Predictability of the coupled troposphere-stratosphere system

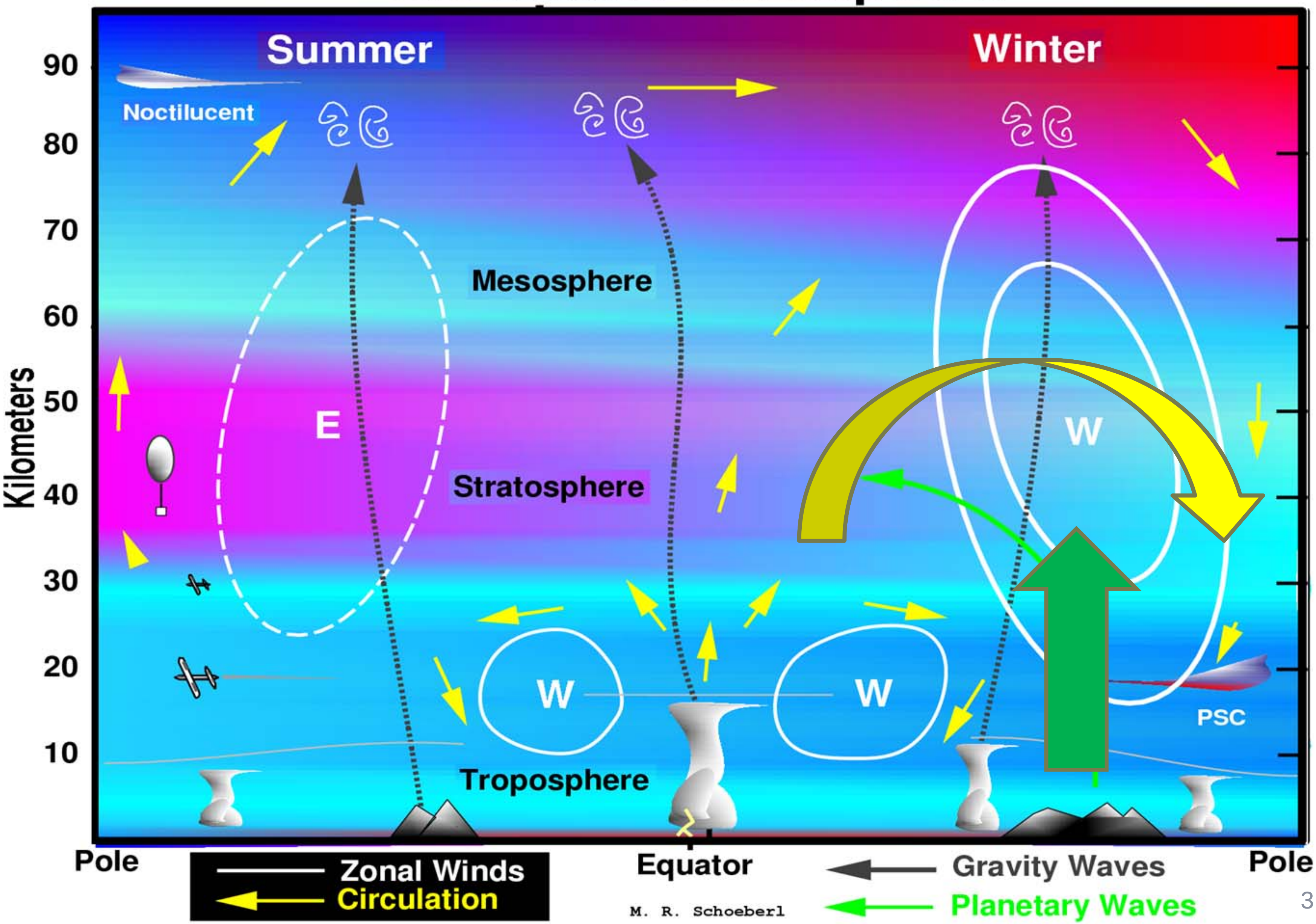
2010-09-08, ECMWF, Reading

Heiner Körnich, MISU
heiner@misu.su.se

Overview

- Observations
- Mechanism
- Forecasting
- Conclusions

The Middle Atmosphere



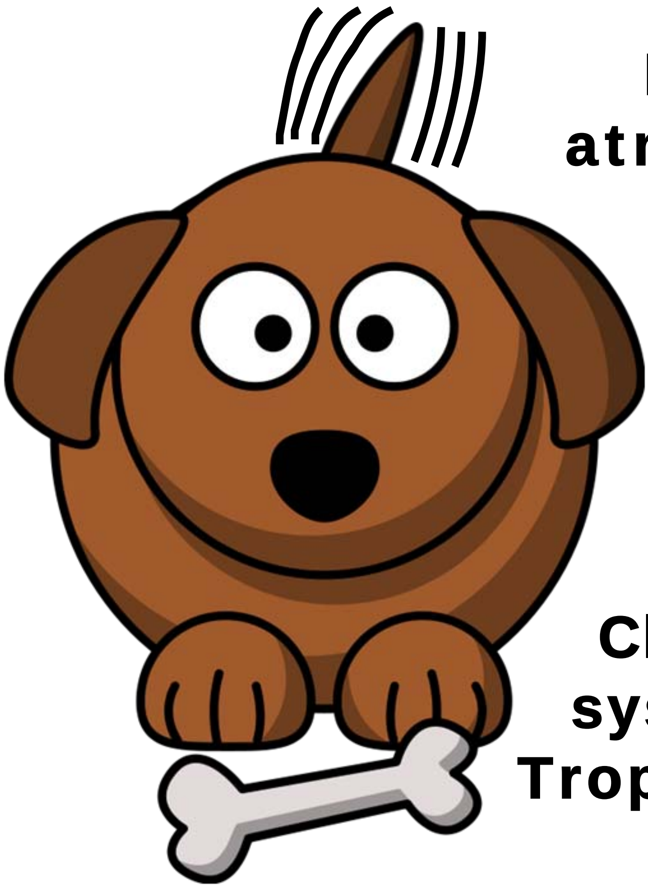
By Mark R. Schoeberl

Dynamical influence goes

Bottom-up

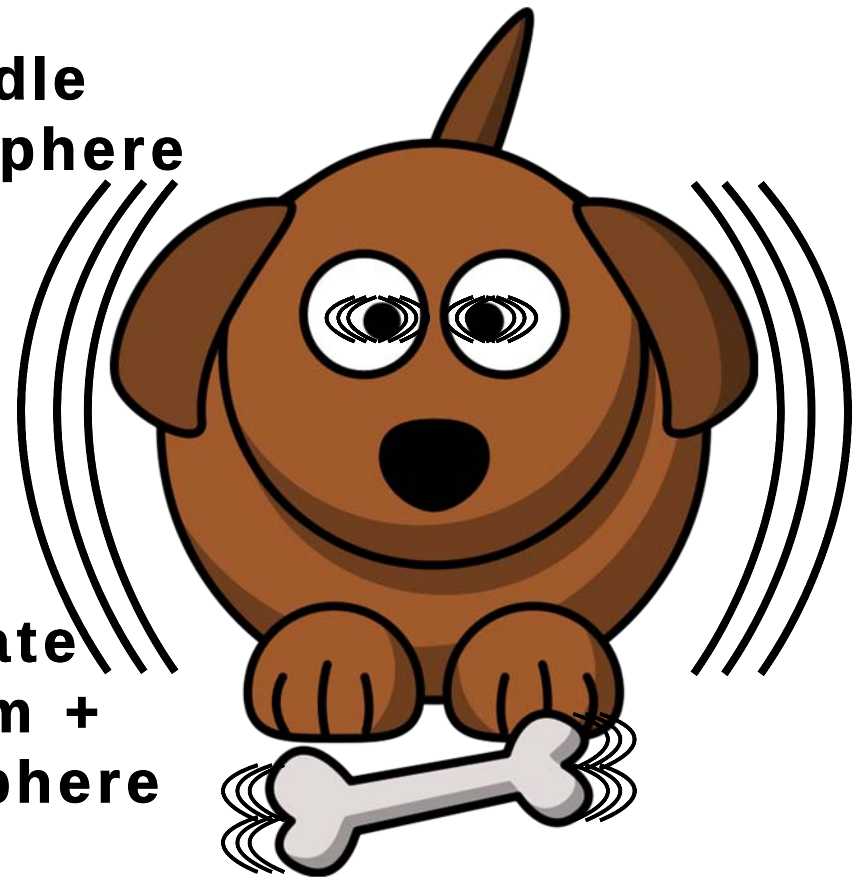
Top-down

Stockholm University



Middle atmosphere

Climate system + Troposphere



Planetary, gravity and tidal waves

"Downward propagation"
Planetary wave propagation

Downward propagating winds

<u>Figures from:</u> **Baldwin, M.P., and T.J. Dunkerton, 2001: Stratospheric harbingers of anomalous weather regimes. *Science*, 294, 581-584.**

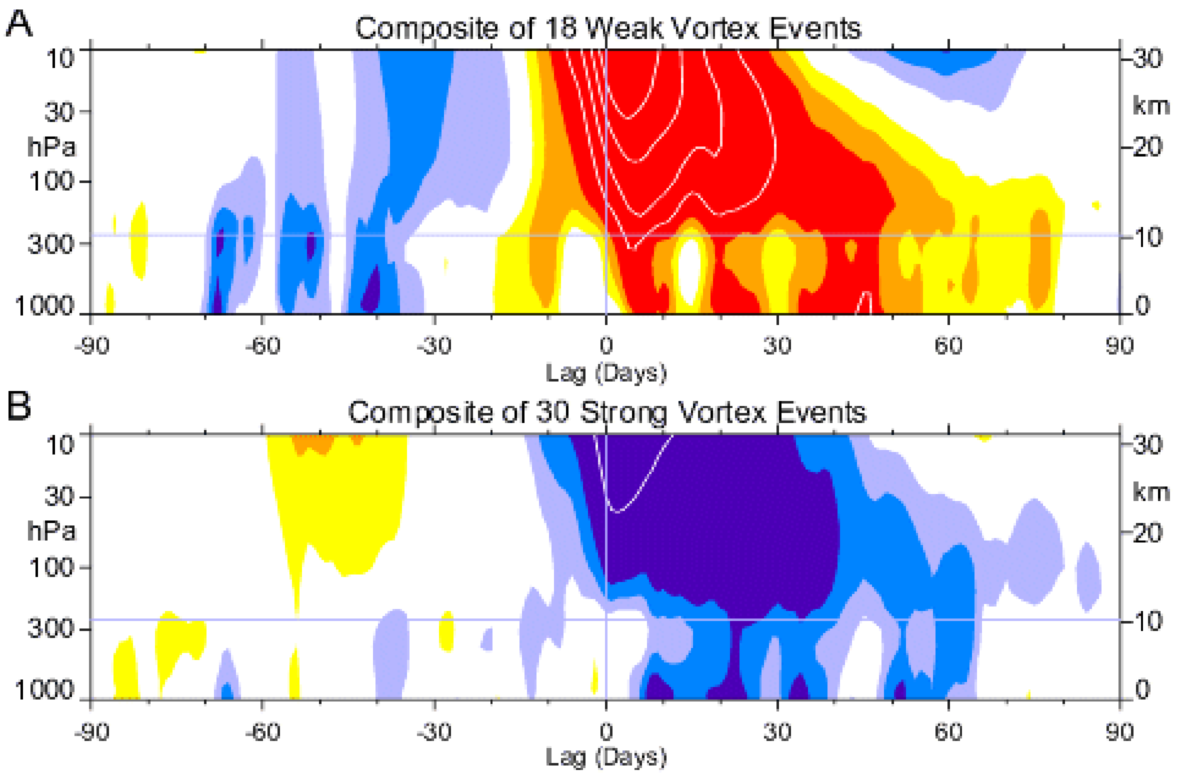
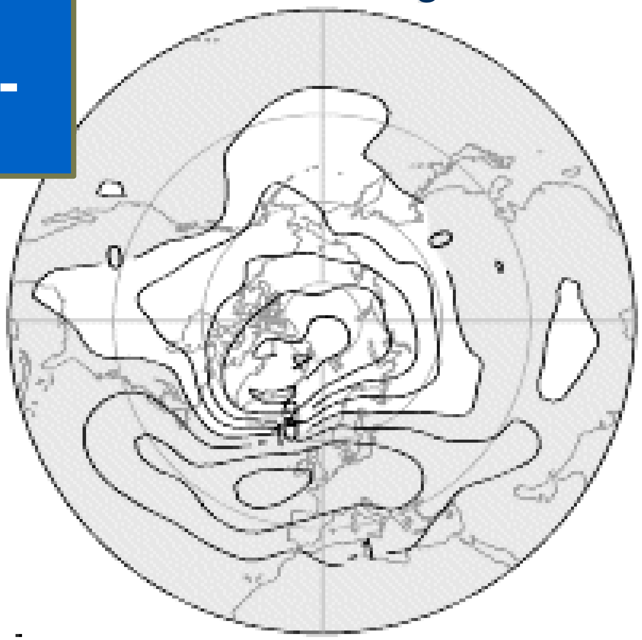


Fig. 2. Composites of time-height development of the northern annular mode for (**A**) 18 weak vortex events and (**B**) 30 strong vortex events. The events are determined by the dates on which the 10-hPa annular mode values cross –3.0 and +1.5, respectively. The indices are nondimensional; the contour interval for the color shading is 0.25, and 0.5 for the white contours. Values between -0.25 and 0.25 are unshaded.

