Dynamical coupling between the stratosphere and troposphere

Tiffany A. Shaw
Columbia University
SPARC DynVar

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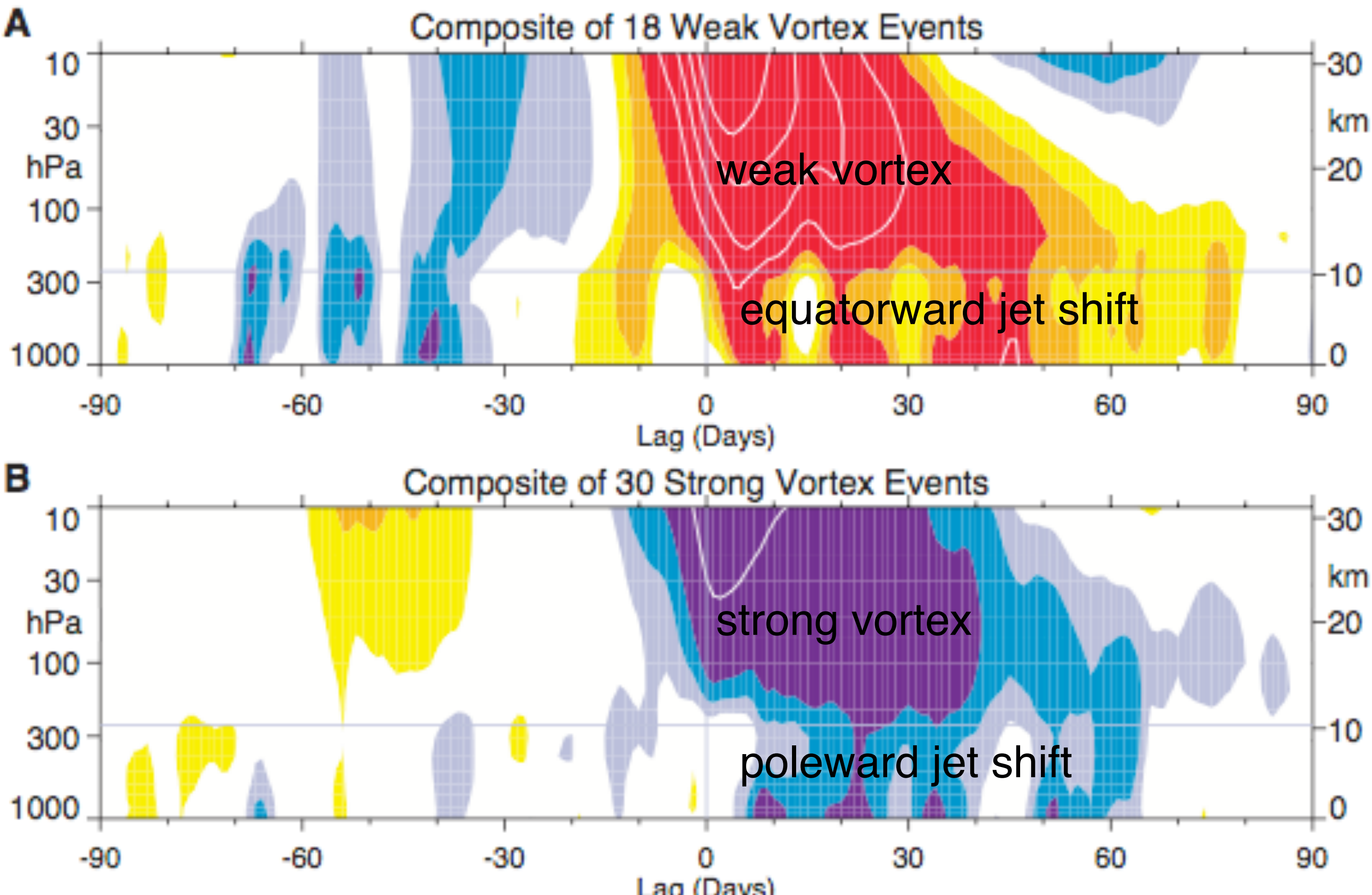
Motivation: Coupling across timescales

