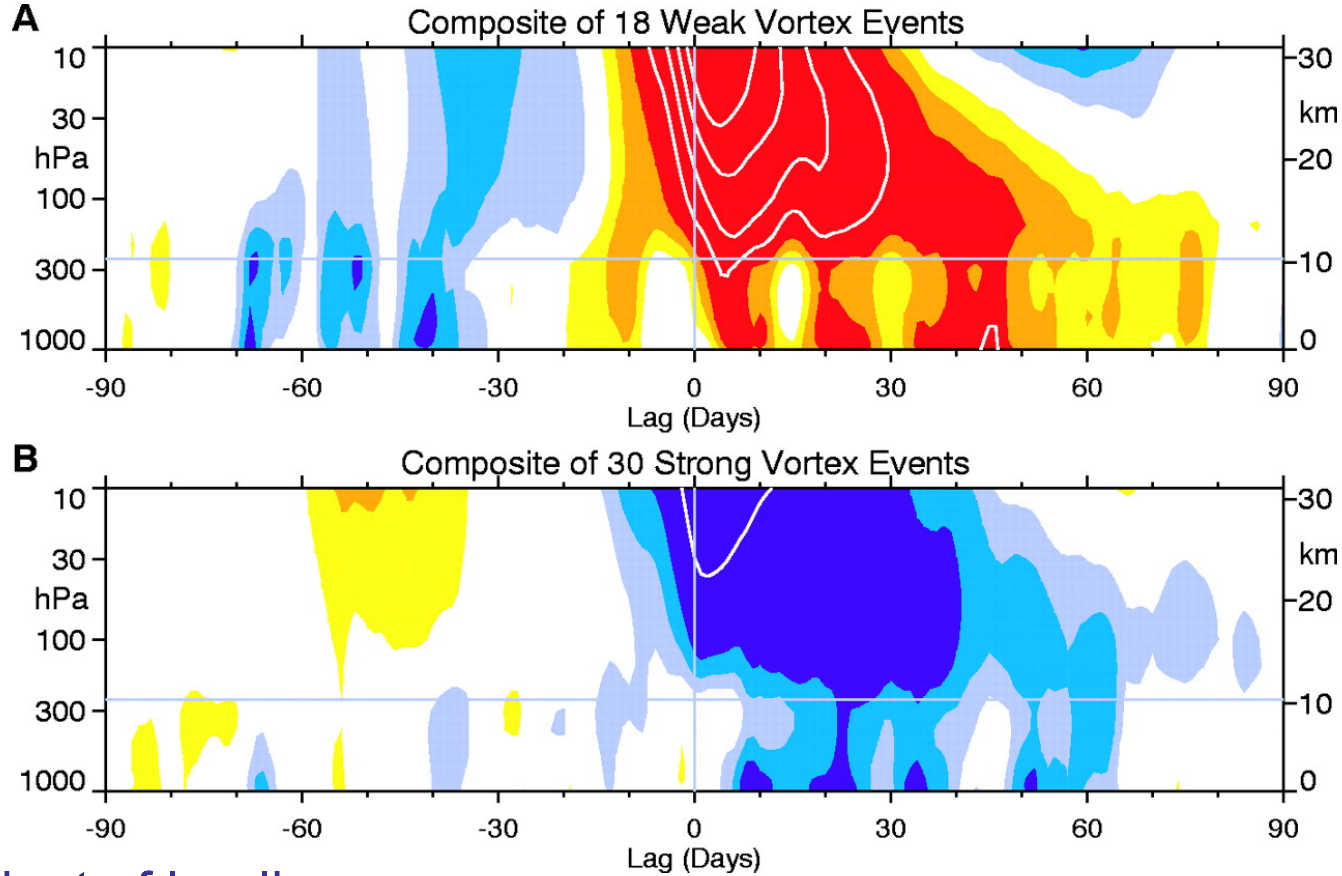




Sigmond et al (2013)

Observations

(Baldwin and Dunkerton 2001)



Composite of coefficient of leading EOF at each level

What do we deduce from Baldwin and Dunkerton (2001)?