Surface pressure response to tropo-stratosphere coupling

NAO-

Weak vortex regimes



Strong vortex regimes

NAO+

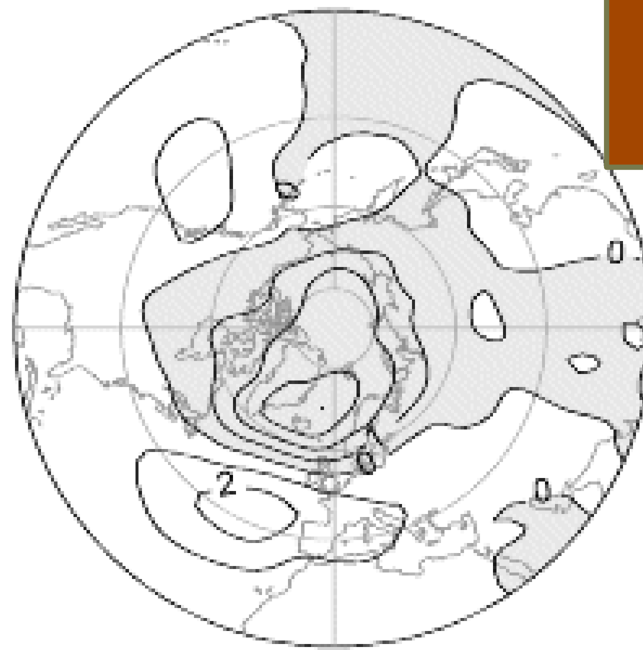
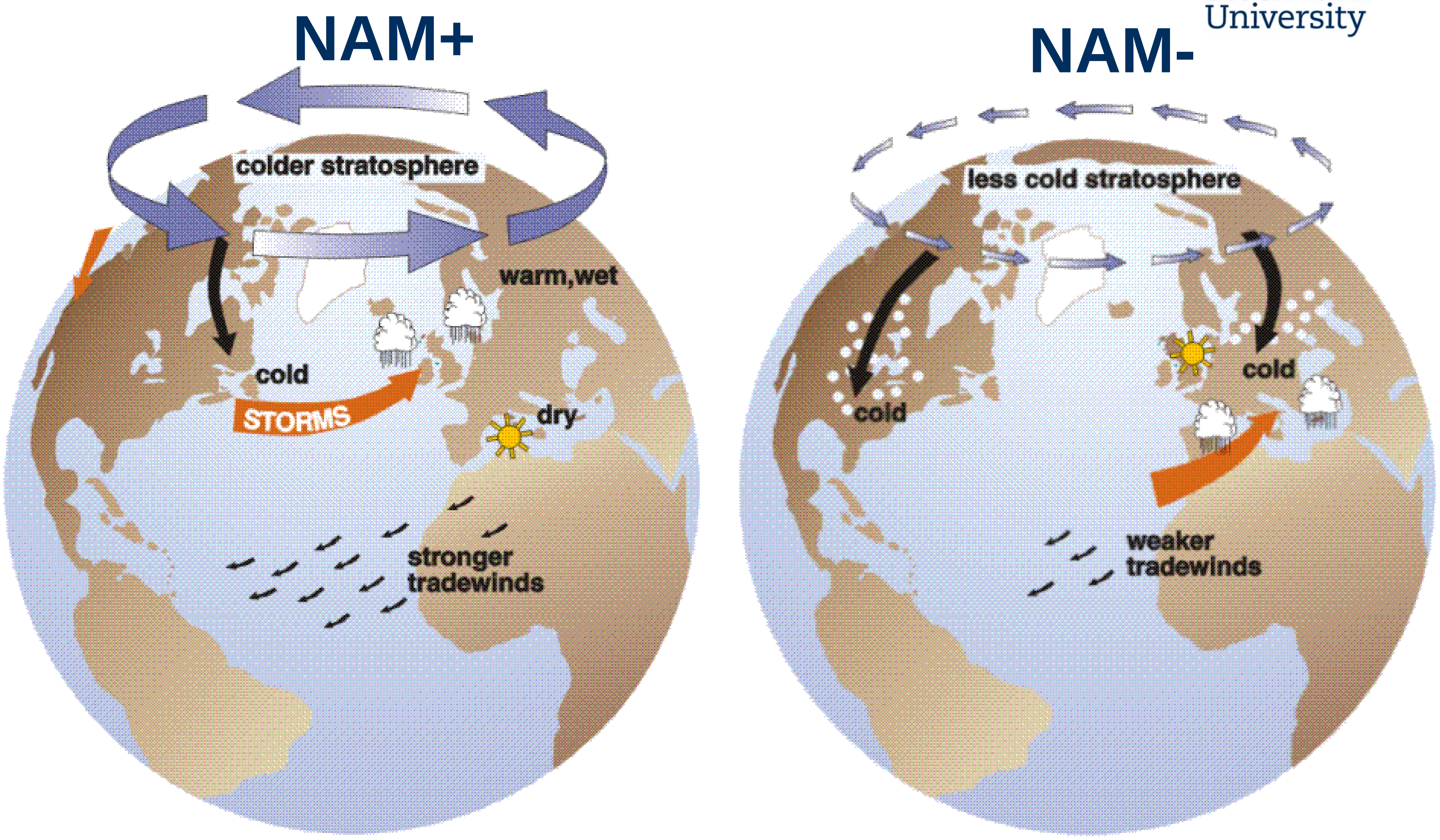


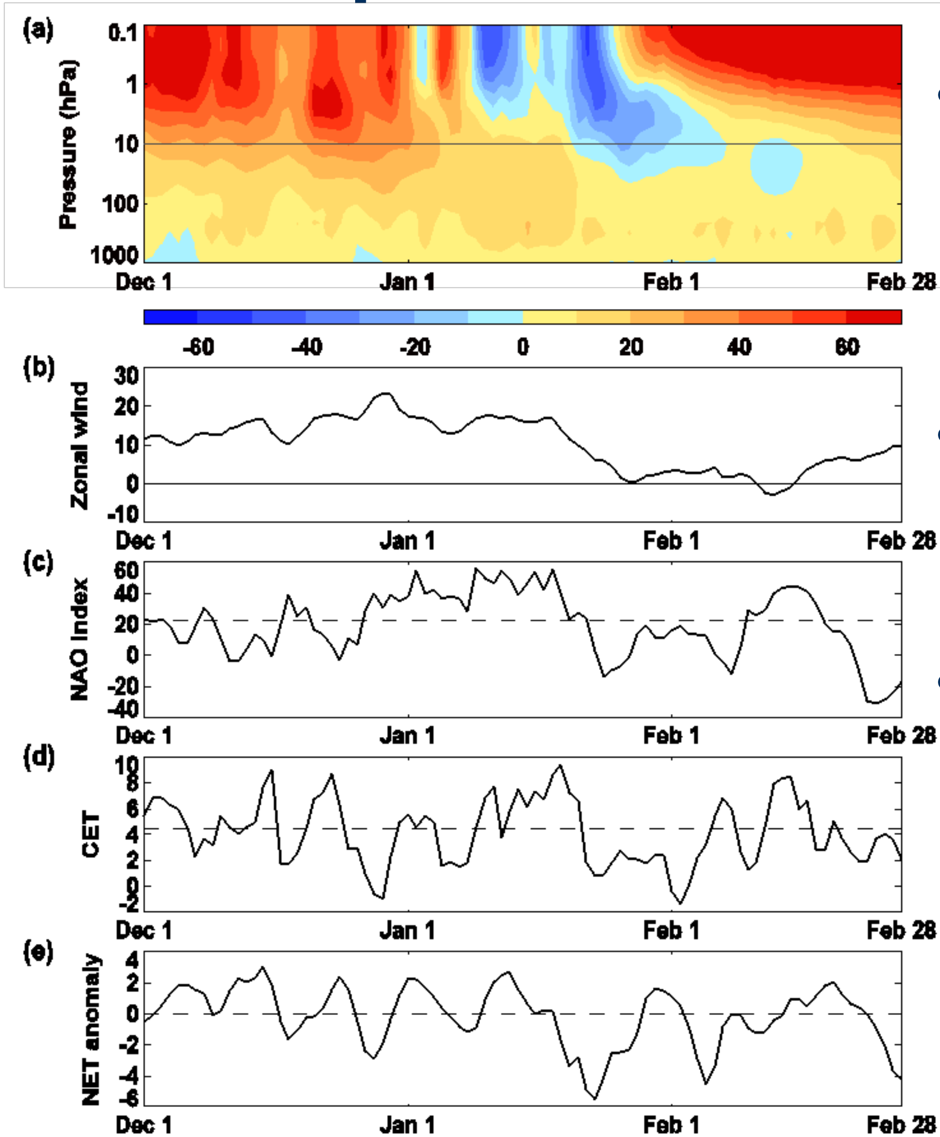
Fig. 3. Average sea-level pressure anomalies (hPa) for (**A**) the 1080 days during weak vortex regimes and (**B**) the 1800 days during strong vortex regimes.
From Baldwin and Dunkerton (Science, 2001)

Impact of the Northern Annular Mode



(c) J. Wallace

Example: Winter 2005/6



- Extreme stratospheric warming, Downward propagation
- Low central England and northern European temperatures
- Extreme snowfall

From: Scaife and Knight (QJRMS 2008)

Surface response to low-frequency variability

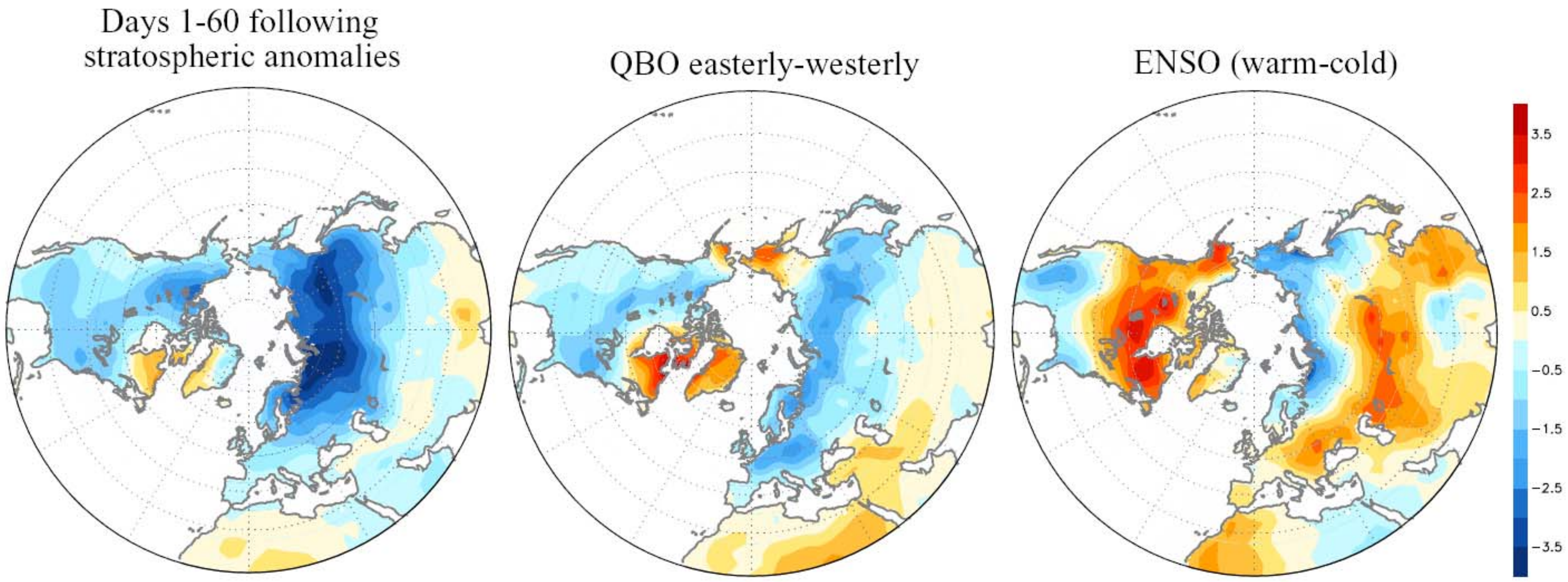
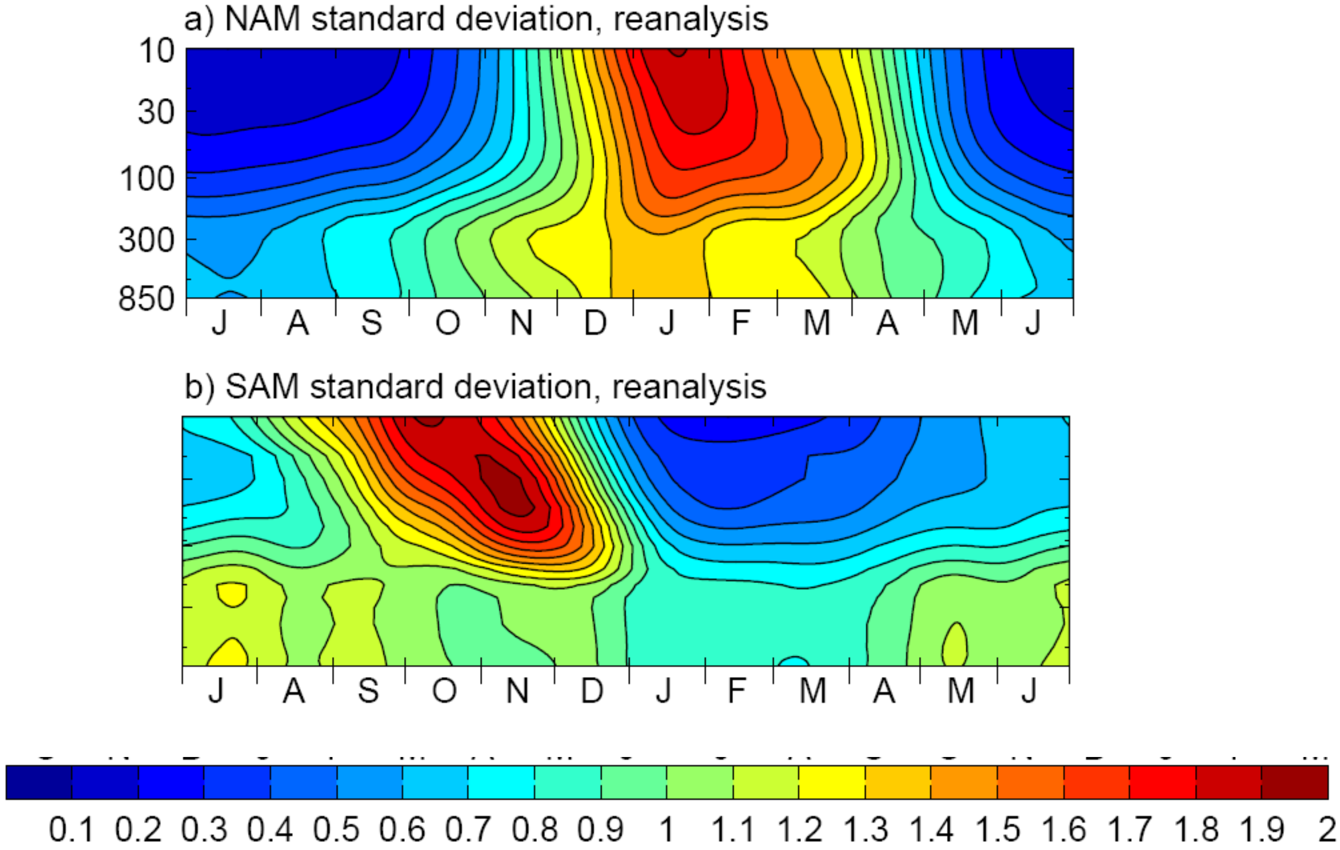


FIG 2. The difference in daily mean surface temperature anomalies between the 60-day interval following the onset of weak and strong vortex conditions at 10-hPa (left panel); between Januarys when the QBO is easterly and westerly (middle panel); and between winters (January-March) corresponding to the warm and cold episodes of the ENSO cycle (right panel). The samples used in the analysis are documented in Fig. 1. Contour levels are at 0.5 C.