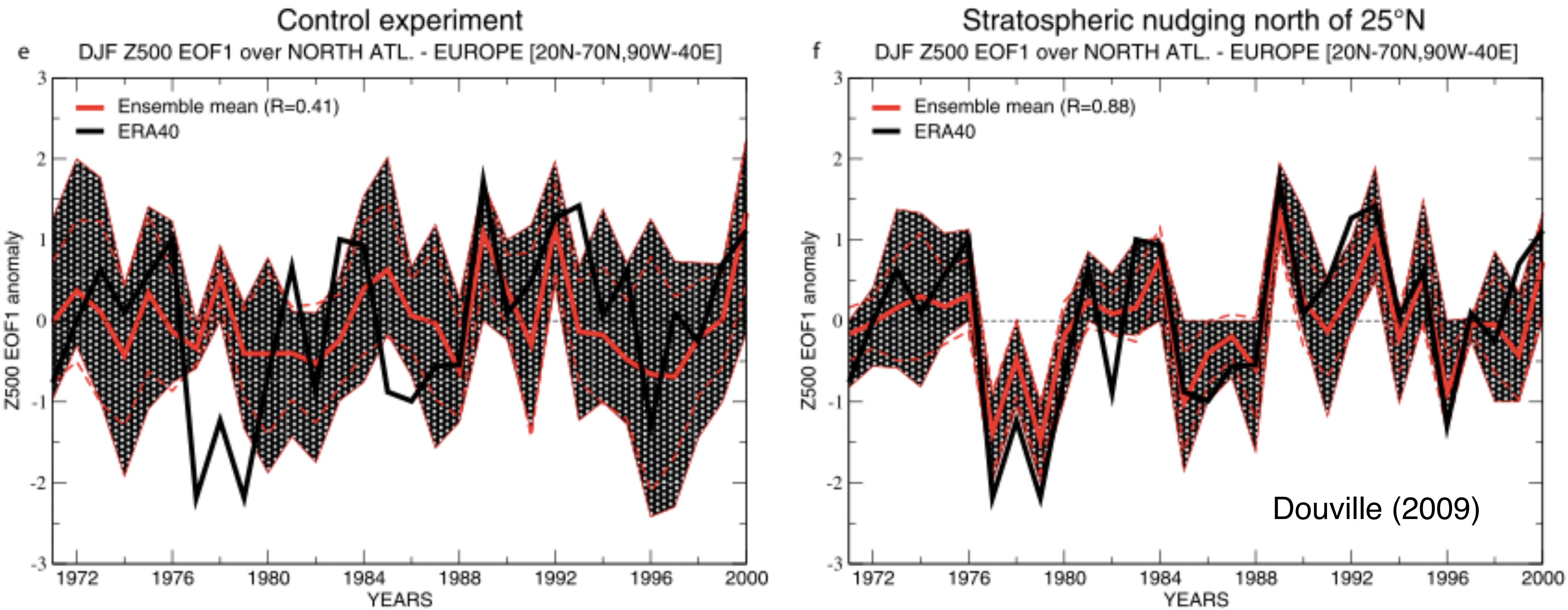


Stratospheric sudden warmings

Strong polar vortex, cold temperatures

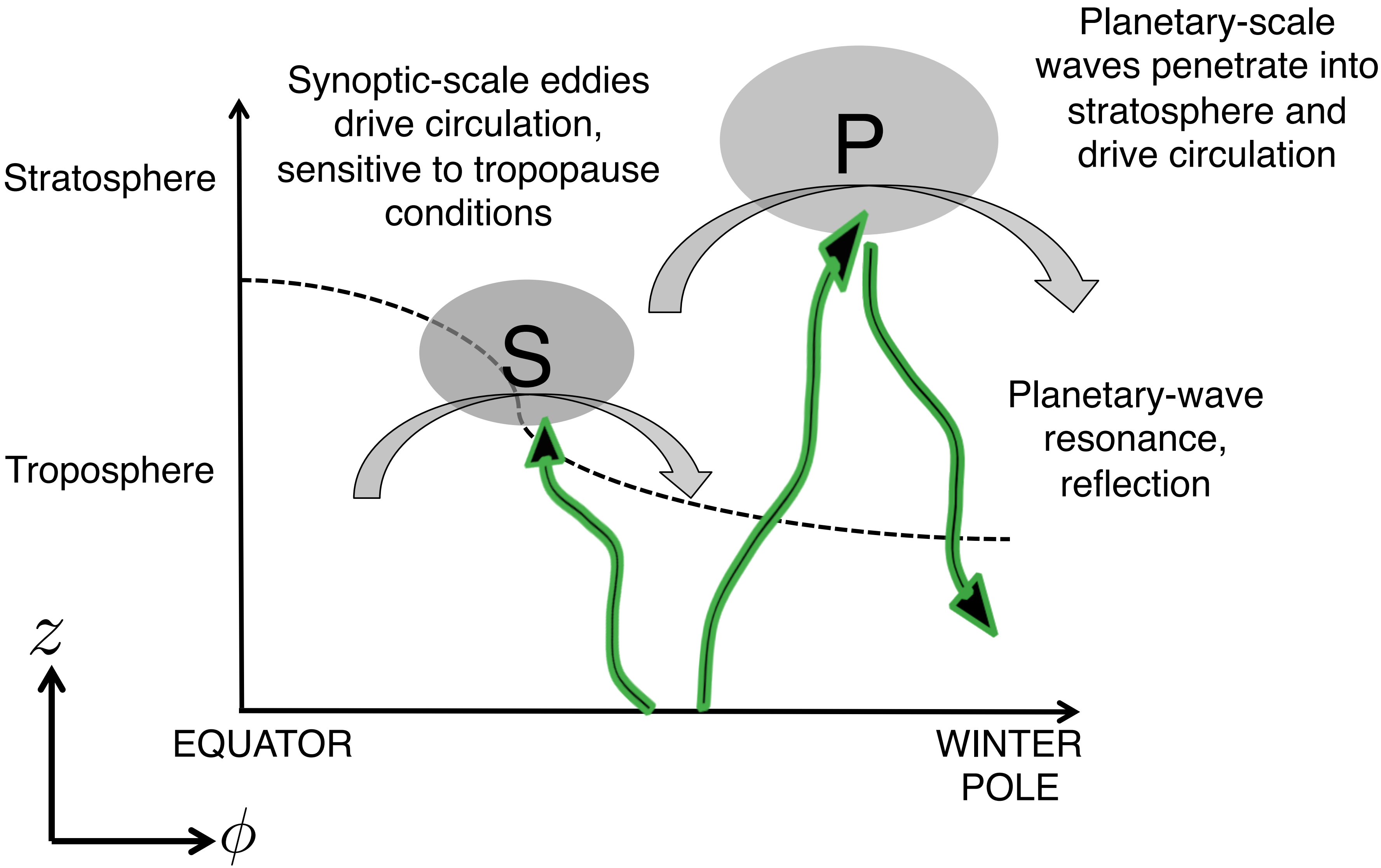
Baldwin & Dunkerton (2001)

See also Limpasuvan et al. (2004, 2005), Sigmond et al. (2013)



See also Greatbatch et al. (2012), Scaife et al (2005)

- Importance of stratospheric dynamics in North Atlantic response to climate change (Scaife et al. 2012, Karpechko & Manzini 2012)



Gravity waves also play an important role
but will not be discussed here

Adapted from Plumb (2002)

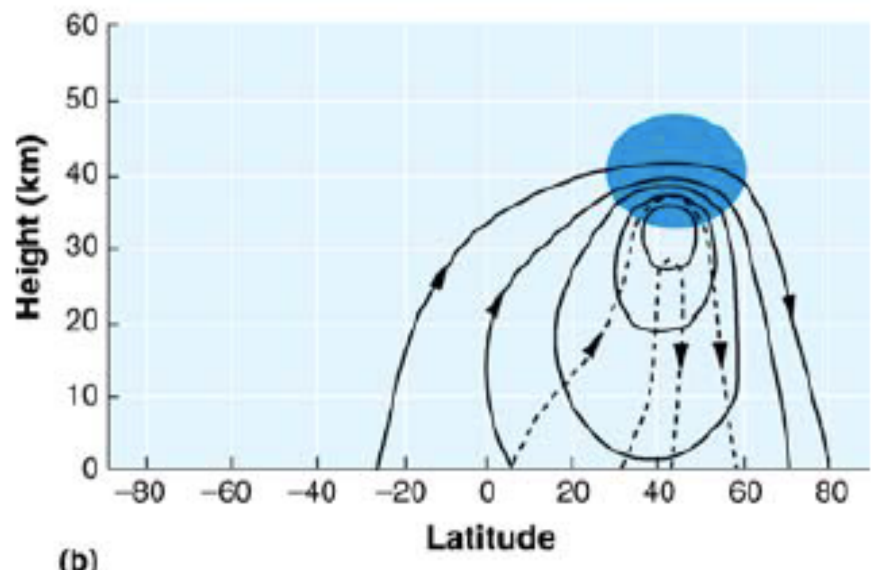
Mechanisms of vertical coupling: Mean meridional circulation

- Non-local balanced response to a **given** stratospheric torque
  - Eliassen adjustment (Eliassen 1951)
  - Downward control (Haynes et al. 1991)
  - PV inversion (Hartley et al. 1998, Black 2002, Ambaum & Hoskins 2002)

$$\overline{w}^* = \mathcal{L}^{-1}(\mathcal{L}_{\mathcal{F}}\mathcal{F} + \mathcal{L}_{\mathcal{Q}}\mathcal{Q})$$

$$\partial_t \overline{u} = \mathcal{L}_1^{-1}(\mathcal{L}_{1\mathcal{F}} + \mathcal{L}_{1\mathcal{Q}})$$

See Andrews et al. (1987)



Haynes (2005)

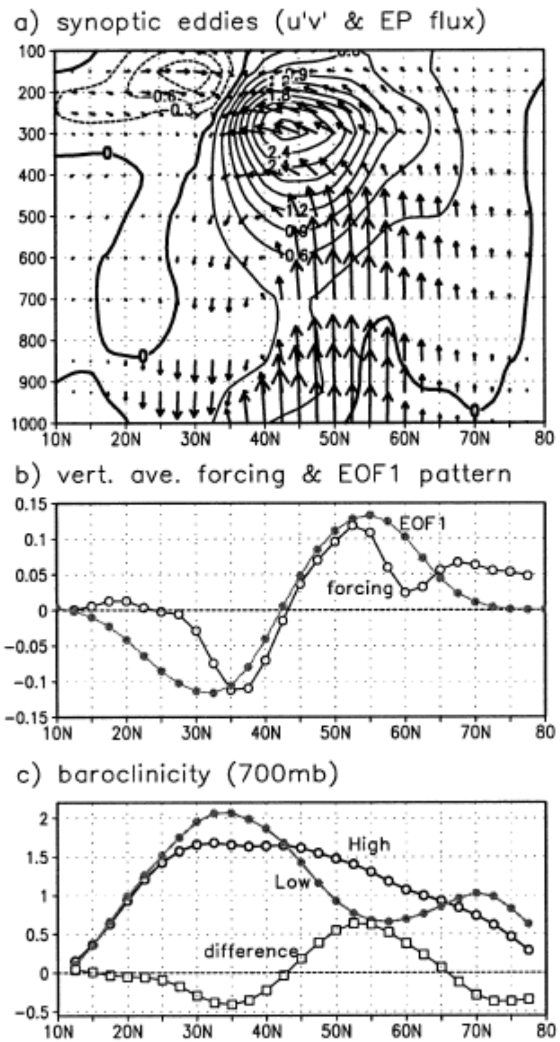
Mechanisms of vertical coupling: Planetary-scale waves