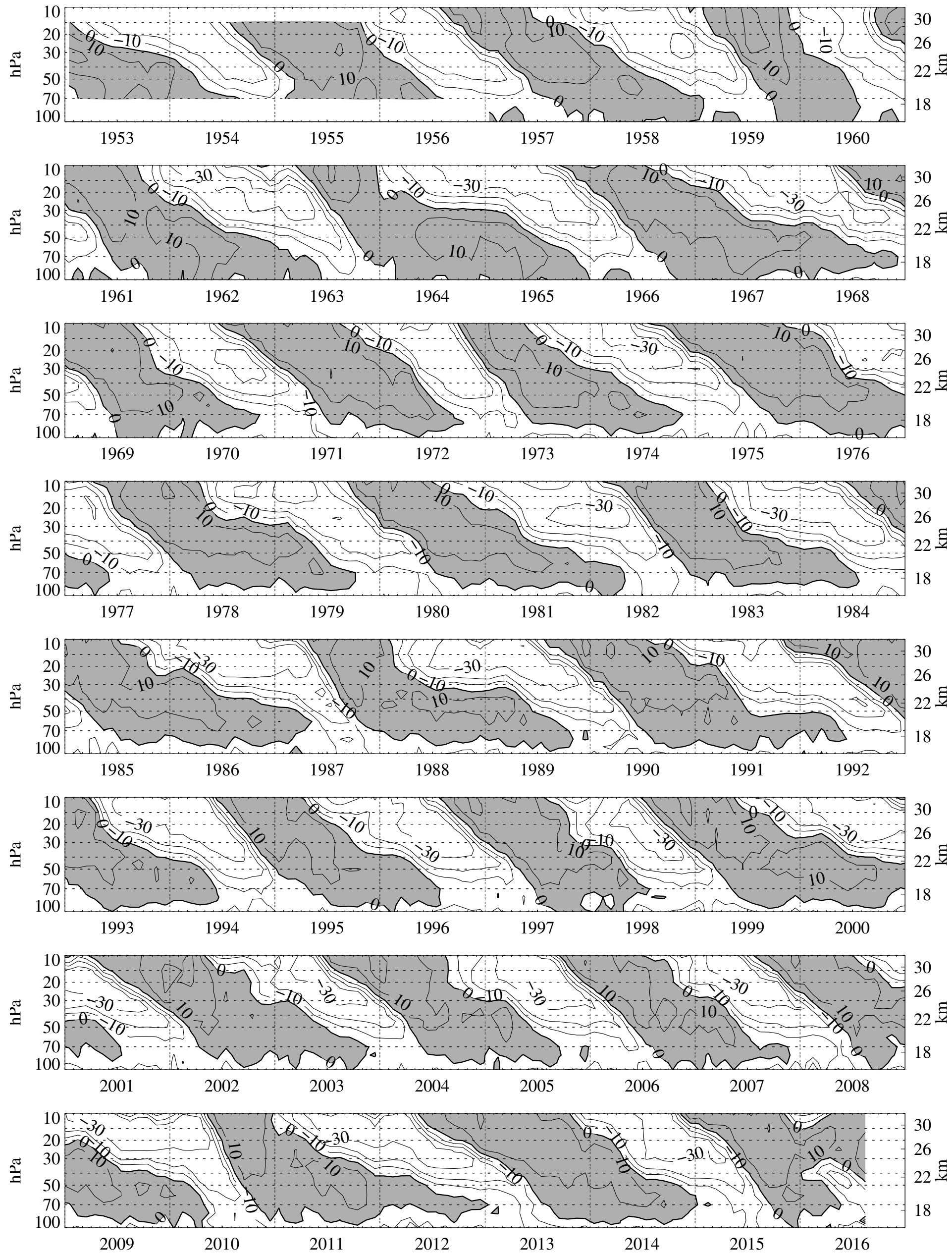
• Perturbation to middle stratosphere leads perturbation to lower stratosphere

•Perturbation to stratosphere leads perturbation to troposphere

• Is there middle stratospheric ‘cause’ and lower stratospheric ‘effect’?

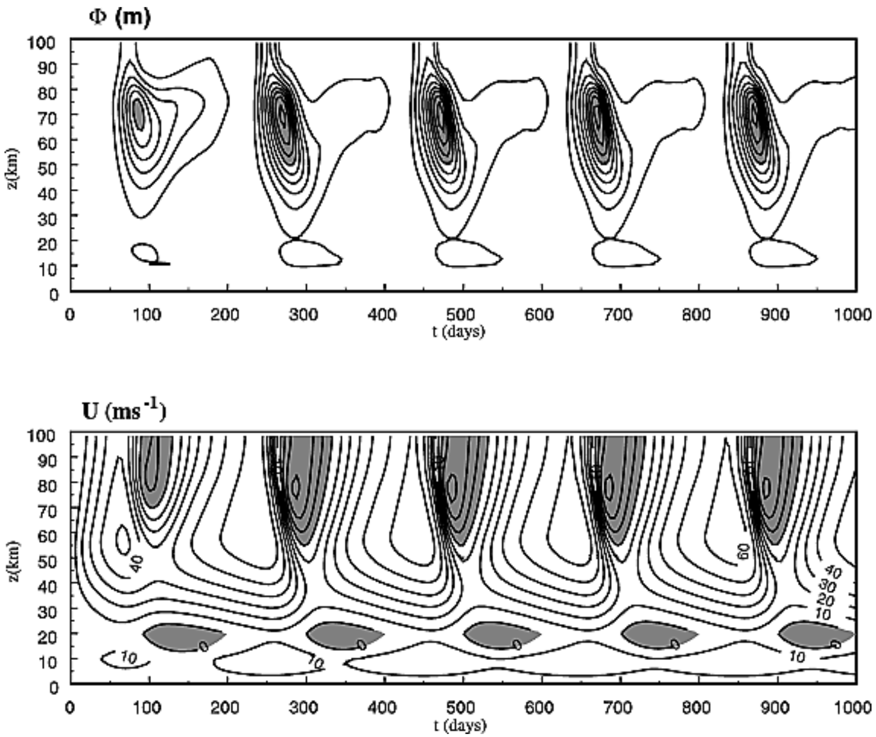
• Is there stratospheric ‘cause’ and tropospheric ‘effect’?

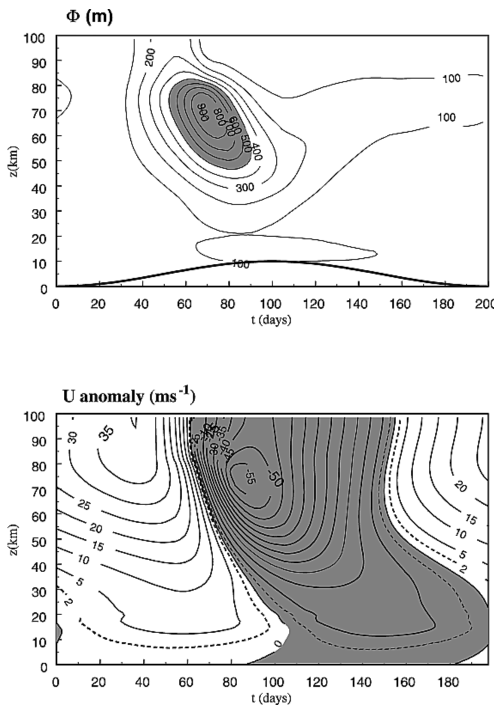
The equatorial QBO



FU Berlin

Does BD2001 imply downward propagation of information?