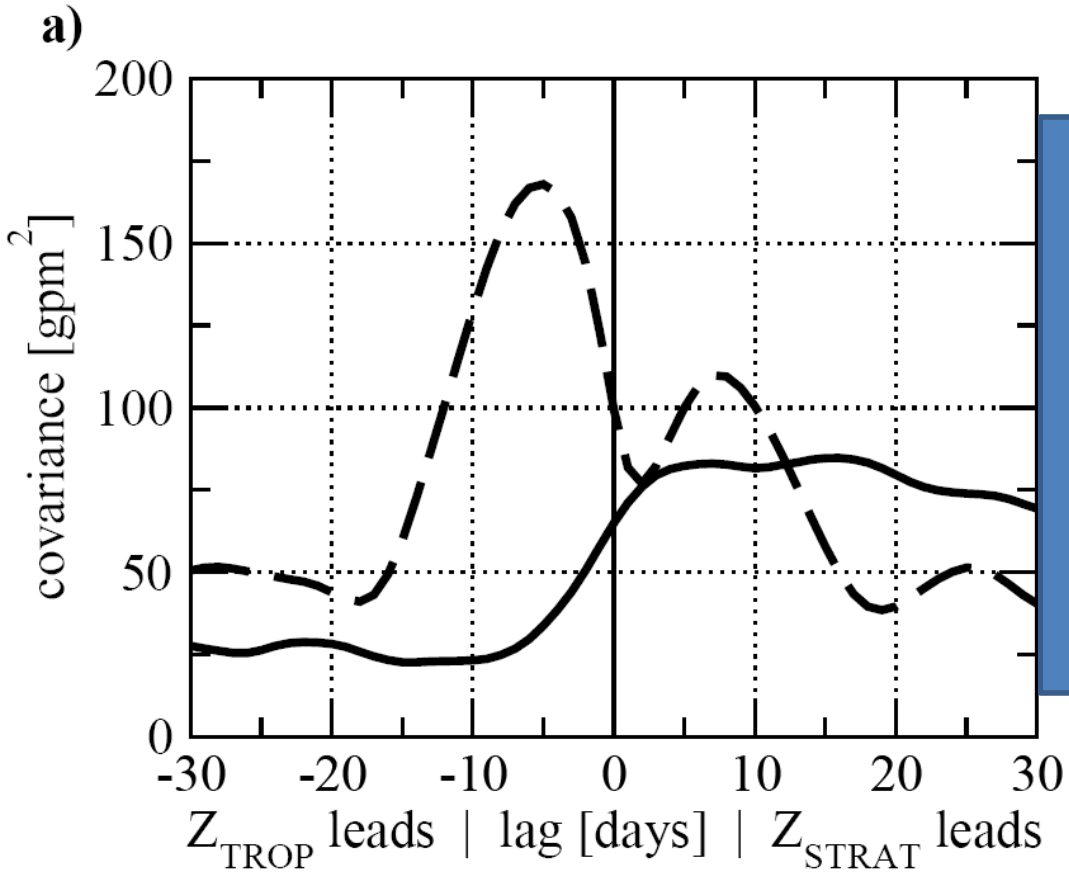
From Thompson et al. (JC 2002)

Annular mode variability on the NH and SH



From Gerber et al. (JGR 2010)

Correlation between tropospheric and stratospheric height fields



Zonal mean response dominates the longer time-scales.

Reflected planetary waves occur on shorter time-scales.

From Perlwitz and Harnik (JC 2004)

Summary: Observations

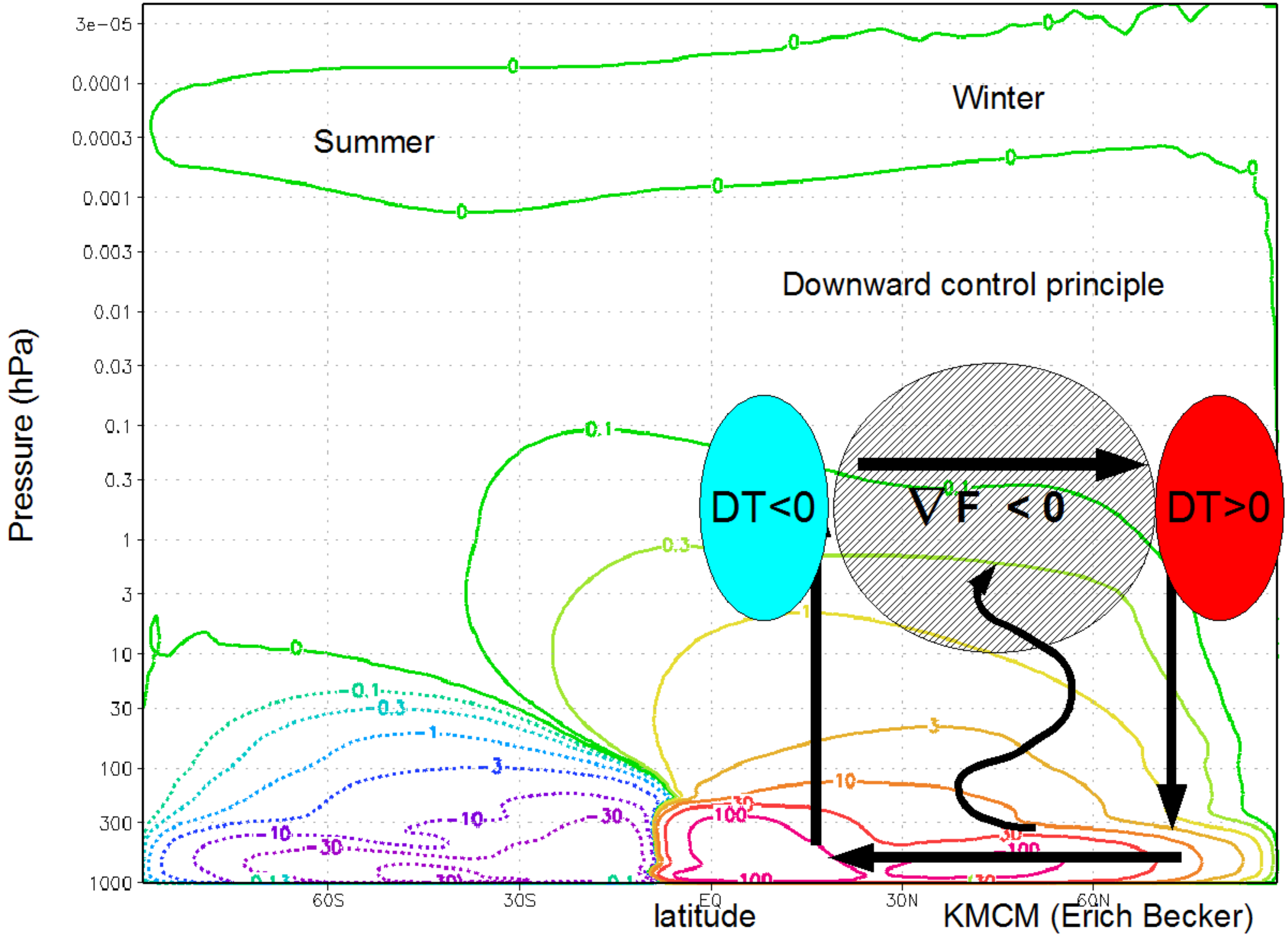
- Stratospheric circulation anomalies affect surface climate via Arctic Oscillation.
- Planetary waves can be reflected downwards from the stratosphere to the troposphere.

Mechanism for the troposphere-stratosphere coupling

Stratospheric warming

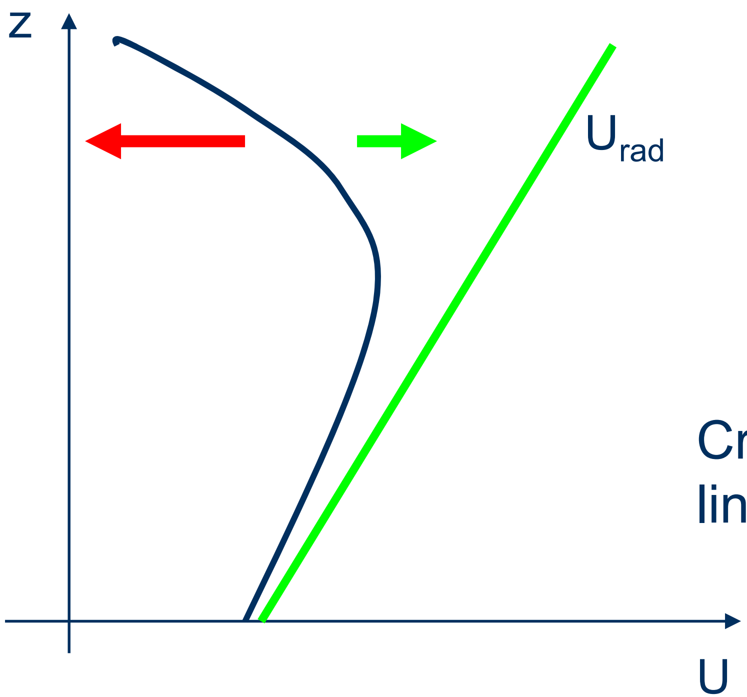
- Basic theory: Matsuno (JAS 1971)
- Increased planetary wave activity flux (Eliassen-Palm flux) from troposphere upwards
- Pre-conditioning of polar vortex
- Breaking of waves in high latitudes give rise to stronger residual circulation and strong polar warming (up to 70 K).
- Change in temperature gradient creates stratospheric easterlies, which propagate down to troposphere.

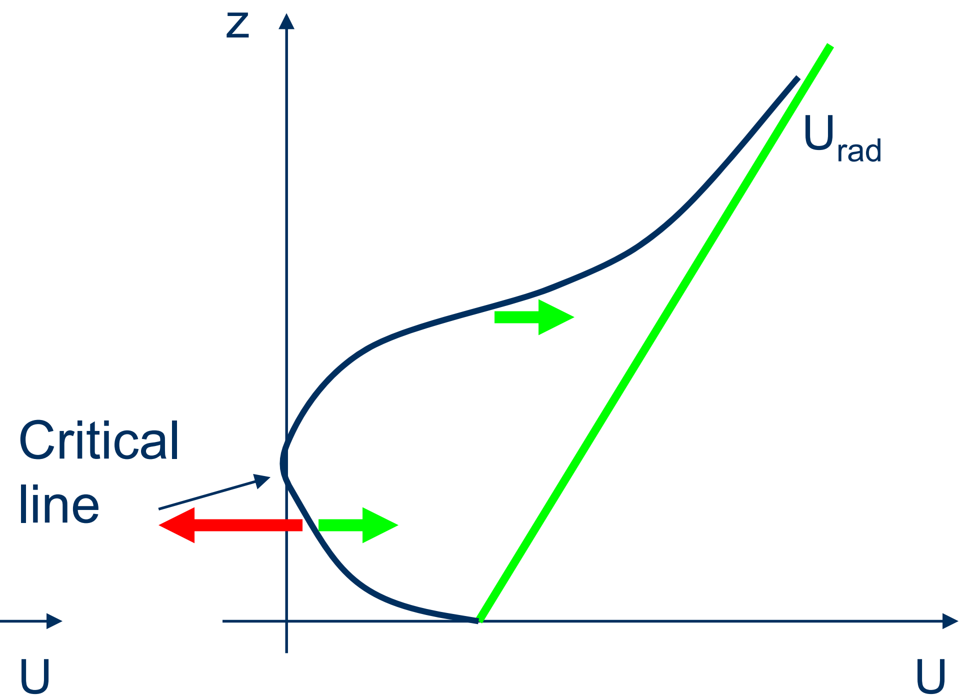
Stratospheric Warmings



Simplest model of downward propagation in stratosphere

$$\frac{\partial [u]}{\partial t} + \frac{[u] - u_{\text{rad}}}{\alpha \tau_{\text{rad}}} = \frac{\nabla \cdot \mathbf{F}}{\rho_0}$$