- Wave behavior determined by **given** zonal-mean flow via index of refraction (e.g. Charney & Drazin 1961, Matsuno 1970)
  - Dissipation at critical layer (e.g. McIntyre & Palmer 1983) $n_{ref}^2 \to \infty$
  - Reflection (e.g. Perlwitz & Harnik 2003, Shaw et al. 2010) $n_{ref}^2 \to 0$
  - Resonance (e.g. Tung & Lindzen 1979, Plumb 1981, Esler & Scott 2005)

$$m^2 + \frac{N^2}{f_0^2}\ell^2 = \frac{N^2}{f_0^2}\left[\frac{\overline{q}_y}{\overline{u}-c} - k^2 + F(N^2)\right] \equiv n_{ref}^2$$

$$\partial_t \mathcal{A} \; + \; \nabla \cdot \mathbf{F} = \mathcal{S} \qquad\qquad \mathbf{F} = \left(-\overline{u'v'}, \frac{gf}{T_0 N^2}\overline{v'T'}\right)$$

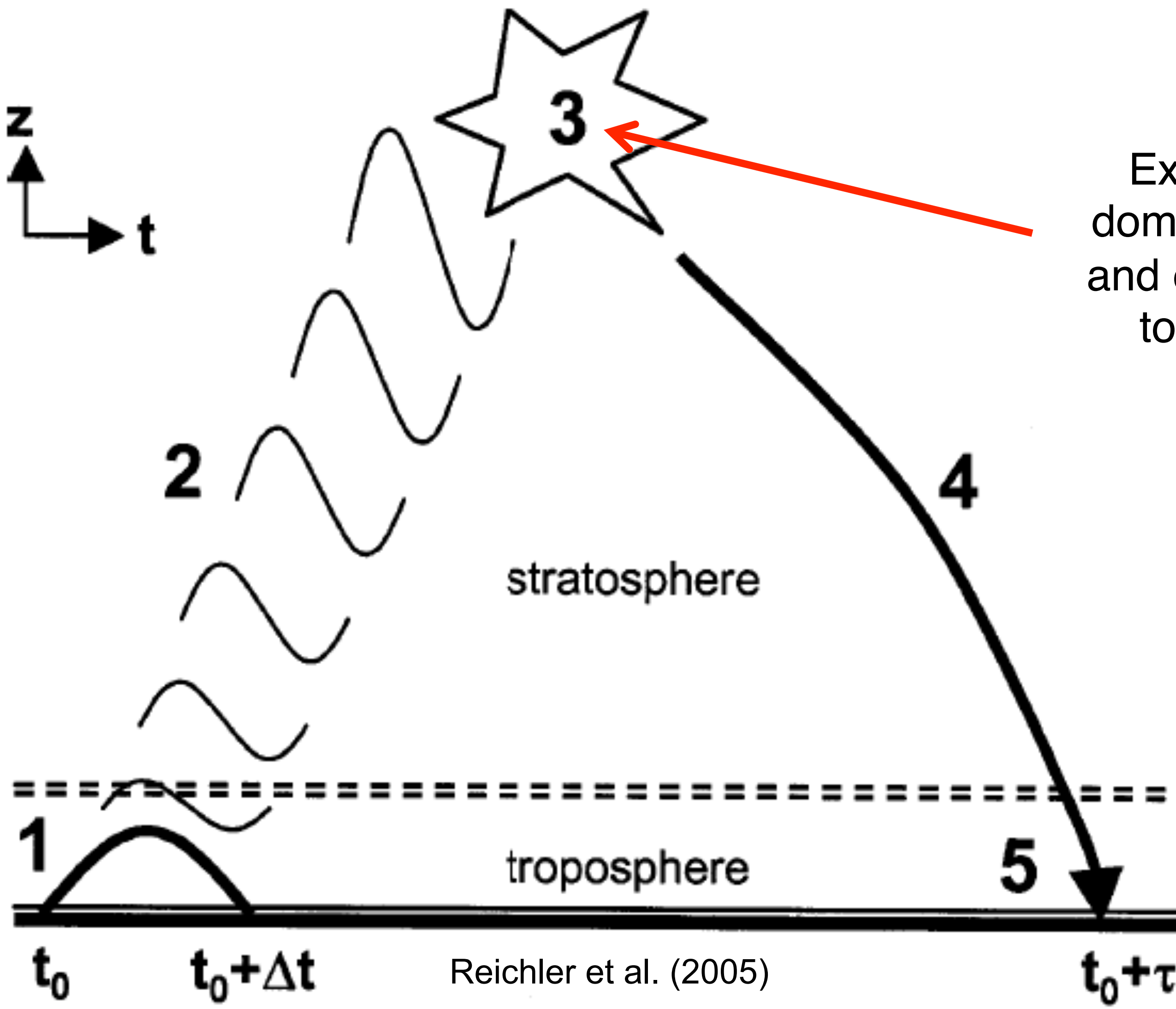
Role of synoptic-scale eddies



Lorenz & Hartmann (2003)

- In the troposphere variability dominated by annular modes, which are sustained by synoptic eddy feedbacks (Lorenz and Hartmann 2001, 2003)
- Mean flow conditions in the vicinity of the tropopause affect synoptic eddies via changes in
  - Lower stratospheric shear (Wittman et al. 2007)
  - Index of refraction (Simpson et al. 2009)
  - Isentropic slope (Thompson & Birner 2012)
  - Eddy length scale (Kidston & Vallis 2010)
  - Eddy phase speed (Chen & Held 2007)
- Synoptic eddies can serve as an "amplifier" of stratospheric forcing