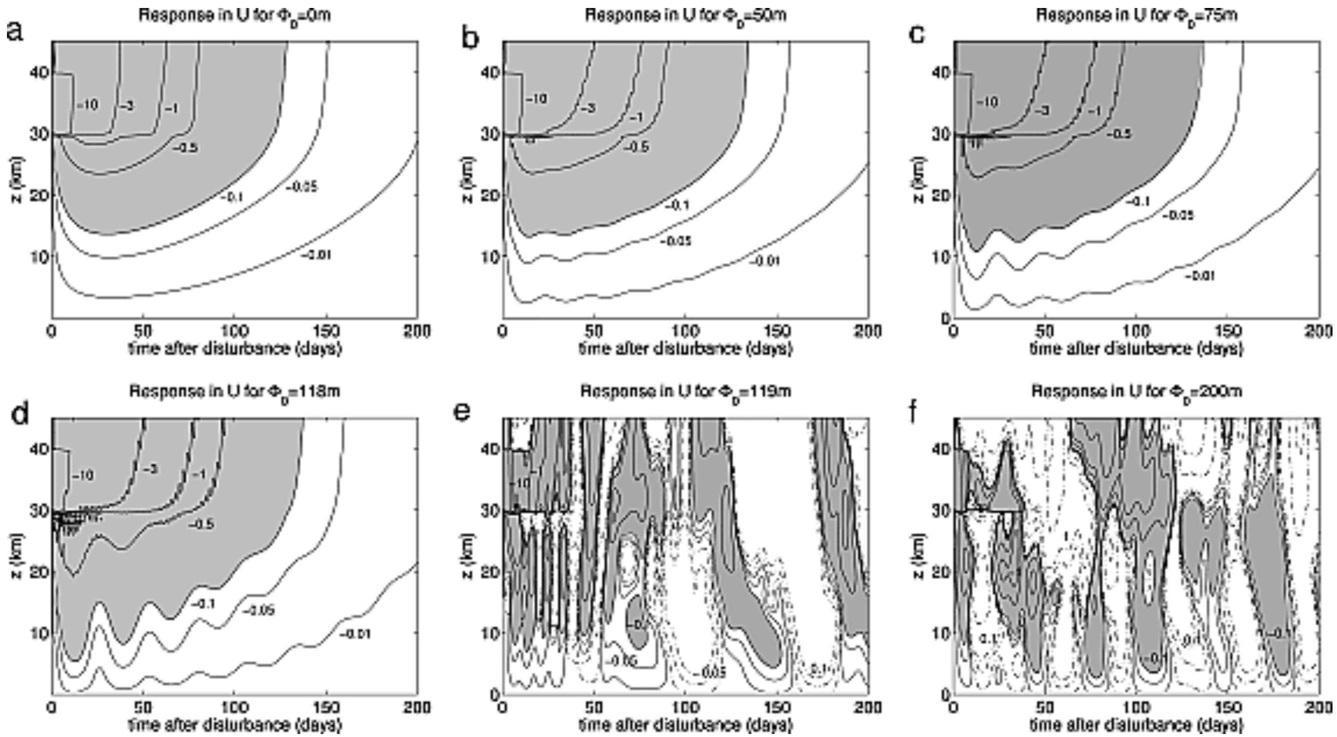


(partial analogy with tropical QBO)

Plumb and Semeniuk (2003)

Downward propagation in the stratosphere?

1-D wave + mean flow model



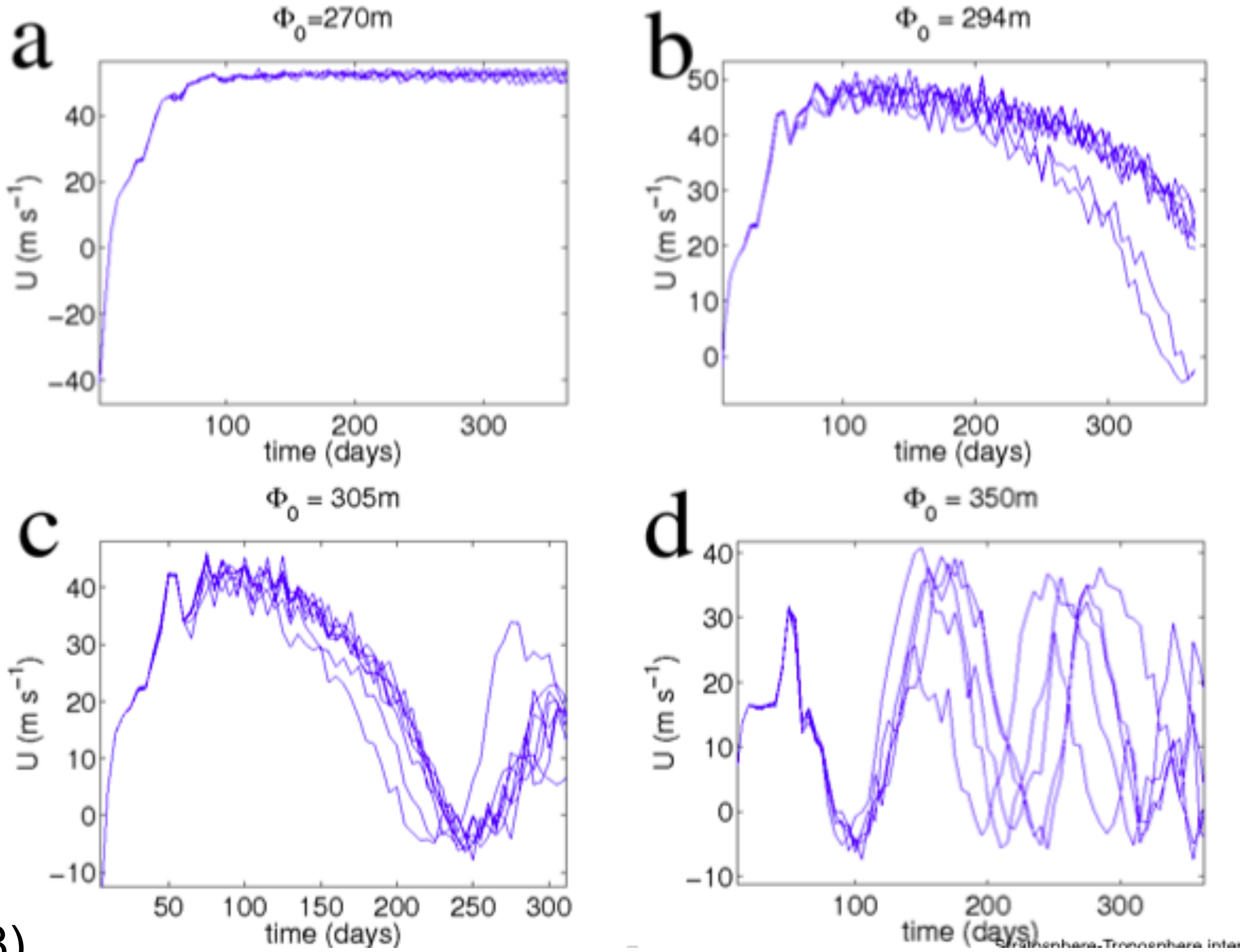
Hardiman and H (2008)