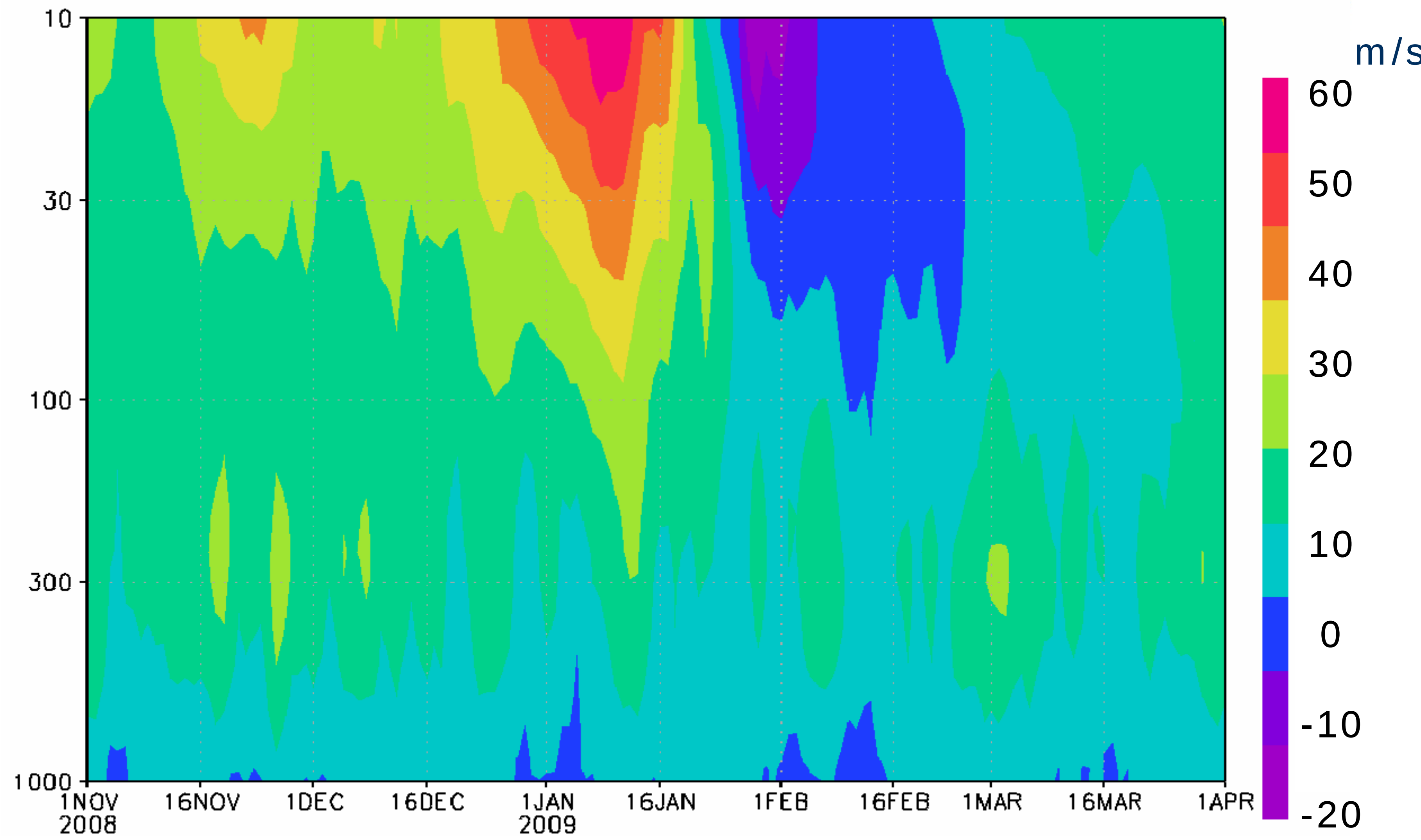




α= (NH/fL)^2

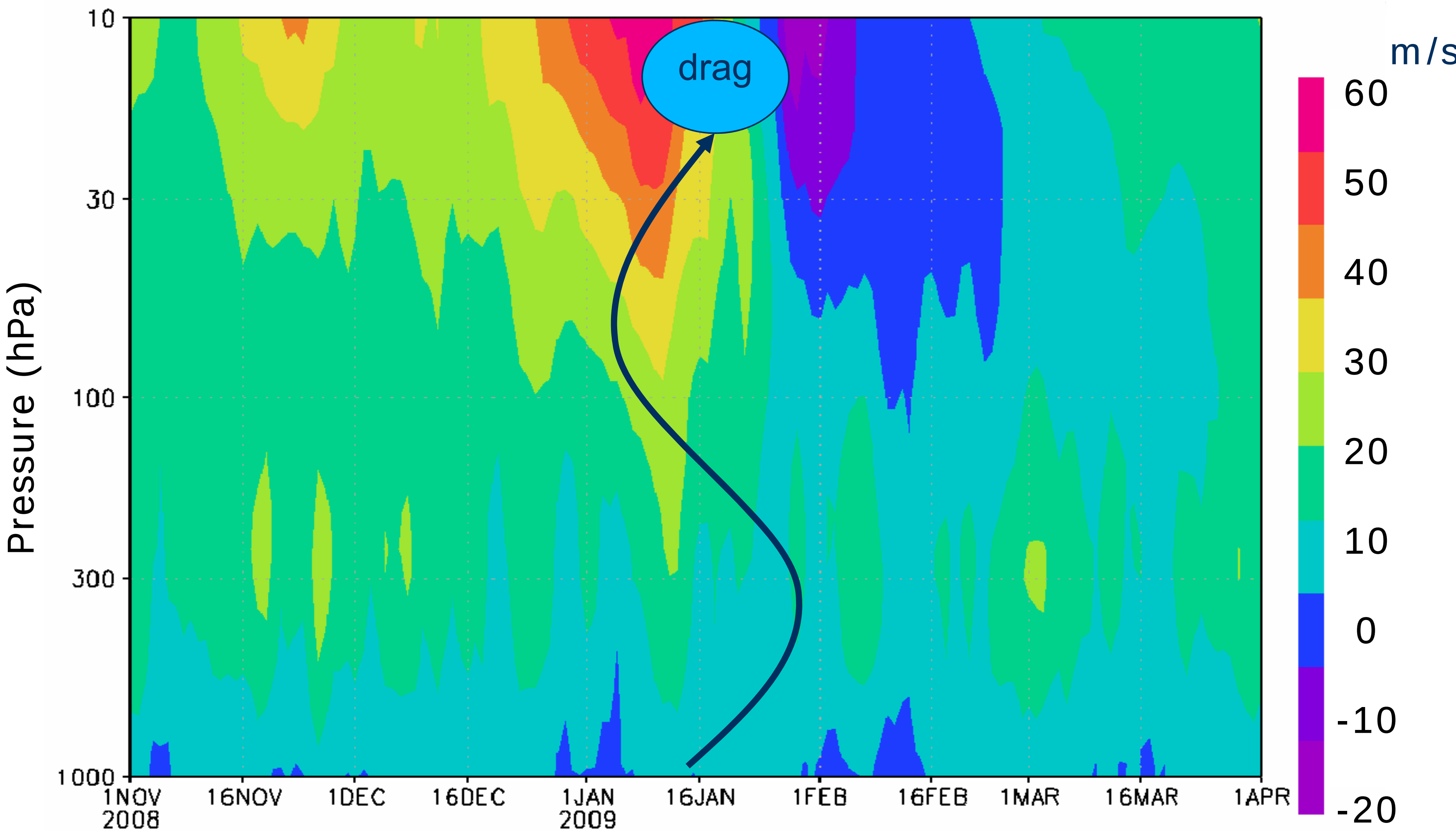
after Christiansen (JAS 1999)

Downward propagation of the zonal wind at 60°N



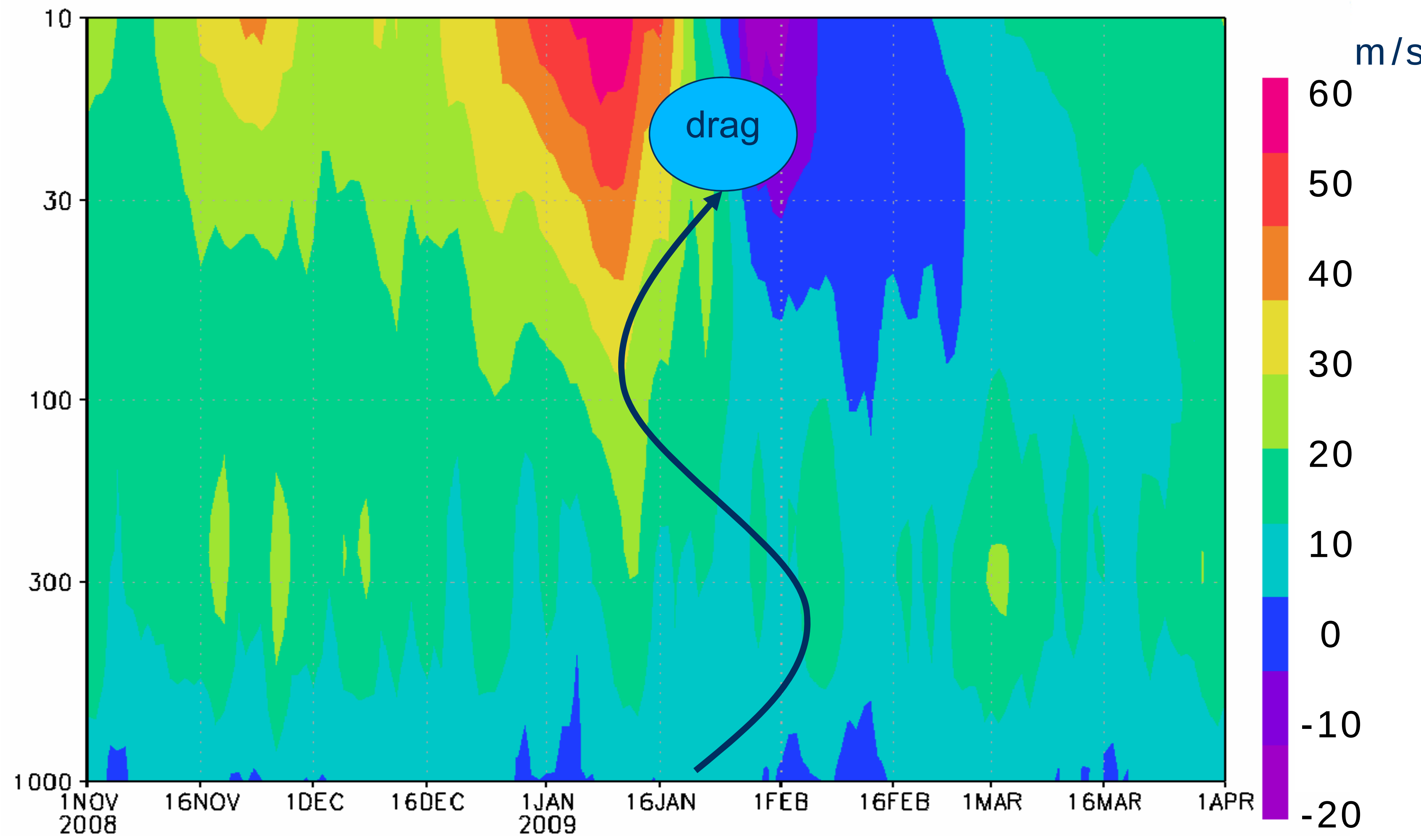
NCEP reanalysis

Downward propagation of the zonal wind at 60ºN



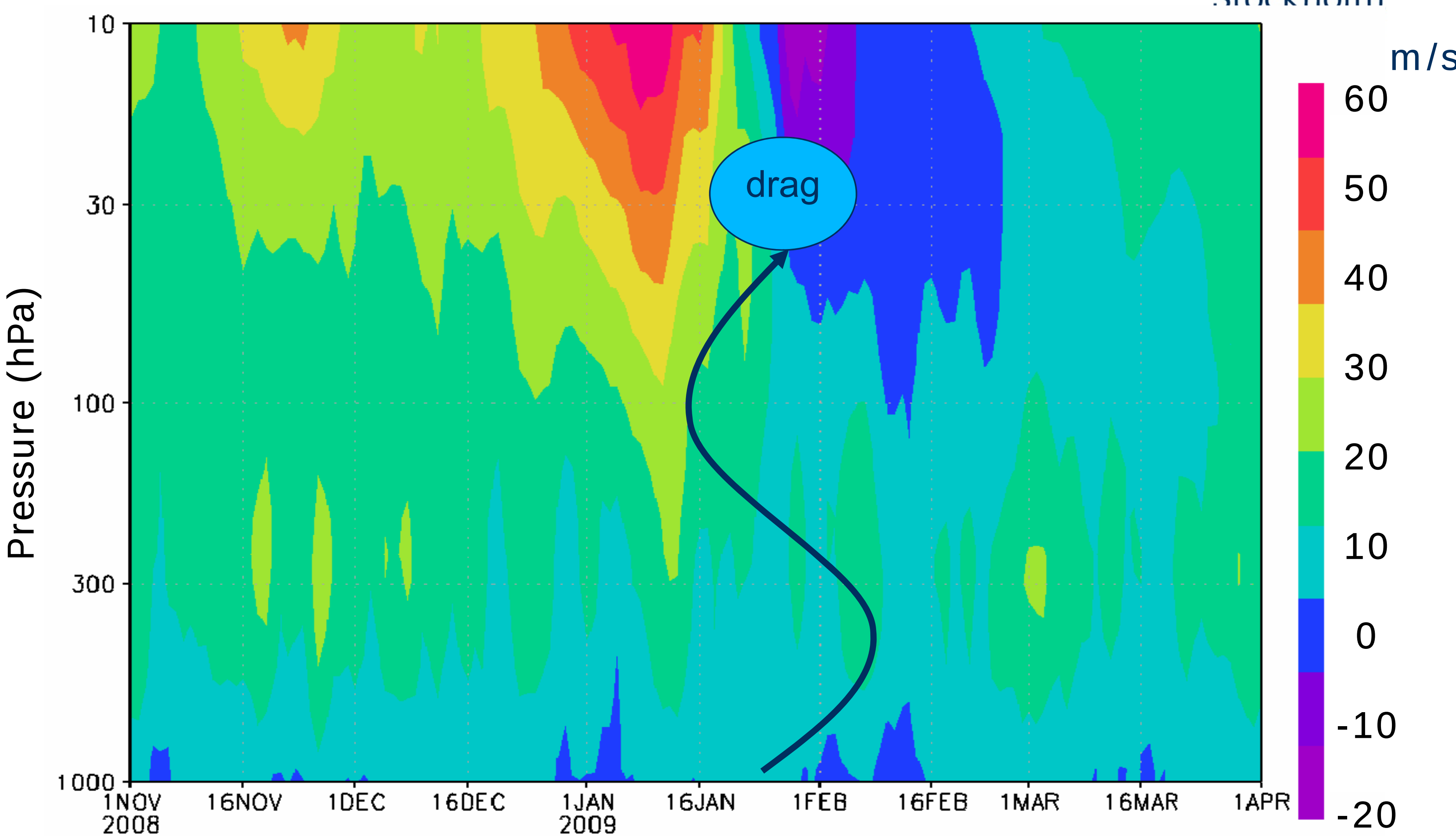
NCEP reanalysis

Downward propagation of the zonal wind at 60ºN



NCEP reanalysis

Downward propagation of the zonal wind at 60ºN



NCEP reanalysis

Balanced wind response

From Thompson et al. (JAS 2006)