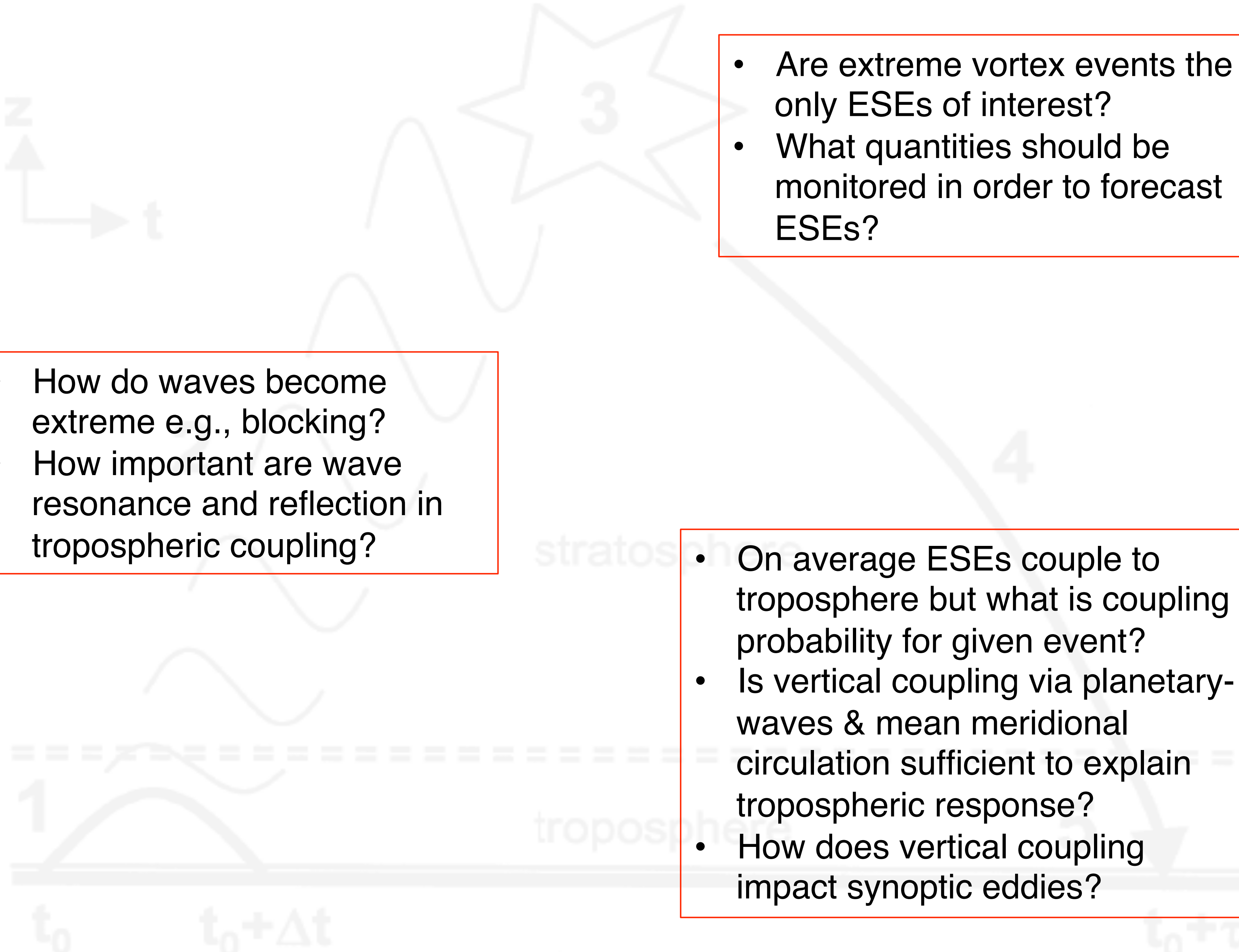
Importance of transiently evolving extreme stratospheric events (ESEs)



Reichler et al. (2005)

Extreme events dominate dynamics and exhibit coupling to troposphere

Strong vortex events are also important



- Are extreme vortex events the only ESEs of interest?
- What quantities should be monitored in order to forecast ESEs?

- How do waves become extreme e.g., blocking?
- How important are wave resonance and reflection in tropospheric coupling?

- On average ESEs couple to troposphere but what is coupling probability for given event?
- Is vertical coupling via planetary-waves & mean meridional circulation sufficient to explain tropospheric response?
- How does vertical coupling impact synoptic eddies?

Importance of planetary-scale wave coupling

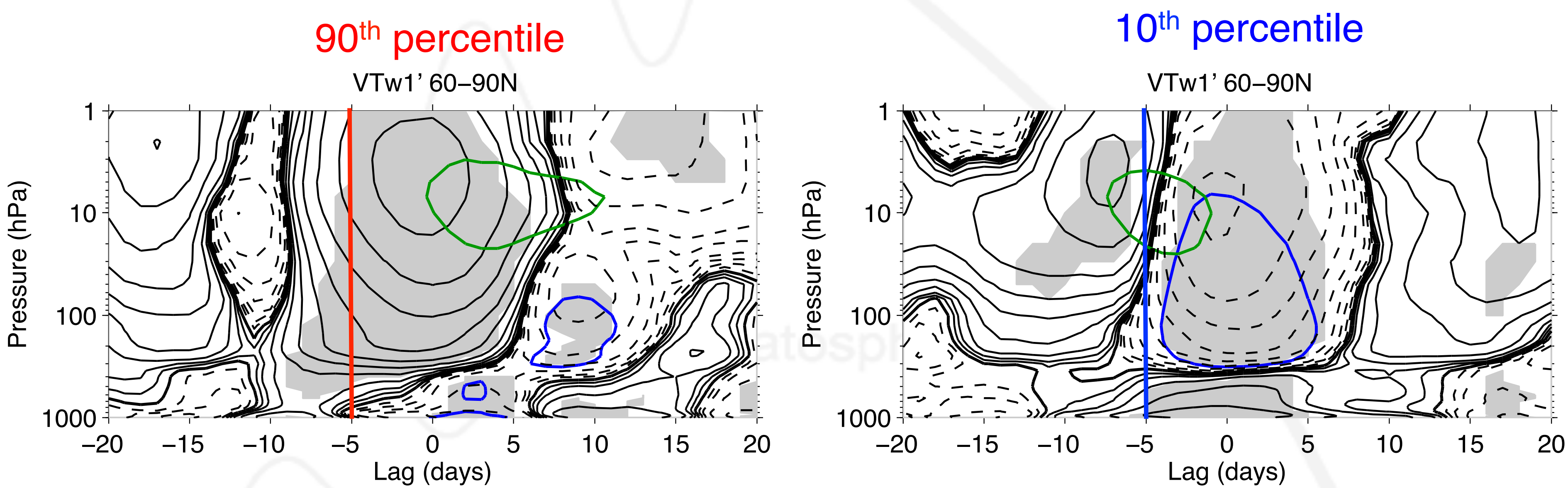
- Extreme vortex events are preceded by anomalous wave activity entering the stratosphere (Polvani & Waugh 2004)

- Extreme positive heat flux events have been linked to
  - Blocking (e.g. Martius et al. 2009, Woolings et al. 2010)
  - ENSO, MJO, snow anomalies via constructive linear wave interference (e.g. Garfinkel & Hartmann 2010, Smith et al. 2010)
  - Wave resonance (Tung & Lindzen 1979, Plumb 1981, Esler & Scott 2005)

- Extreme negative heat flux events have been linked to
  - Downward wave coupling involving transient dynamical cooling (analogous to dynamical warming events)
  - Poleward jet shift in the Atlantic basin (Shaw & Perlwitz 2013a,b)

- Idealized model studies support role of planetary waves in tropospheric coupling (Plumb & Semeniuk 2003, Song & Robinson 2004, Sun et al. 2011)

- Extreme planetary-wave coupling events defined using high-latitude (60-90N) wave-1 heat flux
  - Significantly violate non-acceleration conditions
  - Importance of wave focusing (McIntyre 1982)