3-D mechanistic stratospheric model

Sensitivity to initial conditions

↓

Deep response to upper stratospheric perturbation



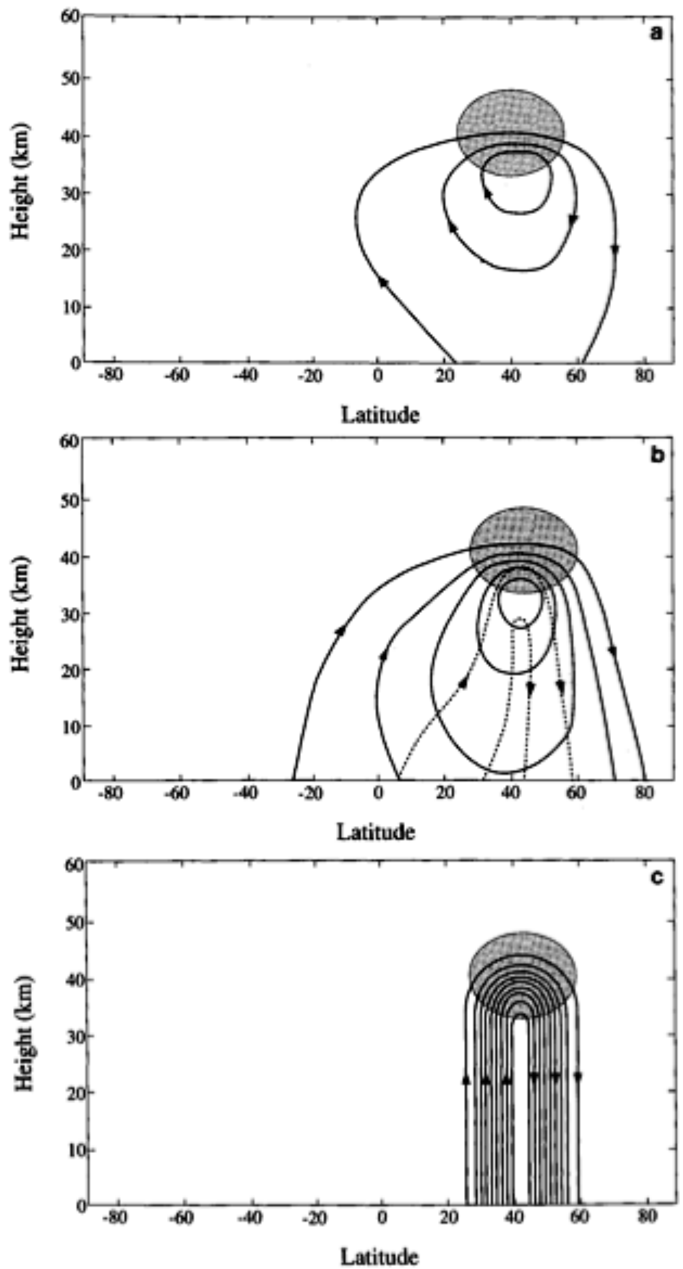
Hardiman and H (2008)

Meridional circulation response to localised eddy force

(Holton et al 1995)

Forcing frequency ω
Thermal damping rate α

Response to stratospheric wave force (or PV rearrangement) deeper than expected from PV inversion