Linearized QG-equations in transformed Eulerian mean:

$$\frac{\partial \overline{u}}{\partial t} - f\overline{\upsilon}^* = \overline{G} + \overline{F}, \qquad (1)$$

$$f\overline{u} = -a^{-1}\frac{\partial \overline{\Phi}}{\partial \phi}, \qquad (2)$$

$$\frac{\partial \overline{\Phi}}{\partial p} = -\frac{R\overline{T}}{p}, \qquad (3)$$

$$\frac{\partial \overline{T}}{\partial t} - \Gamma\overline{\omega}^* = \overline{Q}, \qquad (4)$$

$$(a\cos\phi)^{-1}\frac{\partial}{\partial \phi}(\overline{\upsilon}^*\cos\phi) + \frac{\partial \overline{\omega}^*}{\partial p} = 0, \qquad (5)$$

Wave drag:G

Friction: F

Diabatic heating: Q

All terms can drive a residual meridional circulation.

Equivalent balanced responses by potential vorticity inversion (Black JC 2002, Ambaum and Hoskins JC 2002).

Residual circulation response to stratospheric warming

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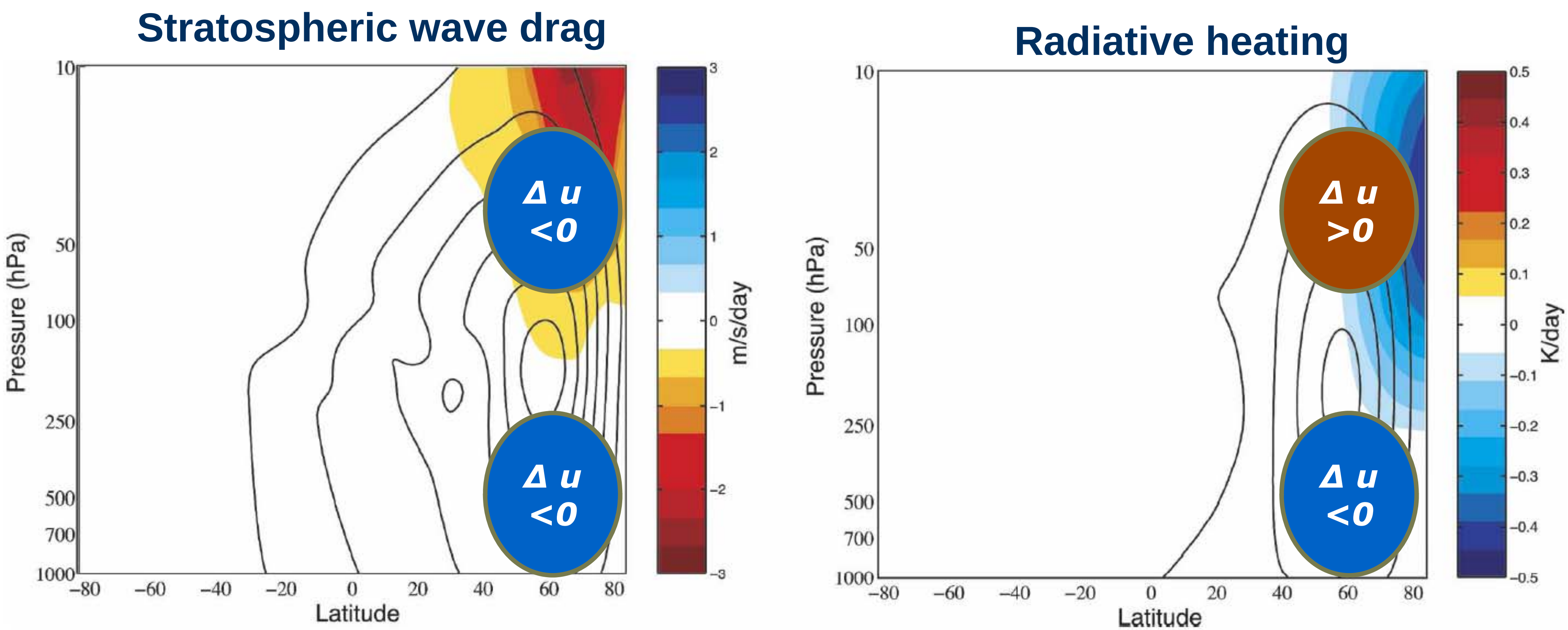
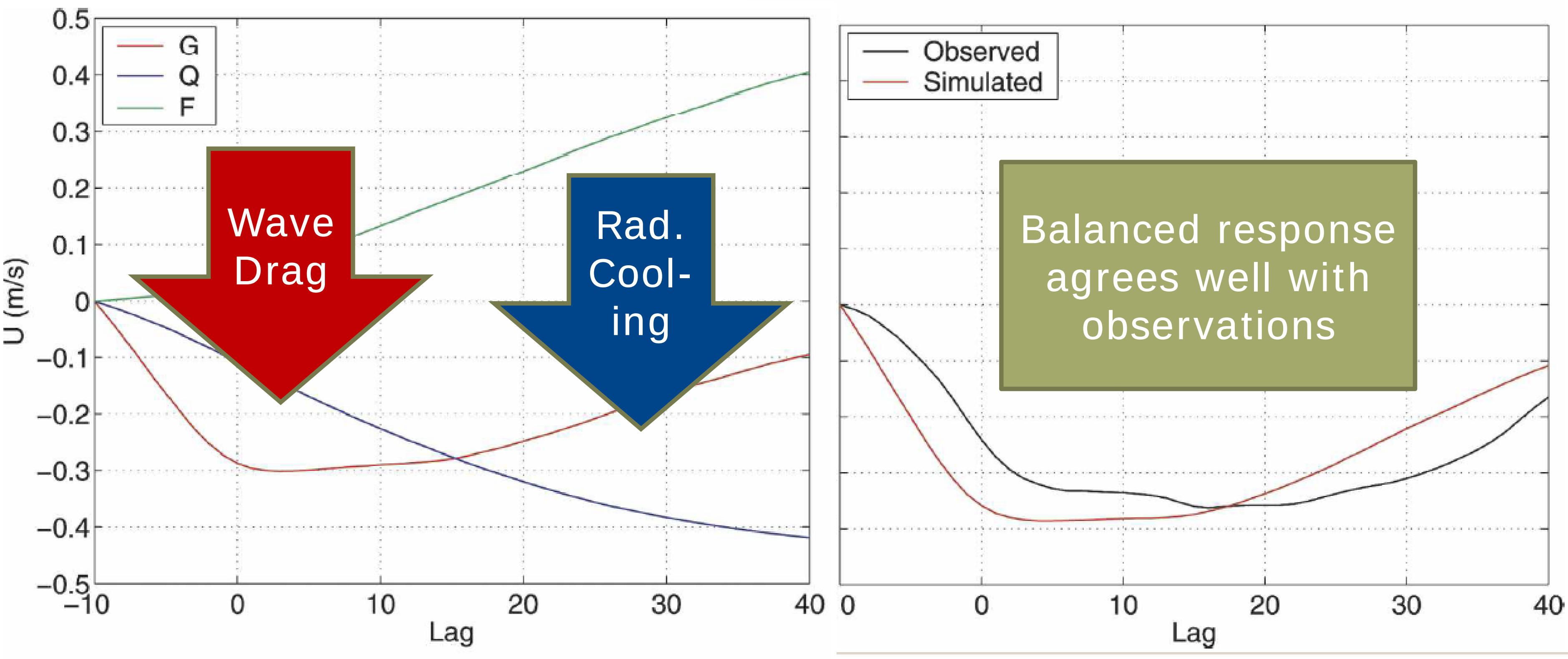


FIG. 3. (left) The model streamfunction response (contours) to the observed day −5 momentum forcing (shading). (right) As in (left), but for the model streamfunction response to the day +5 radiative heating (shading). Contour interval is 40 (left) and 20 Pa m s^{-1} (right). Units of shading are m s^{-1} day^{-1} (left) and K day^{-1} (right). Positive values of the streamfunction denote clockwise motion.

From Thompson et al. (JAS 2006)

Balanced wind response

mean over 55N-75N at 925 hPa



Zonal wind anomalies at 300 hPa based on ERA40

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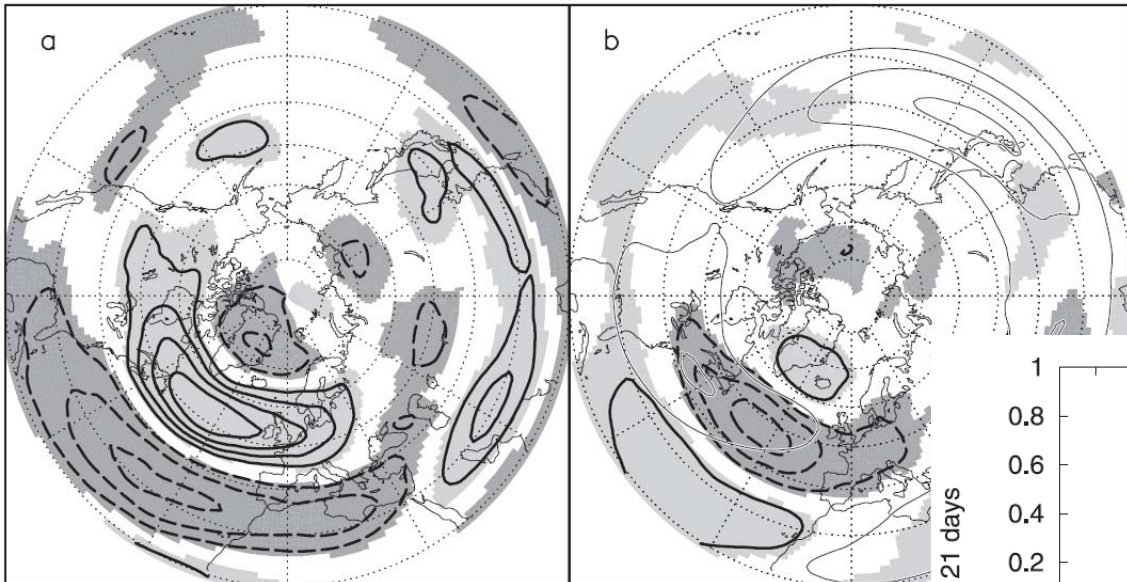
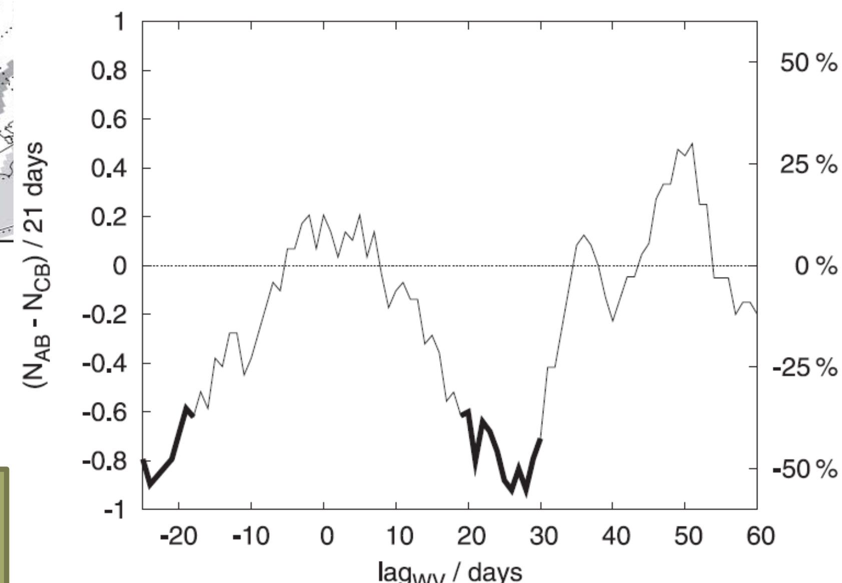
Anti-cyclonic wavebreaking   Cyclonic wavebreaking



Wind anomaly following wave breaking events.