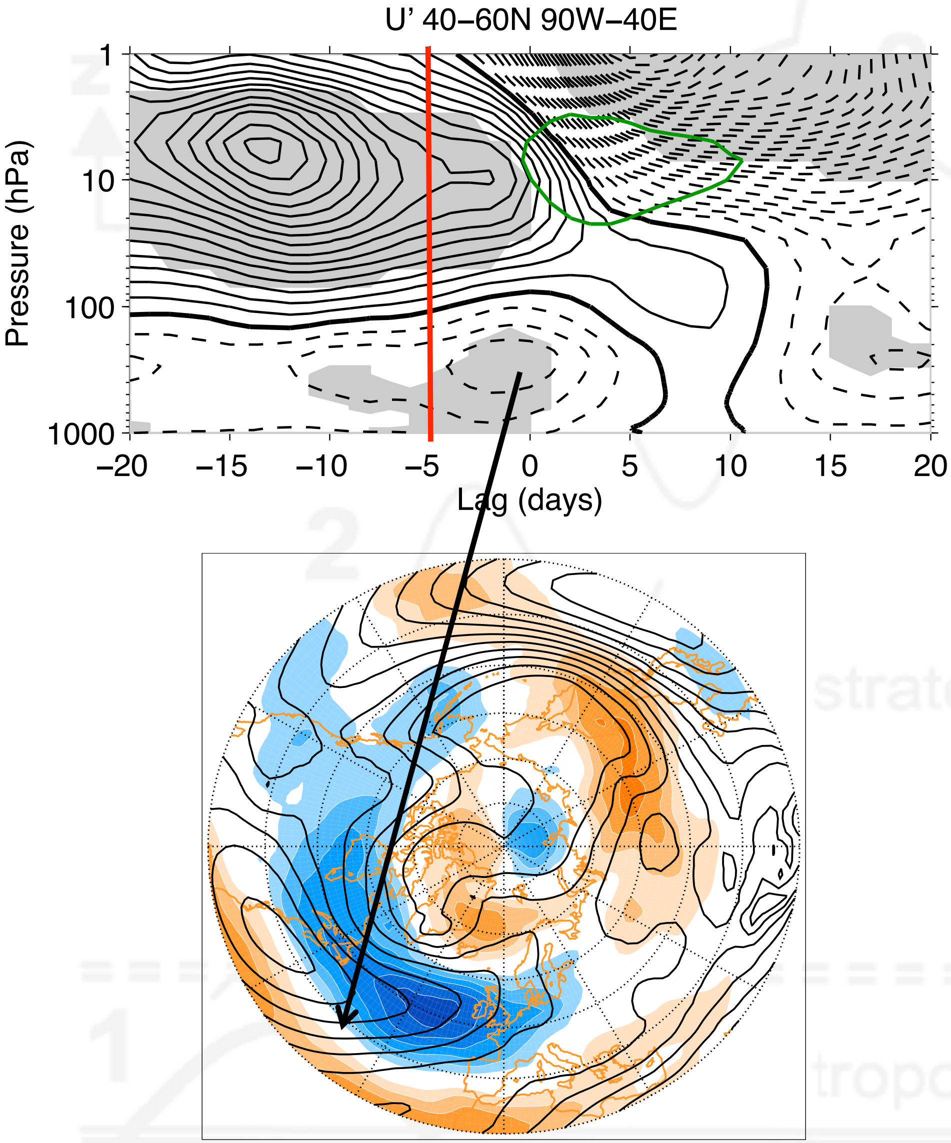


Transient EP flux convergence = dynamical warming
Reversal of zonal-mean zonal wind

Transient EP flux divergence = dynamical cooling
Reversal of residual circulation

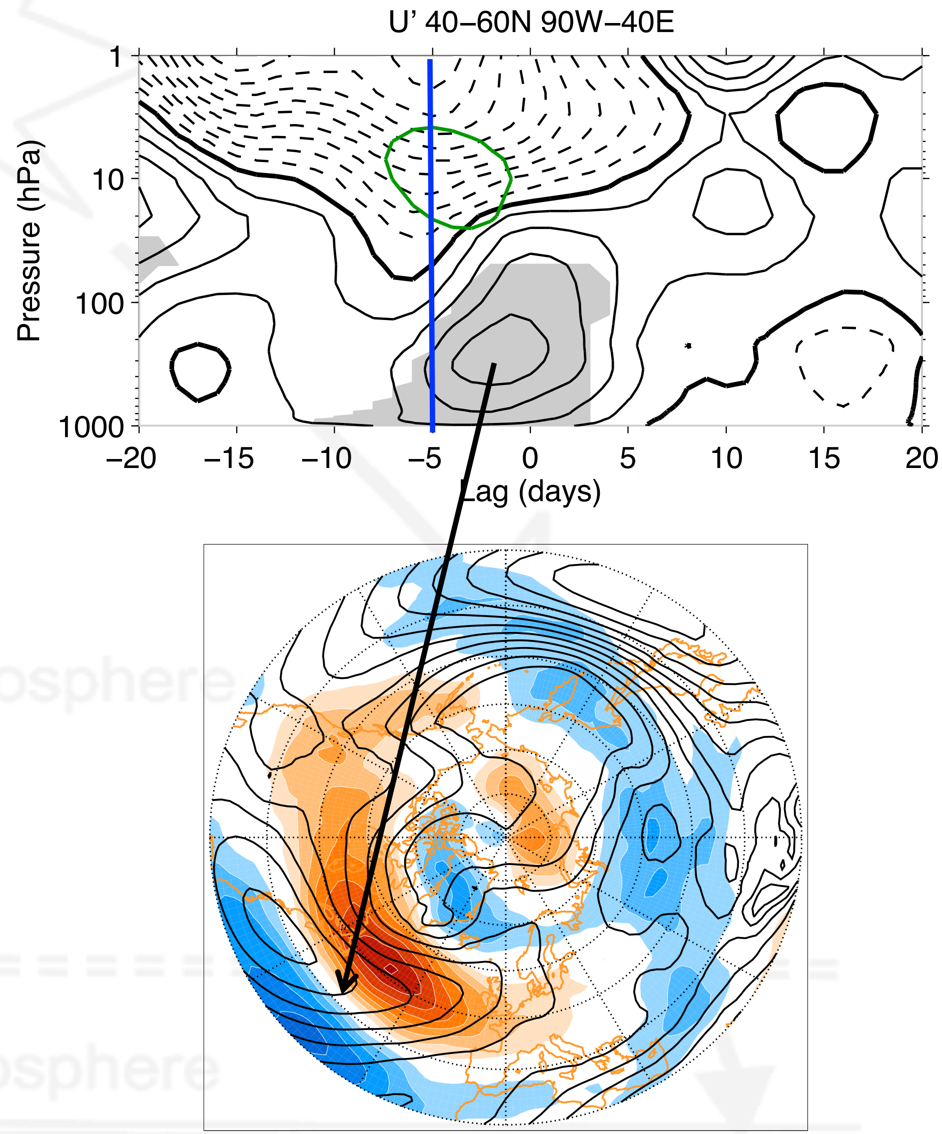
Figures courtesy of E. Dunn-Sigouin
See poster by Shaw & Perlwitz