$\omega / \alpha = \infty$

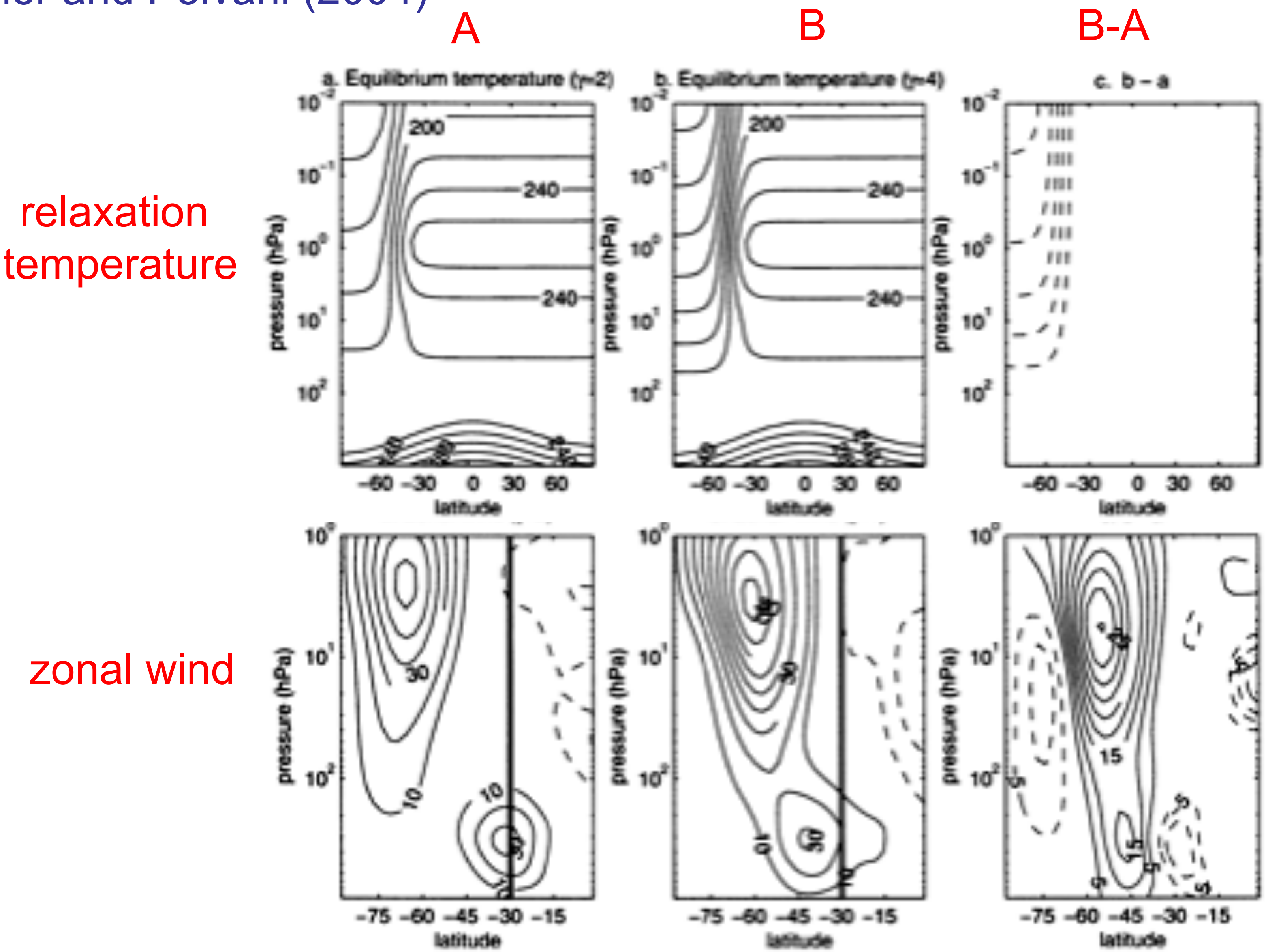
(instantaneous PV inversion)

$\omega / \alpha = 0.34$

$\omega / \alpha = 0$

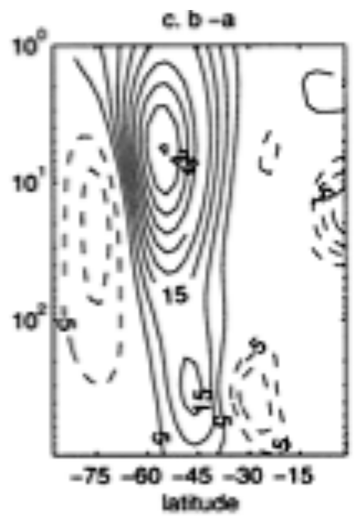
(‘downward control’ limit)

Kusher and Polvani (2004)



Kusher and Polvani (2004)