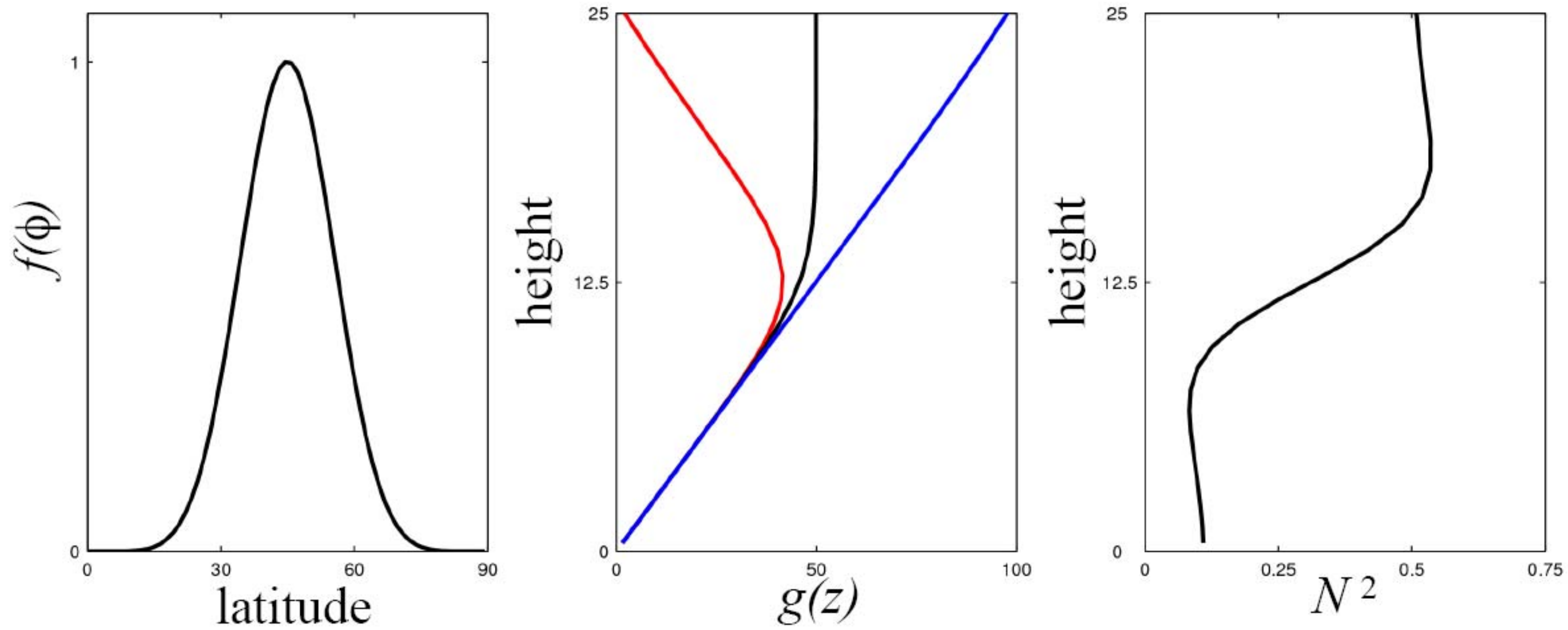
After stratospheric warming events cyclonic breaking dominates.

Baroclinic waves feedback to stratospheric circulation anomalies.

From Kunz et al. (JC 2007)

Modified Eady problem with 3d primitive equations

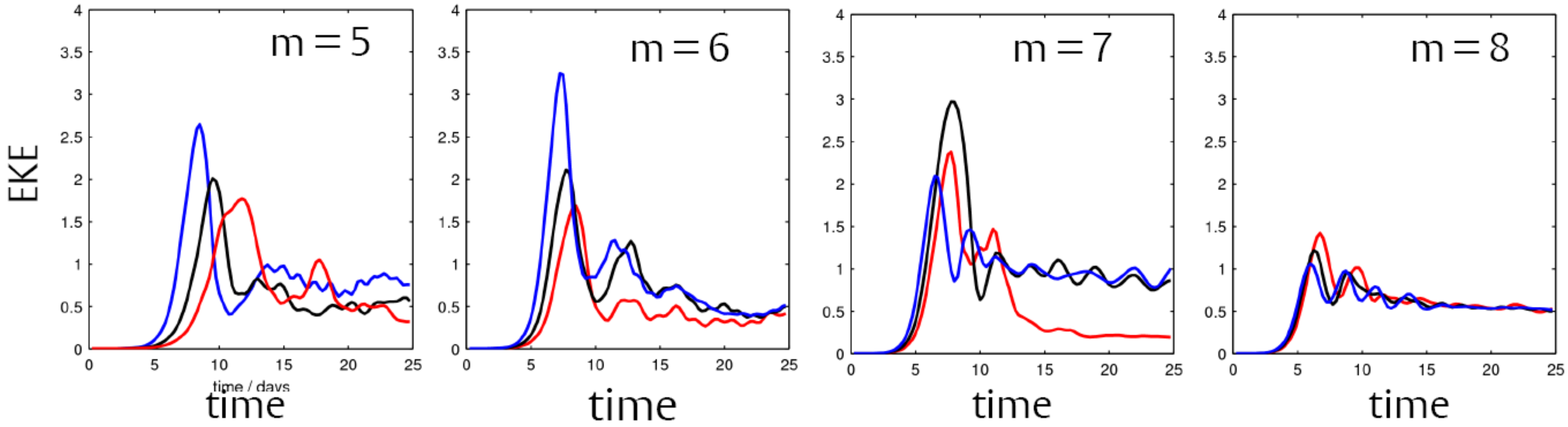
Stockholm University



- 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

From Wittmann et al. (JAS 2007)

Nonlinear lifecycles

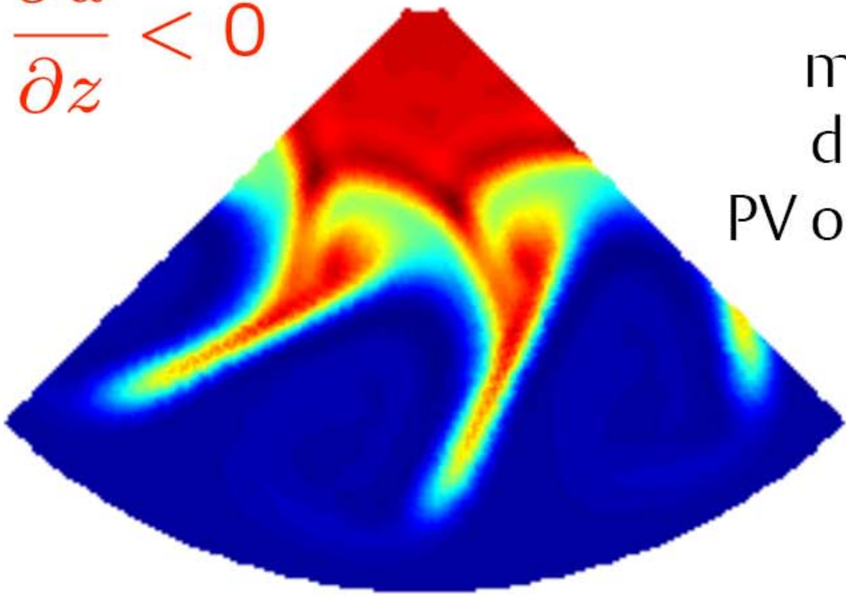


- Growth rates as expected from linear calculations:
  - For low wavenumbers, rates increase with shear.
  - For high wavenumbers, rates decrease with shear.
- Saturation amplitude depends on shear.
- Transition from Anti-cyclonic to cyclonic wavebreaking at m=7?

From Wittmann et al. (JAS 2007)

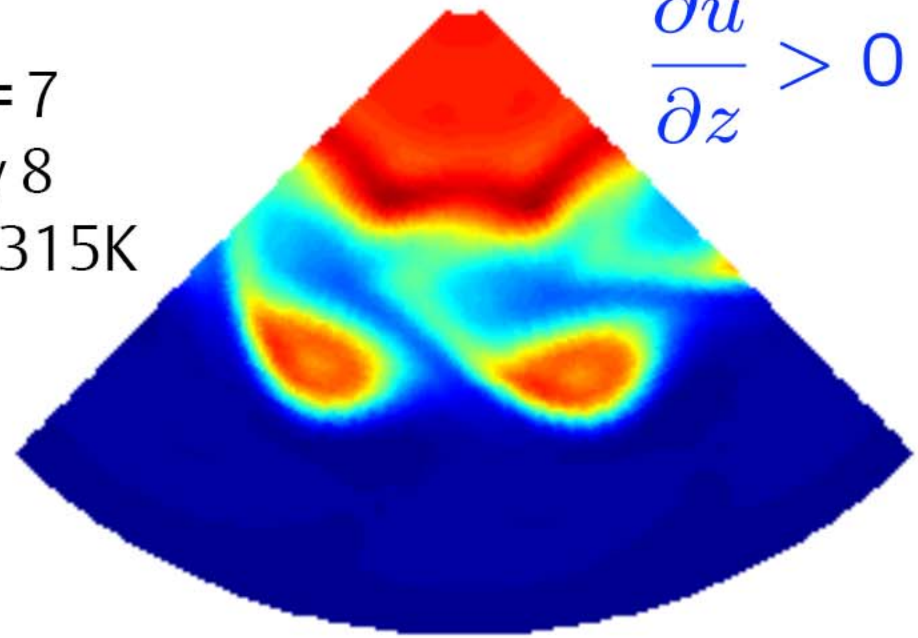
LC1 / LC2 transition

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



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

Agrees with observations (Kunz et al. JC 2007)

Refractive index for Rossby waves

Harnik and Lindzen (JAS 2001) suggested a separation of the meridional and vertical propagation.

$$Real\left[\Psi(y,z)\,e^{ik(x-ct)}\right]$$

In … ential vorticity

e…

$$\frac{\partial^2\Psi}{\partial y^2}+\frac{f_0^2}{N^2}\frac{\partial^2\Psi}{\partial z^2}+n_k^2\Psi=0$$

Refractive index: $$n_k^2(y,z)=(\bar{u}-c)^{-1}\frac{\partial\bar{q}}{\partial y}-k^2-\frac{f_0^2}{4HN^2}$$

Waves will propagate towards large n_k^2 and avoid regions with negative values.

Vertical reflectiveness defined as: u(2hPa) – u(10hPa), averaged over58N to 74N

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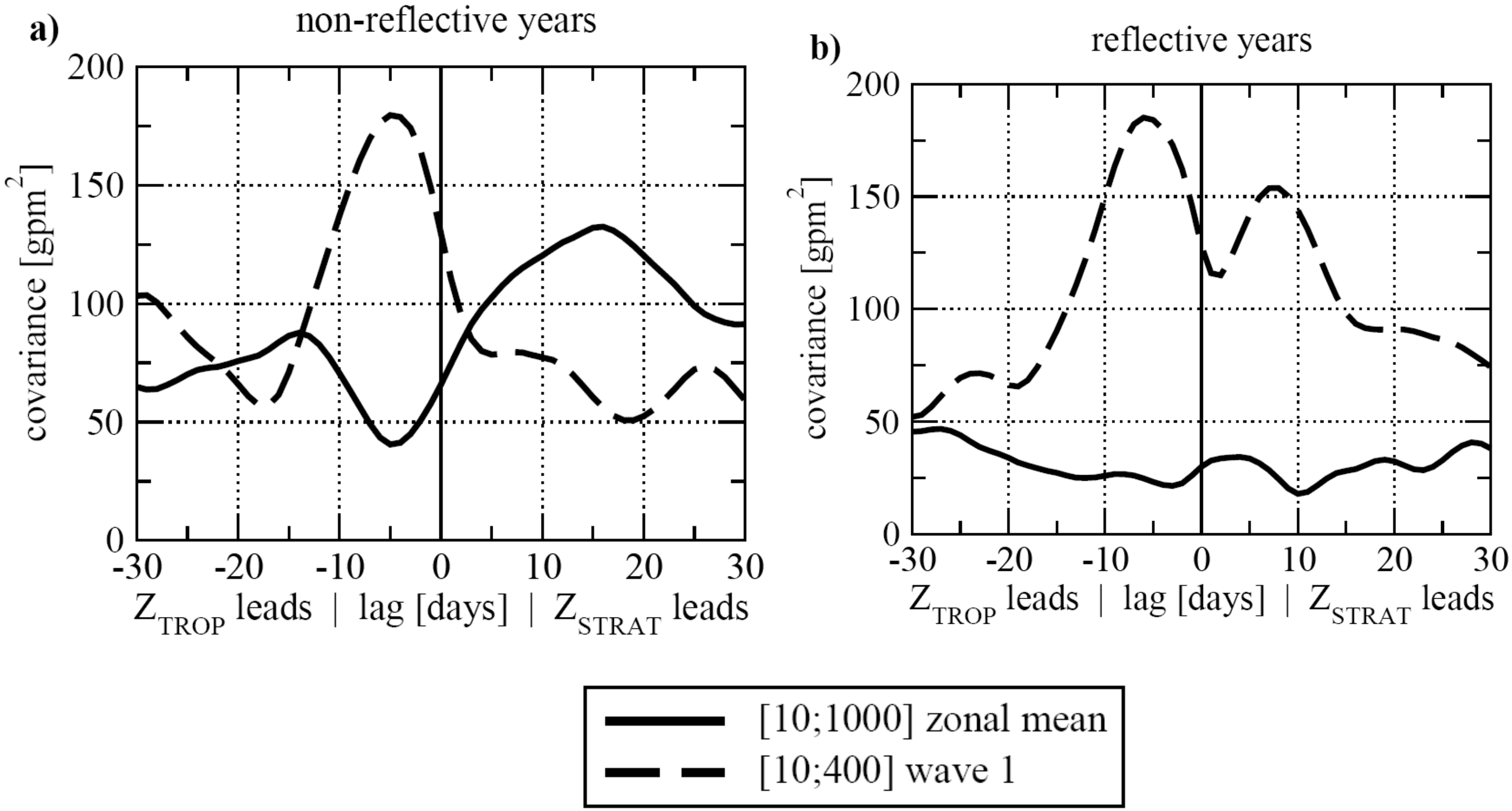
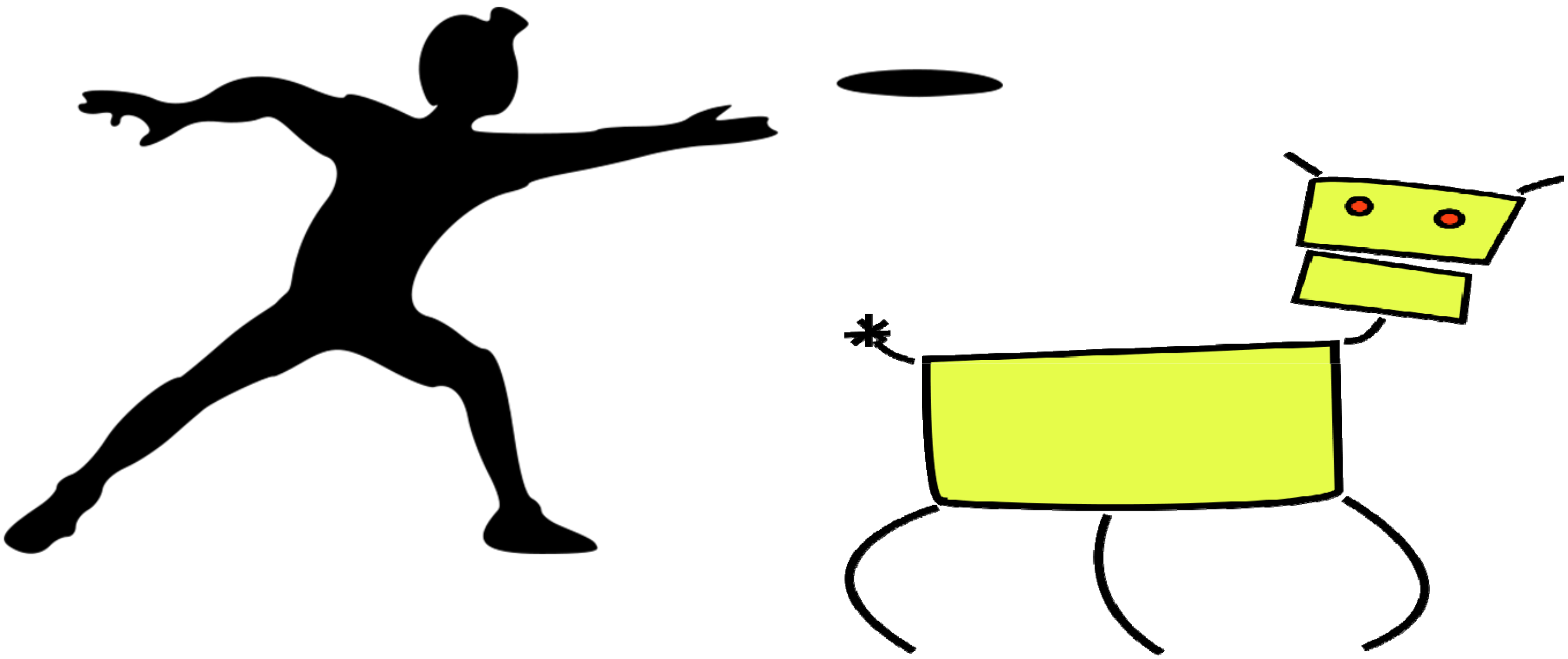