90^{th} percentile

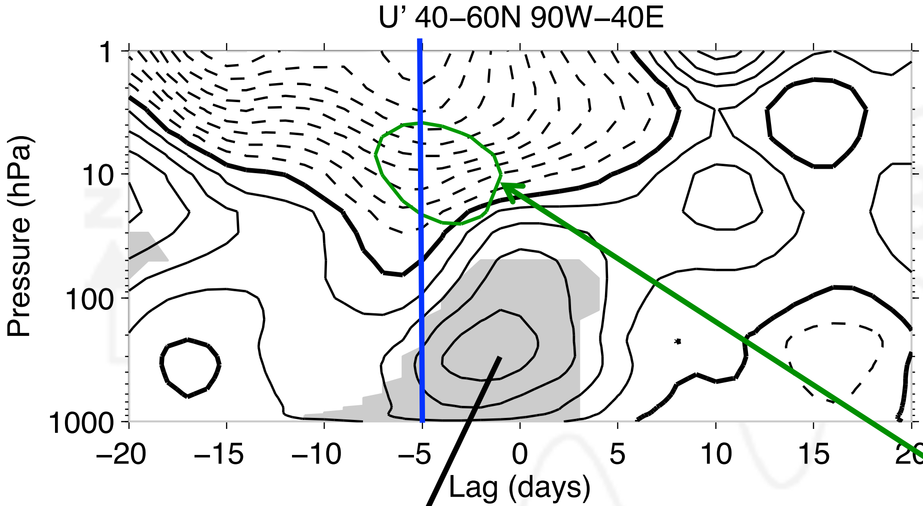


Equatorward jet shift in the Atlantic basin

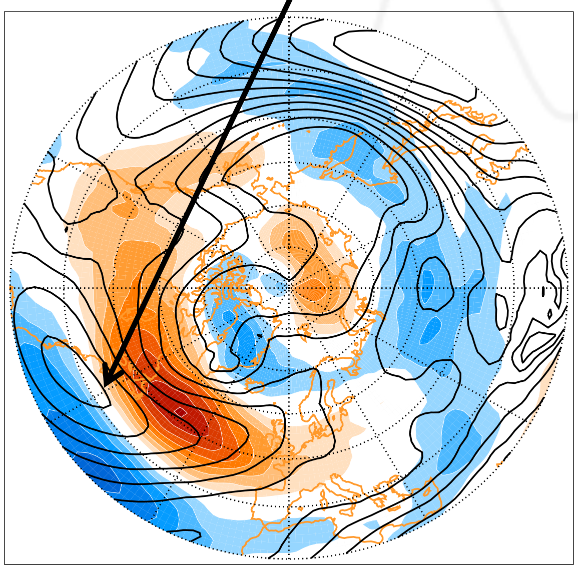
10^{th} percentile



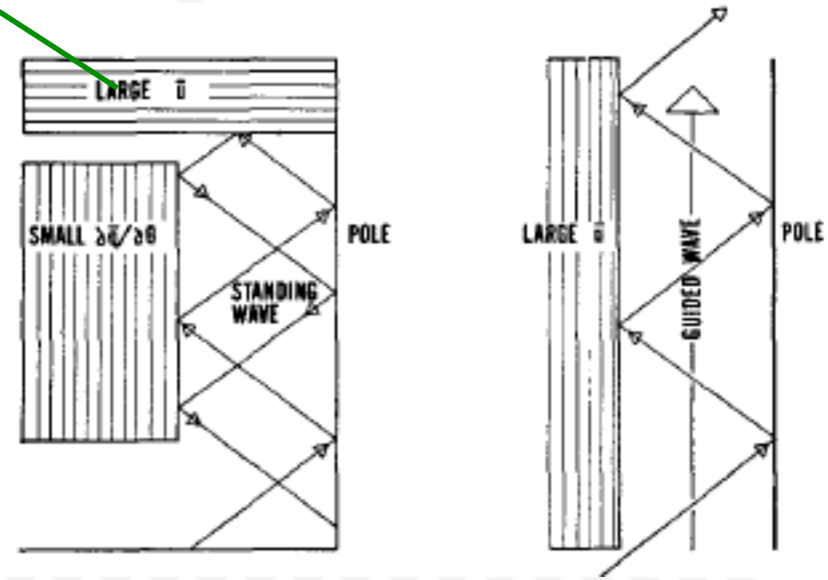
Poleward jet shift in the Atlantic basin



- Stratospheric variability linked to NAO-like variability (Shaw et al. 2014)
- Importance of wave-induced cavity (cf. Matsuno 1970, McIntyre 1982), self-tuning (Plumb 1981)



Poleward jet shift in the Atlantic basin



- Planetary wave signal amplified by synoptic eddies (not reversible, dominate zonal mean)

- Extreme heat flux events linked to tendency of mean flow
  - Transient dynamical (adiabatic) warming and cooling events via vertical advection (see poster by Shaw & Perlwitz)
  - Circulation coupled to wave source/sink in troposphere (Shaw & Perlwitz 2013b)

- Extreme heat flux events occur during vortex events (Dunn-Sigouin & Shaw 2014)

- Transient change dominate long time averages

- Stratospheric radiative timescales are also important (Charlton and O'Neil 2010, Hitchcock et al. 2010, 2013)
  - Coupling to chemistry during ESEs needs to be explored

Importance of feedbacks from synoptic-scale eddies

- During extreme vortex events synoptic scale eddies organize and feedback onto anomalies near the tropopause (Limpasuvan et al. 2004, 2005, Kunz & Greatbatch 2013)

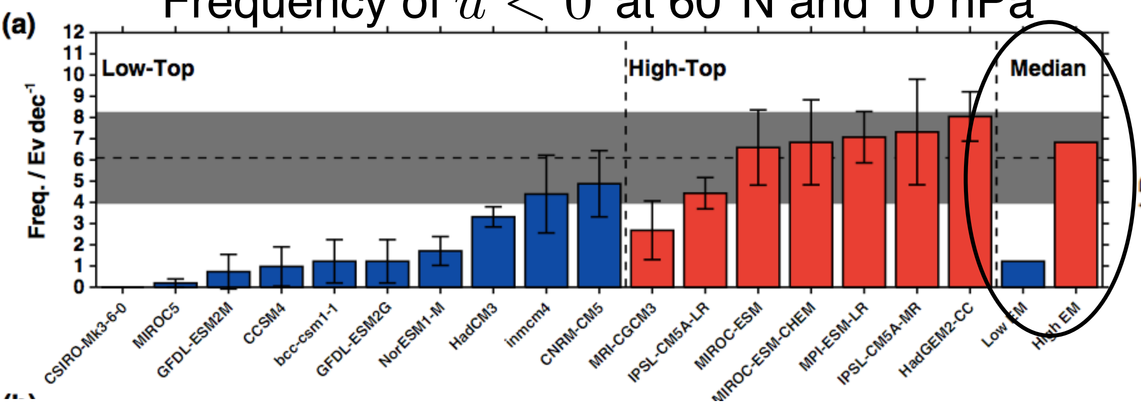
- Eddies may feedback onto mean meridional circulation anomalies
  - Song & Robinson (2004) showed that "downward control with synoptic eddy feedbacks" (DCWEF) is not sufficient to explain tropospheric response in idealized model simulations (see also Charlton et al. 2005)

- Feedbacks onto planetary-scale wave modulated basic state have also been suggested (DeWeaver & Nigam 2000)

- Strong synoptic eddy feedbacks make it difficult to determine cause of original anomaly (Garfinkel et al. 2013)
  - Must focus on transient evolution