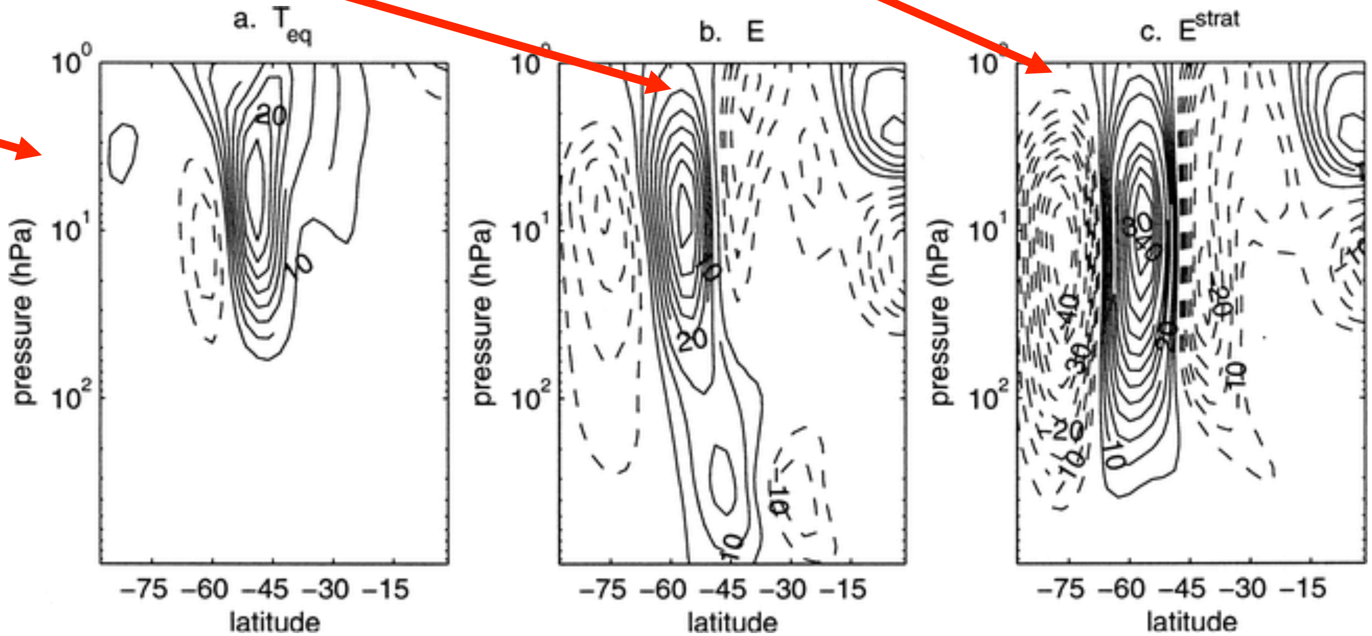
Response of zonally symmetric model



Change in eddy force (stratosphere only)

Change in eddy force

Change in T_{eq}



Song and Robinson 2004 DCWEF

Mechanisms for stratospheric effect on troposphere

Zonally symmetric dynamics in stratosphere

A: instantaneous dynamics are non-local in vertical

B: downward propagation through diabatic effects

Planetary wave dynamics in stratosphere

C: "downward" wave propagation

D: coupled wave/mean-flow dynamics in stratosphere

Troposphere

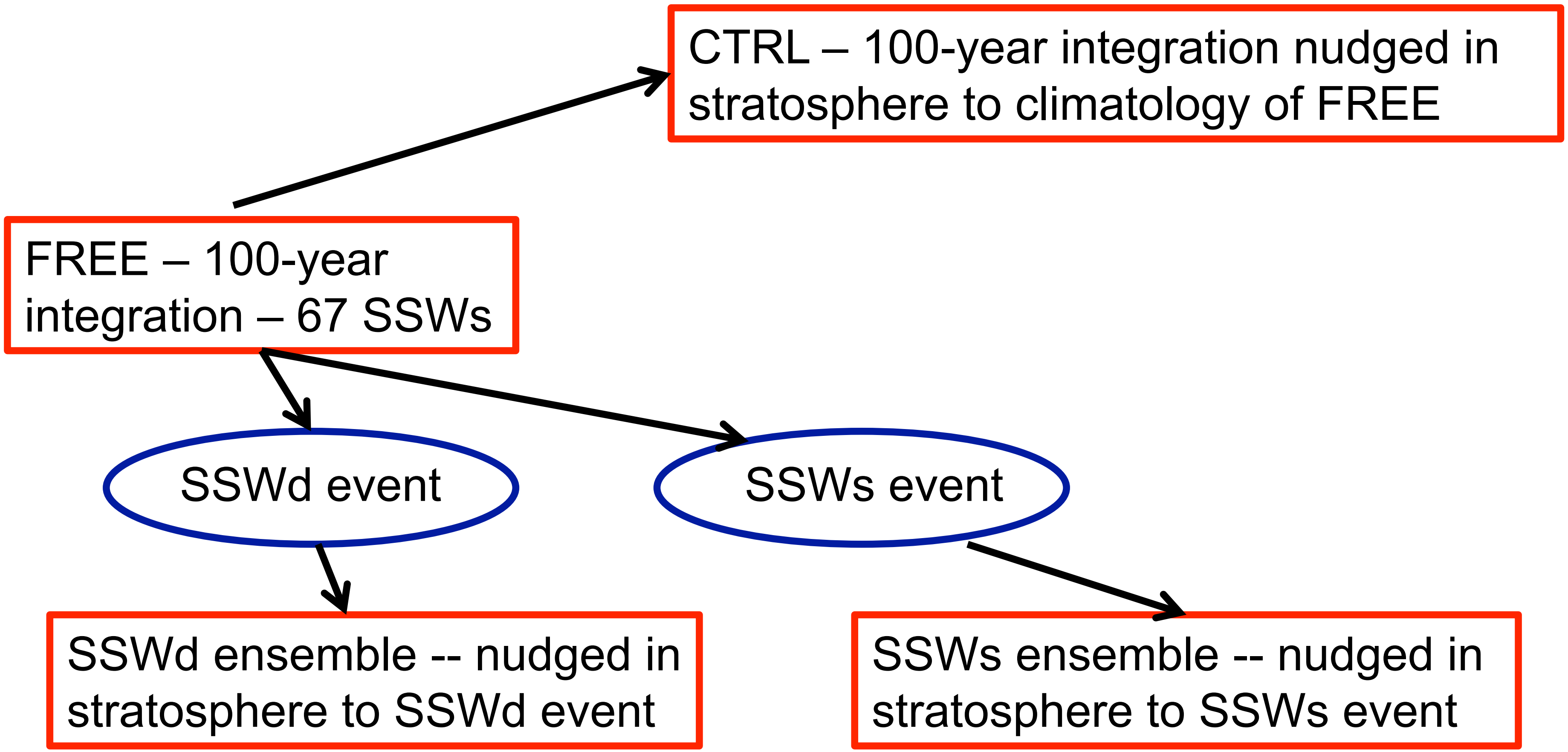
E: 'passive' troposphere

F: direct modulation of baroclinic eddies

G: coupled baroclinic eddy/mean-flow dynamics in troposphere

The Downward Influence of Stratospheric Sudden Warmings

Hitchcock and Simpson (2014)



Several slides shown in lecture omitted from this version, see original paper:

Hitchcock, P., and I. R. Simpson (2014), The downward influence of stratospheric sudden warmings, J. Atmos. Sci., 71, 3856–3876,doi:10.1175/JAS-D-14-0012.1.