From Perlwitz and Harnik (JC 2004)

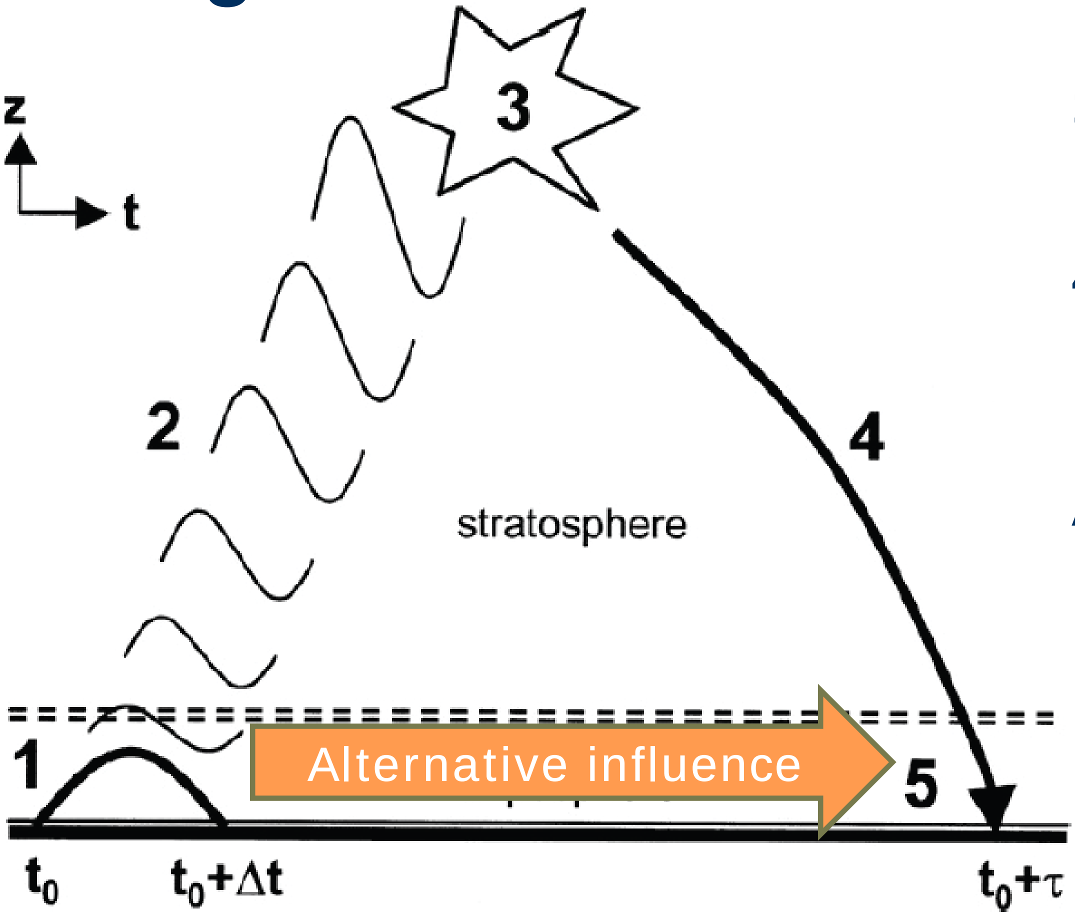
Summary: Mechanism

- Surface anomaly results from balanced wind response to stratospheric wave drag and radiative heating anomaly.
- Baroclinic eddies respond to change in wind shear at the tropopause.
- Planetary waves can be reflected back into the troposphere.

Forecasting troposphere-stratosphere coupling



Forecasting a stratospheric warming event



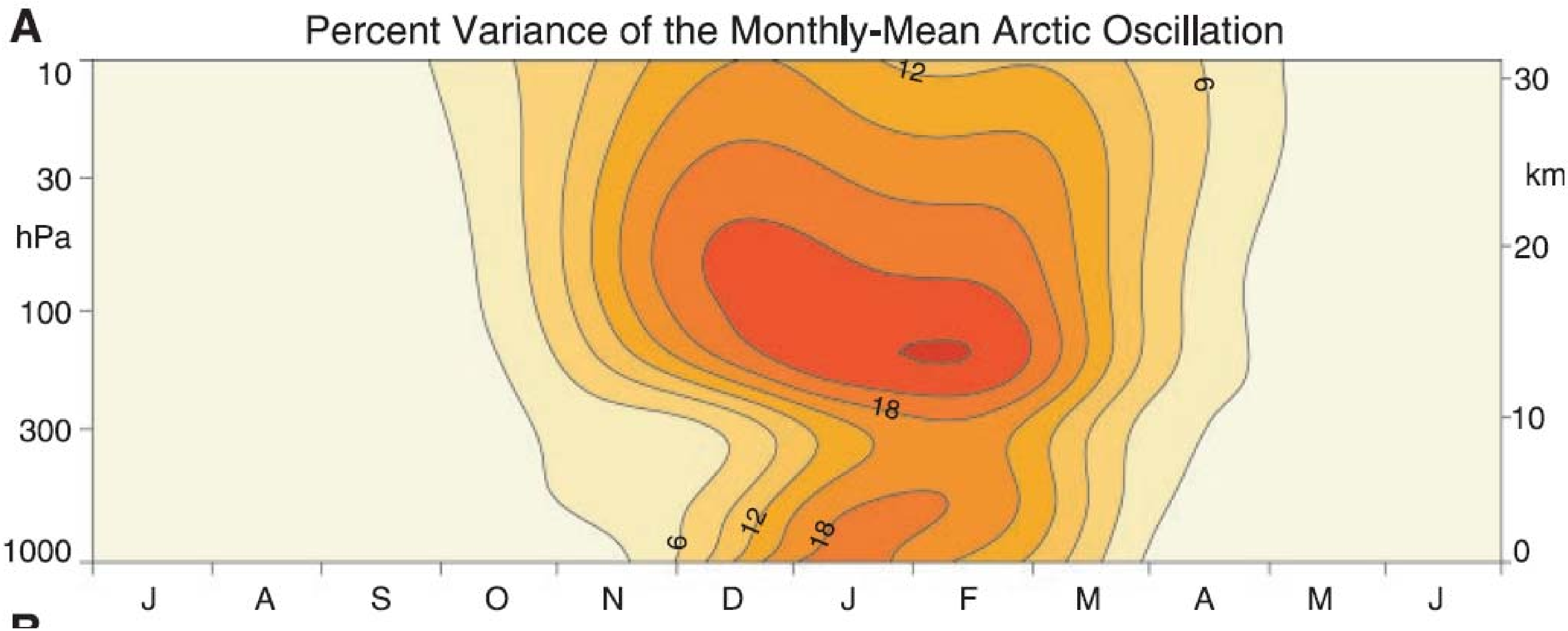
1.+2.+3. Forecast the preconditioning and growth of the warming.

4.+5. Forecast the maintenance and decay of the warming.

Alternative: Tropospheric anomaly survives long enough.

From Reichler et al. (JAS 2005)

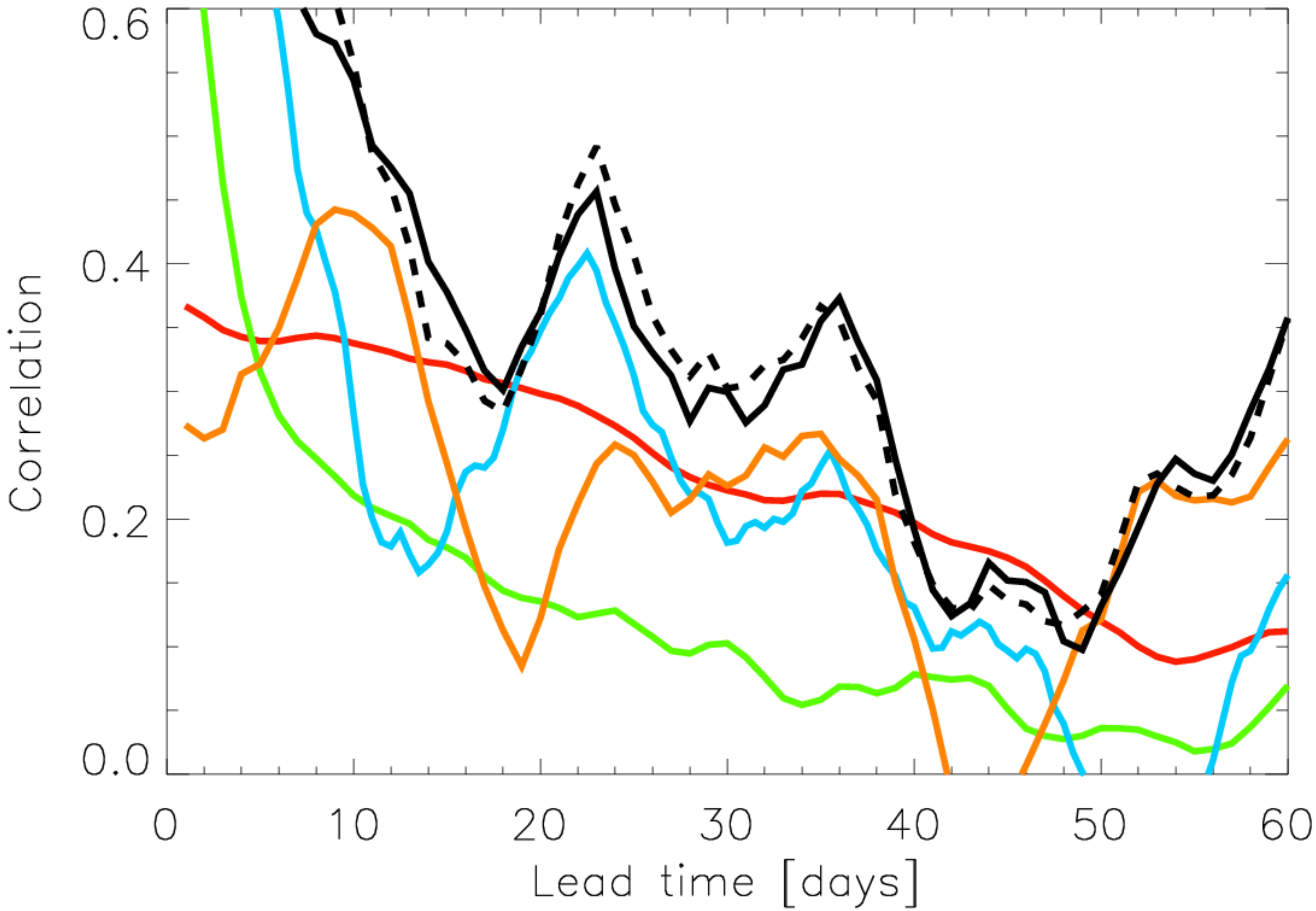
Statistical forecasting of surface AO maximes in lower stratosphere



From Baldwin et al. (Science 2003)

Using Annular Mode index yields a better monthly-mean forecast than using the surface Annular Mode (AO).