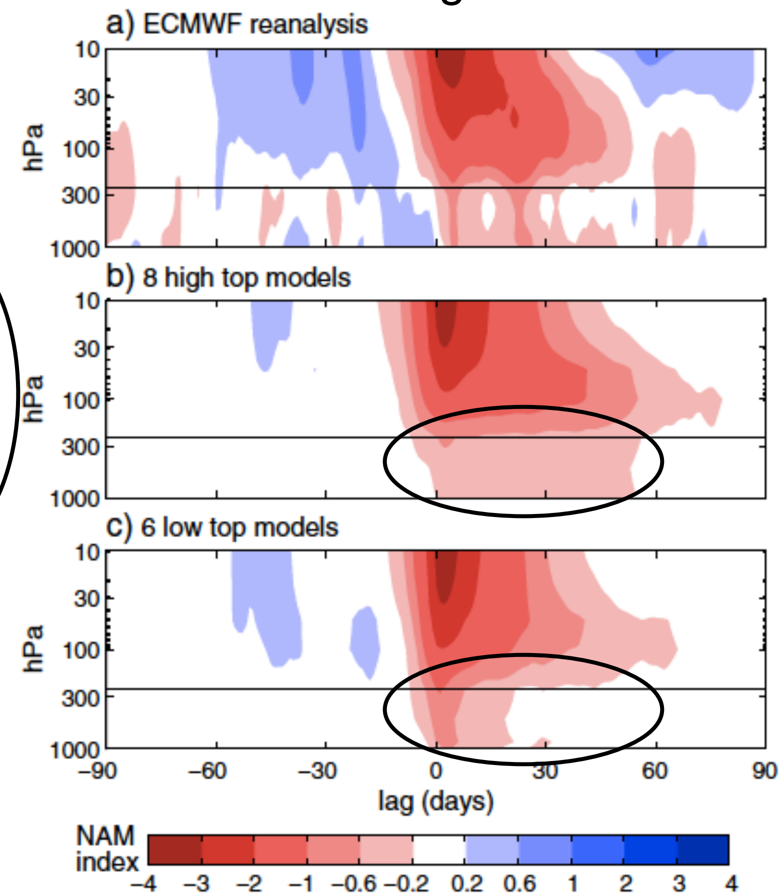
Impacts of a degraded stratosphere: Insights from CMIP5

Frequency of $\overline{u} < 0$ at 60°N and 10 hPa

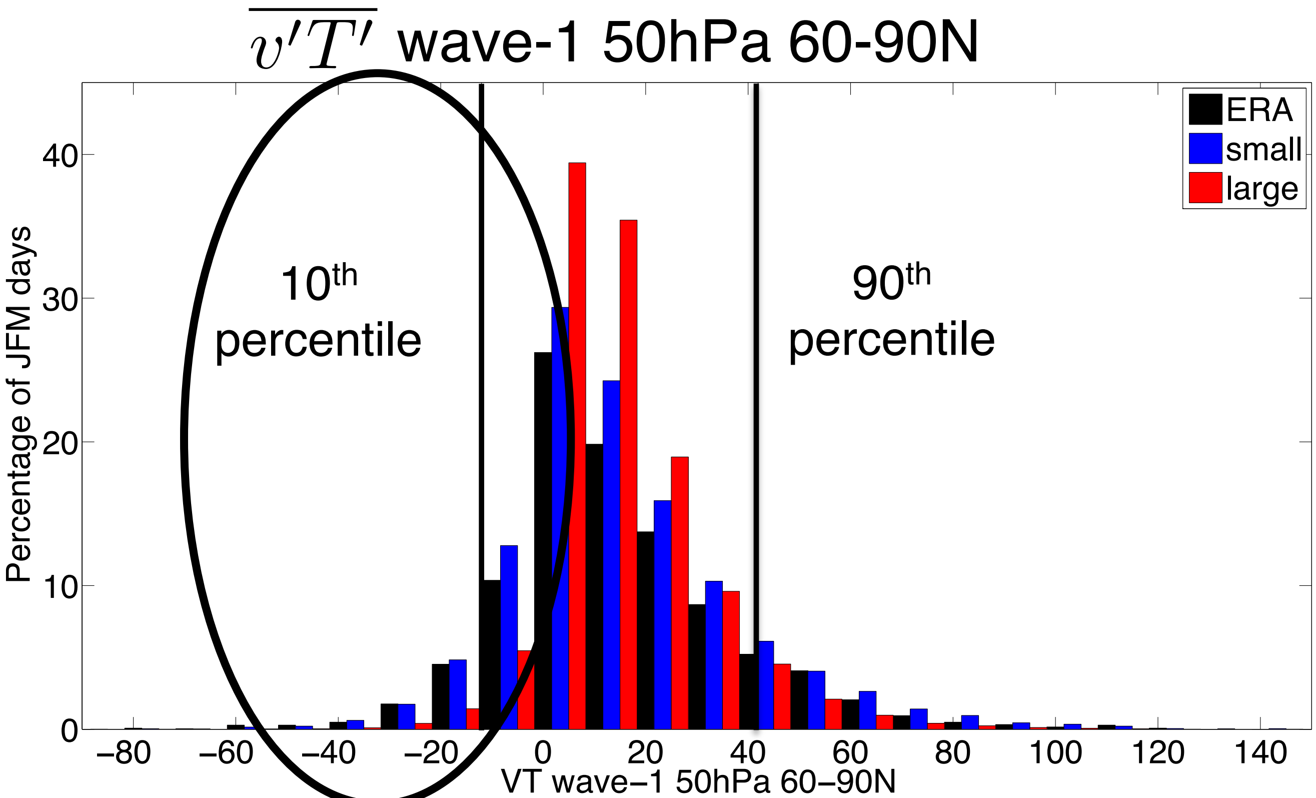


Charlton-Perez et al. (2013)

Downward migration of NAM



Impacts of a degraded stratosphere: Insights from CMIP5



Shaw et al. (2014)

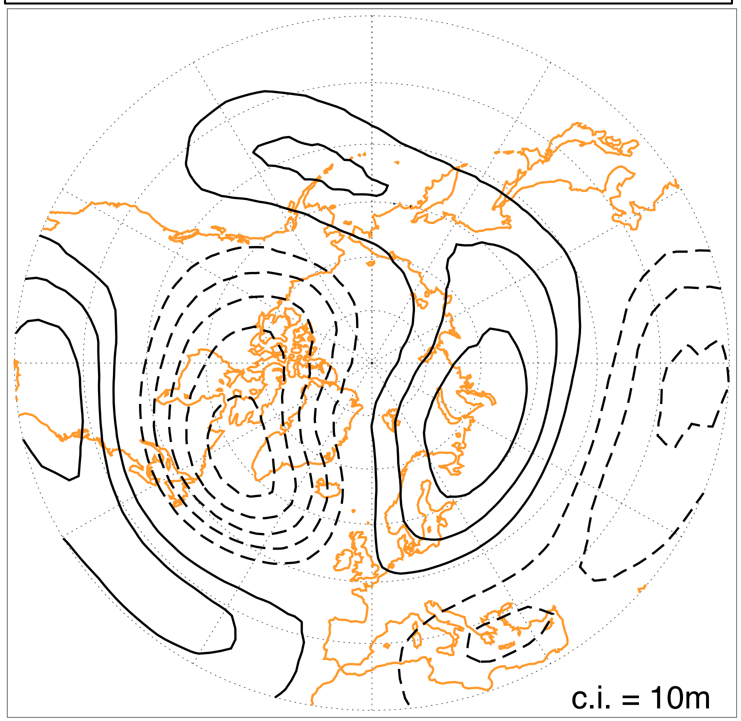
CMIP5 models exhibit large differences in their representation of stratospheric heat flux extremes