Analysis of eddy feedbacks

Hitchcock and Simpson (2016)

$$\frac{\partial U}{\partial t} = M_s + M_p + C + X + W$$

Tropospheric vertical integral of momentum equation

Synoptic-scale eddies (M_s)

Planetary-scale eddies (M_p)

Coriolis force (C)

Friction (X)

Vertical eddy momentum transport (W)

$$\frac{\partial u}{\partial t} = m_s + m_p + x + F_C$$

Project on to EOF1

Allow possible tropospheric feedbacks

$$m_s = \tilde{m}_s + b_s u + F_s \qquad m_p = \tilde{m}_p + b_p u + F_p \qquad x = -ku$$

$$\frac{\partial u}{\partial t} = \tilde{m}_s + \tilde{m}_p - (k - b_s - b_p)u + F_s + F_p + F_C$$

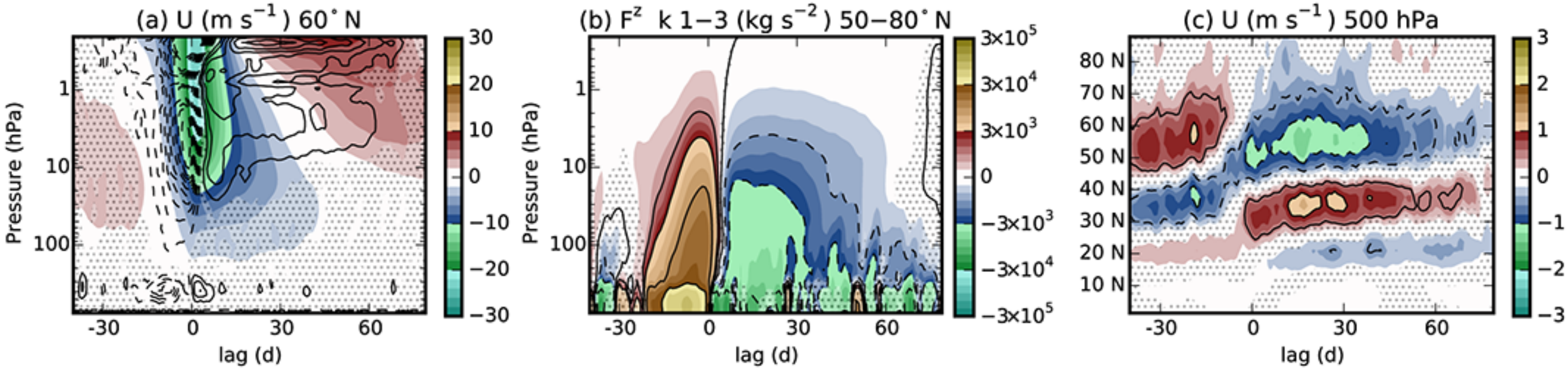
Several slides shown in lecture omitted from this version, see original paper:

Hitchcock, P., and I. R. Simpson (2016), Quantifying forcings and feedbacks following stratospheric sudden warmings, J. Atmos. Sci., 73,3641–3657, doi:10.1175/JAS-D-16-0056.1.

Simple GCM Study

'Base' integration: 90000 days (after spin-up), 465 SSW events

composite SSW event



Hitchcock and H (2016)