Small = dominantly high-top models

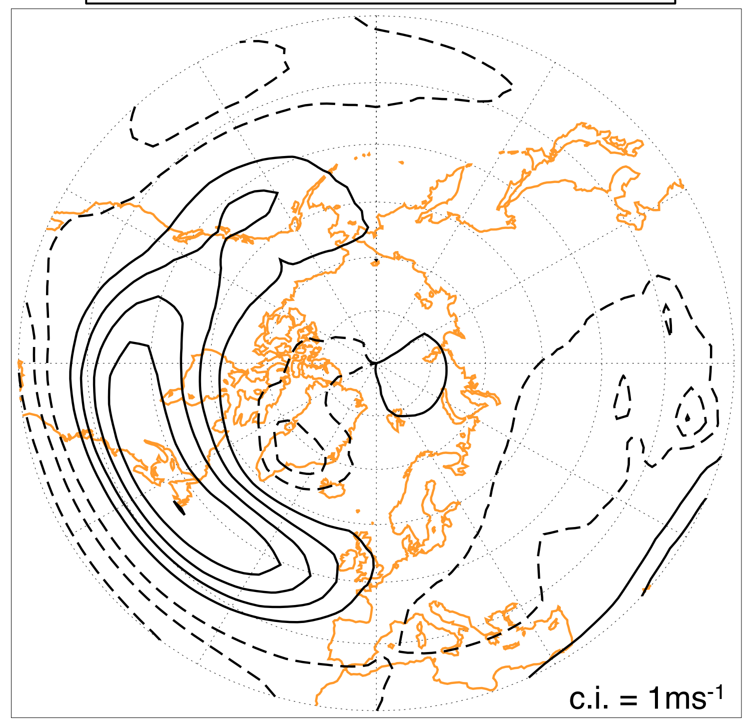
Large = low-top models

Biased stratospheric heat flux extremes linked to biased N. Atlantic jet stream in the troposphere

Z eddy Small – Large bias

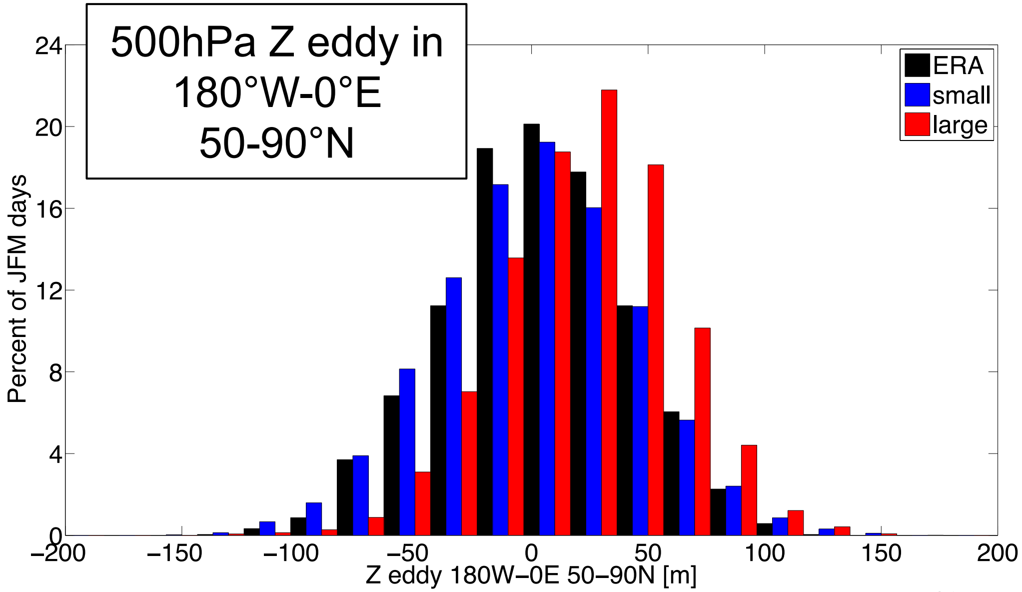


U Small – Large bias

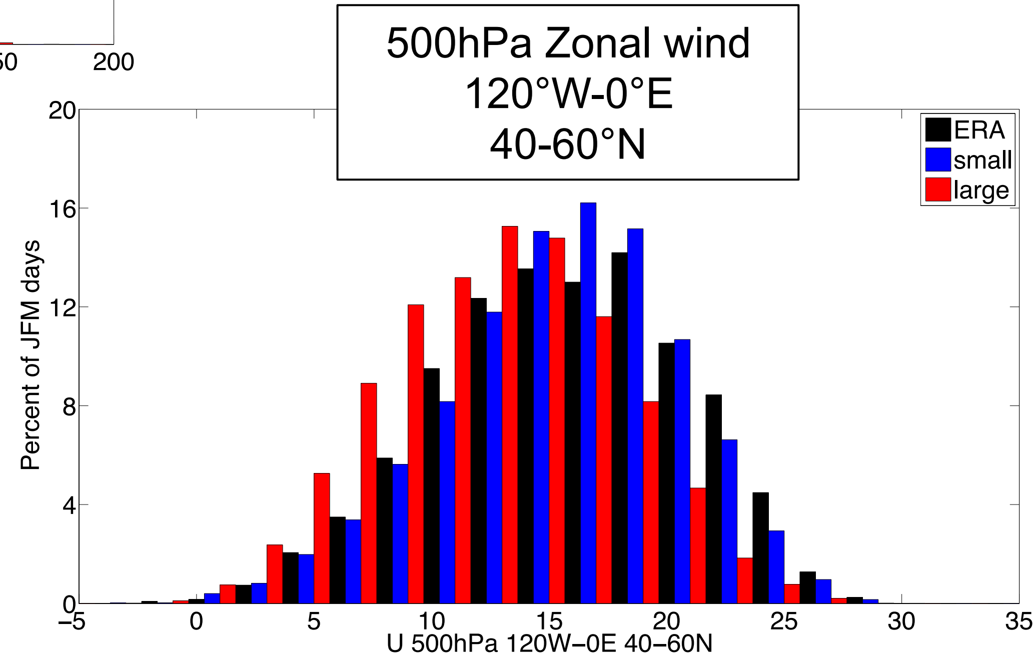


Shaw et al. (2014)

Stratospheric biased linked to biased distribution of tropospheric variability



Shaw et al. (2014)



What have we learned?

- Key ingredients for dynamical stratosphere-troposphere coupling are mean meridional circulation, planetary and synoptic scale waves
  - Mechanisms span all time scales

- Understanding transient dynamical coupling via extreme events is key
  - Time-integrated evolution relates to longer time scales (e.g. interannual variability, response to 2 x CO2) due to irreversibility

- Planetary-scale waves exhibit rich behavior in high latitudes
  - Transient dynamical warming & cooling events (role of 'self-tuning'?)
  - Coupled to equatorward and poleward jet shifts in the Atlantic basin

- Synoptic-scale eddies exhibit strong positive feedbacks that amplify anomalies (tropospheric response not reversible)

- In general low-top models underestimate stratospheric variability
  - Biased stratospheric variability impacts climatology and variability of Atlantic jet stream in the troposphere
  - Model lid height is not sufficient condition for assessing tropospheric impacts (effect of tuning parameterizations)

Where should we go from here?

- Is it time to declare victory on high top/low top? (Shepherd)
  - What are the necessary criteria for a stratosphere-resolving model?
- Outstanding questions regarding mechanisms should be targeted with idealized and comprehensive model experiments
- In order to test mechanisms models must represent relevant dynamics
  - Extreme vortex and planetary wave coupling events, synoptic eddies
- Role for mechanism denial experiments with idealized GCMs
  - Used in studies of the MJO (Kim et al. 2011)
  - Suppress (Domeisen & Plumb 2012) or prescribe (Domeisen et al. 2013) synoptic wave fluxes
  - Transient experiments (e.g. Hardiman & Haynes 2008)
  - Not trivial to control eddy feedbacks