Nudging experiments

Nudging applied to zonal mean *u* for $p < p_b$

'Control' integration: 37000 days, nudging to climatology of base integration

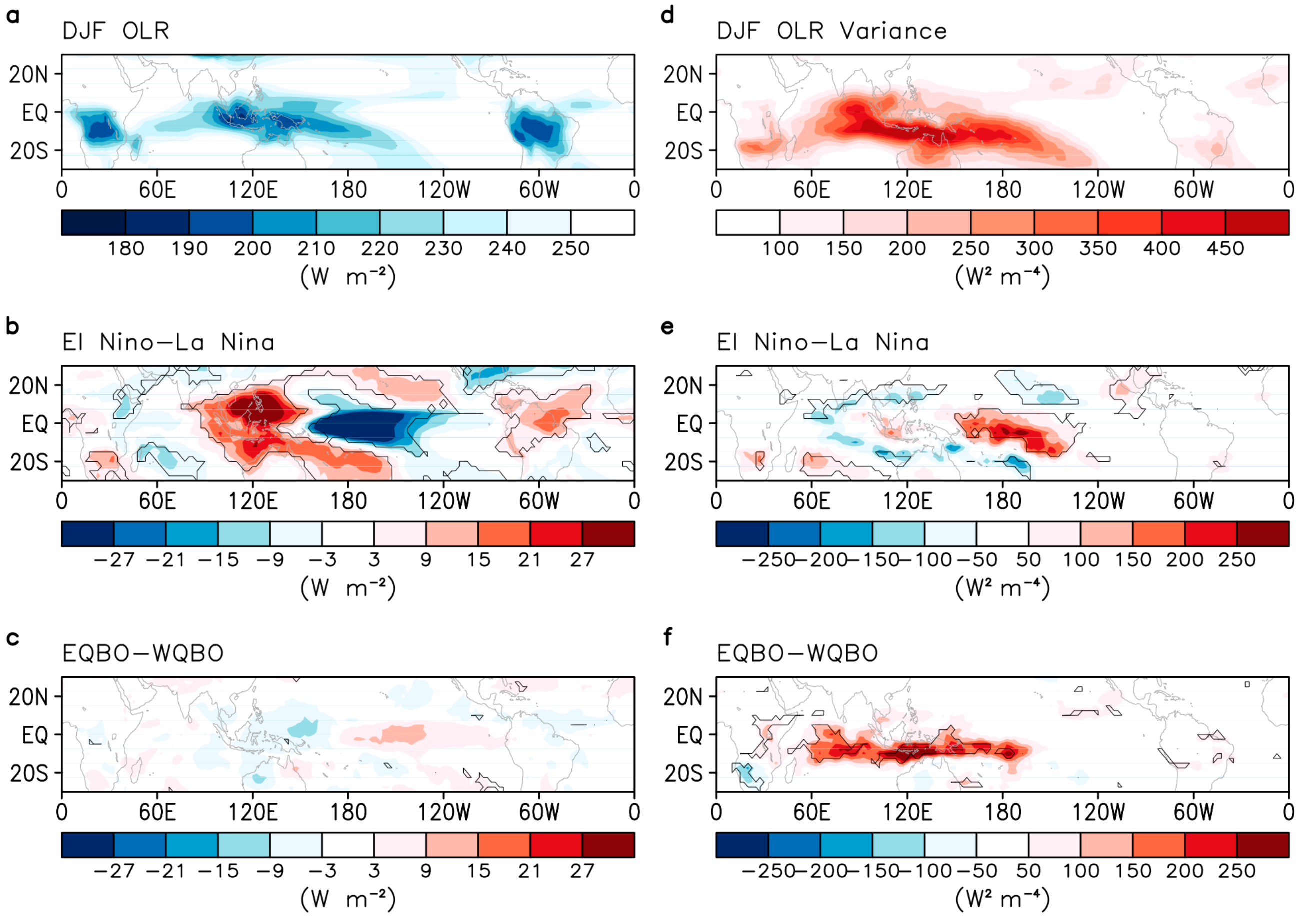
SSW ensembles: 740 x 160 days, initialised from different times in control integration, nudged to composite SSW, starting at $t=-40$.

Hitchcock and H (2016)

Several slides shown in lecture omitted from this version, see original paper:

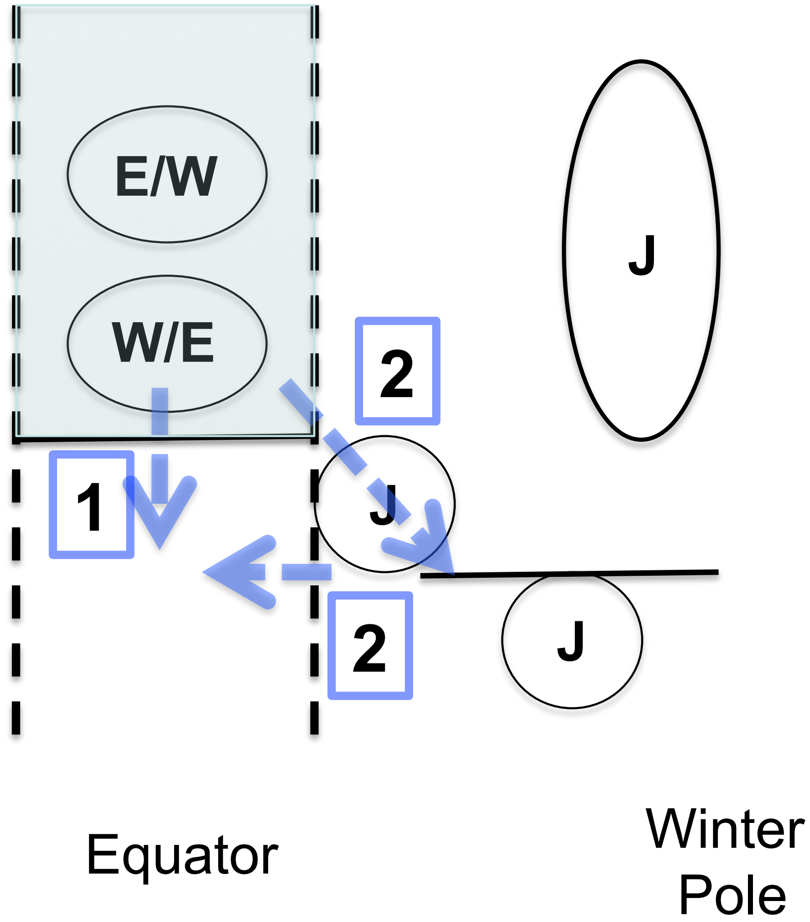
Hitchcock, P., Haynes, P.H. (2016), Stratospheric control of planetary waves, Geophys. Res. Lett., 43, 11,884–11,892, doi:10.1002/2016GL071372

QBO effect on MJO



Son et al (2017)

QBO effect on tropical troposphere?



Route 1: vertical coupling
Route 2: coupling via subtropical jet

Summary

•2-way coupling between troposphere and stratosphere in extratropics now accepted as important, with implications for understanding and modelling variability and systematic change on seasonal to centennial timescales.

•Mechanisms now much clearer, e.g. role of synoptic-eddy feedbacks, but different mechanisms may be relevant in different cases (e.g. NH vs SH).

•Some aspects remain mysterious – e.g. deep amplification of planetary waves, but perhaps this is a problem of language rather than 'missing physics'.

•2-way coupling in the tropics is an interesting area for future research (again with potential applications in seasonal and longer-term forecasting).