Dynamical + statistical forecast improves skill of surface wind forecast



Statistical forecast using 70hPa zonal wind **(orange)** or 1000 hPa **(green)**

Dynamical ensemble forecast (ifs, top 10hPa) **(blue)**

Combined statistical and dynamical forecast **(black solid)**

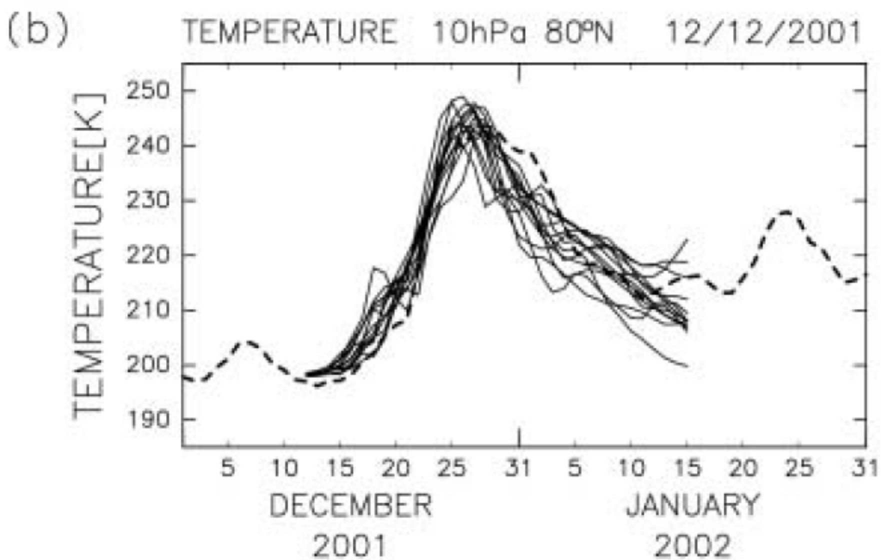
From Christiansen (JGR 2005)

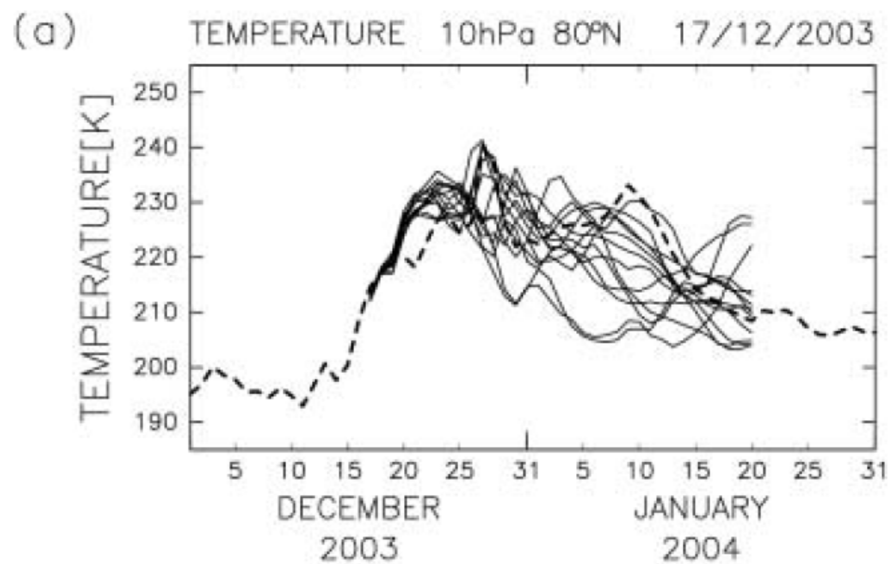
Prediction of stratopheric warmings

from Hirooka et al. (JMSJ 2007)

- One-month ensemble forecasts by the Japan Meteorological Agency (JMA-GSM0103).
- Model resolution T106, 40 levels up to 0.4 hPa.

Predictability of strat. Warming can be 16 days (2001) or only 9 days for complex situations (2003/4).



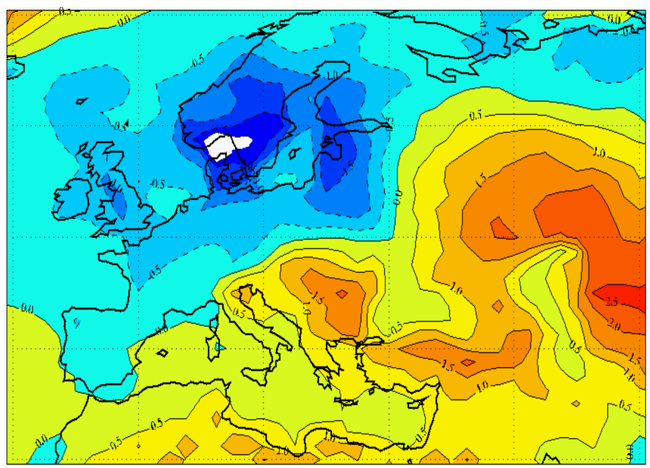


Predictability of stratospheric warmings

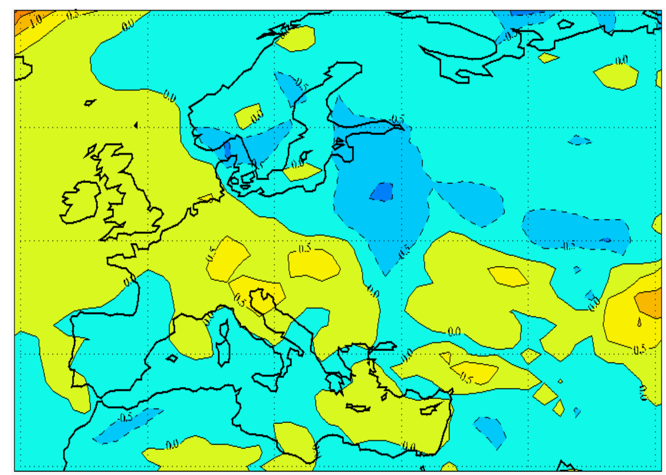
	24 Feb 1984 (Ext | Stand)	7 Dec 1987	15 Dec 1998	26 Feb 1999	Event Mean
Maximum lead time for capture (days)	13 | 5	15 | 10	12 | 12	9 | 6	**12 | 8**
Peak easterly magnitude (fraction of observed)	0.4 | 0.1	0.7 | 0.2	0.7 | 0.3	0.6 | 0.4	**0.6 | 0.3**

Improved seasonal prediction of European winter cold spells:

Extended



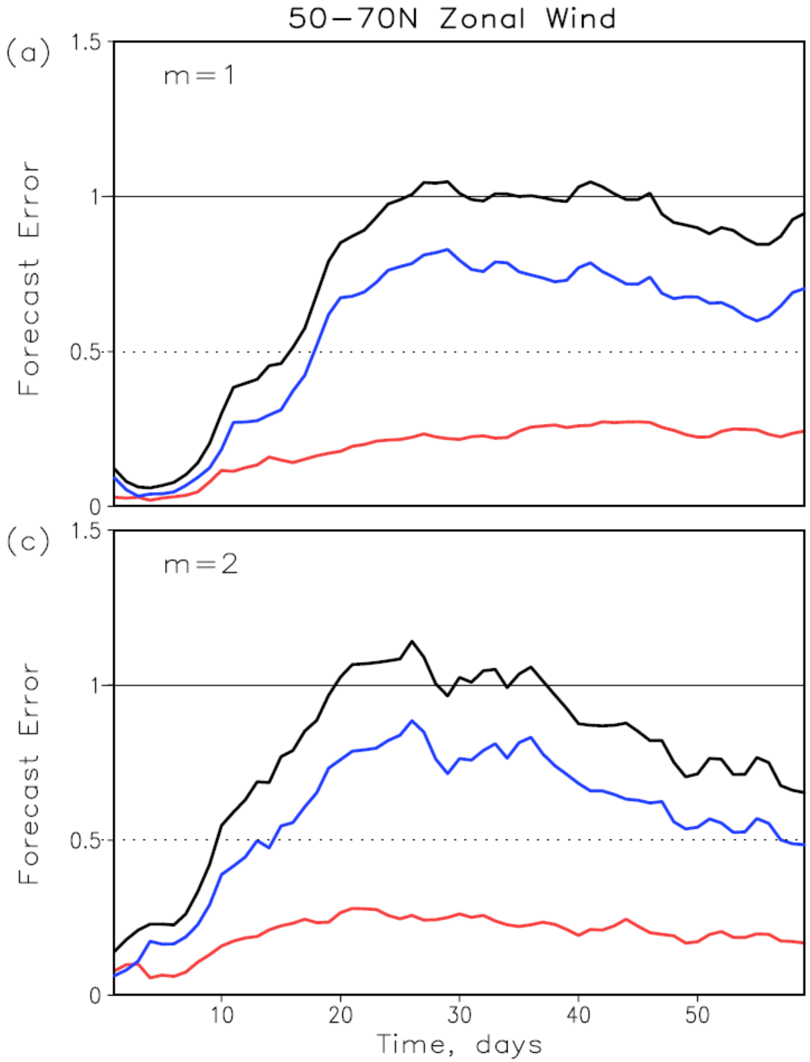
Standard



From Marshall and Scaife (JGR 2010)

Courtesy of A. Scaife

Forecast error for waves at 10 hPa for amplitude (red) and phase (blue)



NCEP Climate Forecast System Interactive Ensemble (CFSIE)
T62, 64 levels up to 0.2 hPa

10 years initialized from January 1.

Forecast error in waves results mainly from phase.

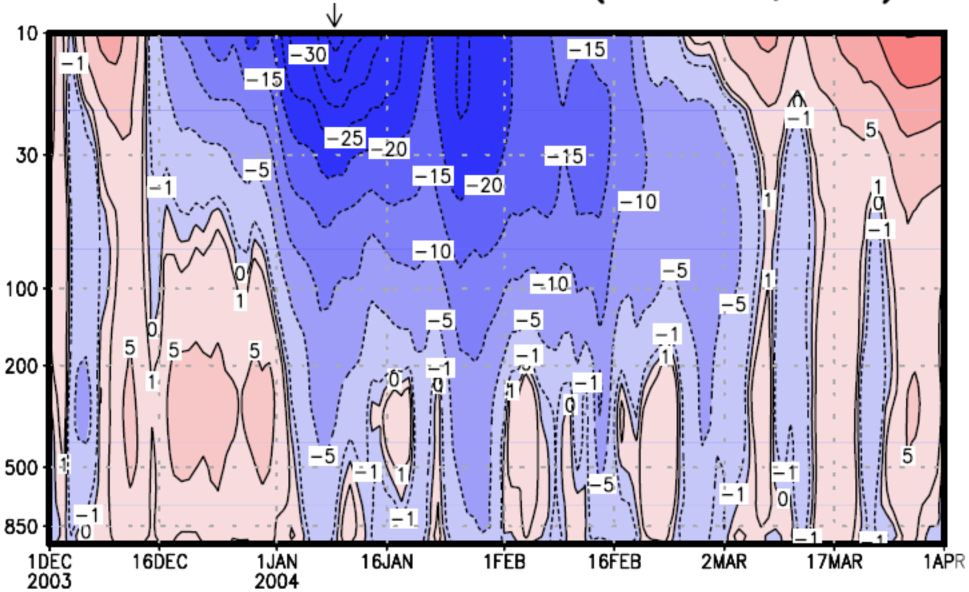
The phase errors affect the divergence of the Eliassen-Palm flux limiting the predictability of stratospheric warmings.

From Stan and Straus (JGR 2009)

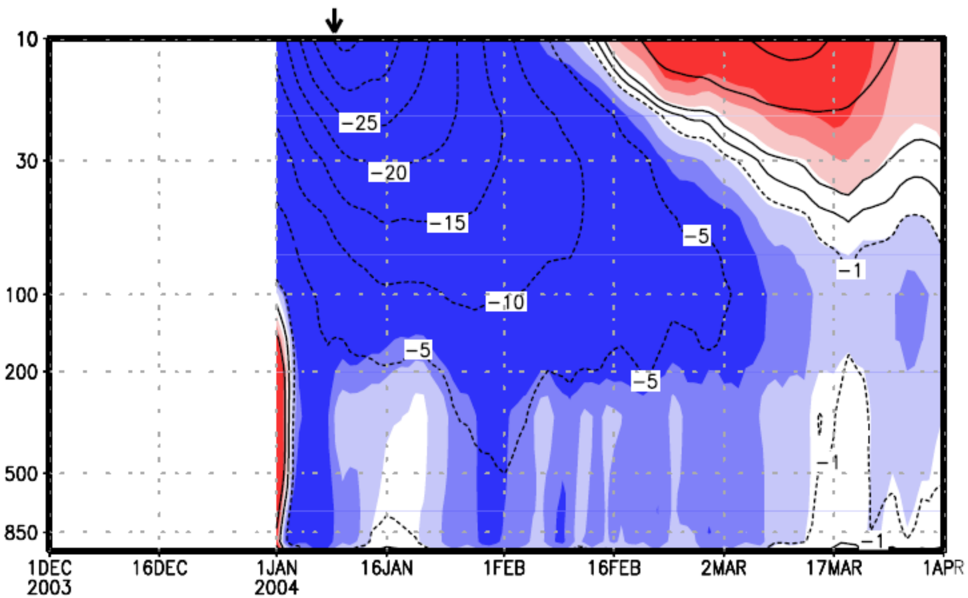
Predicting the tropospheric response

Stockholm University

Anomalous zonal wind (55–65N, Obs)



Forecasted anomalous zonal wind



From Kuroda (GRL 2008)

JMA-model, T95, 40 levels up to 0.4 hPa.

Stratospheric predictability: 3 months.

Tropospheric predicitability: 2 months

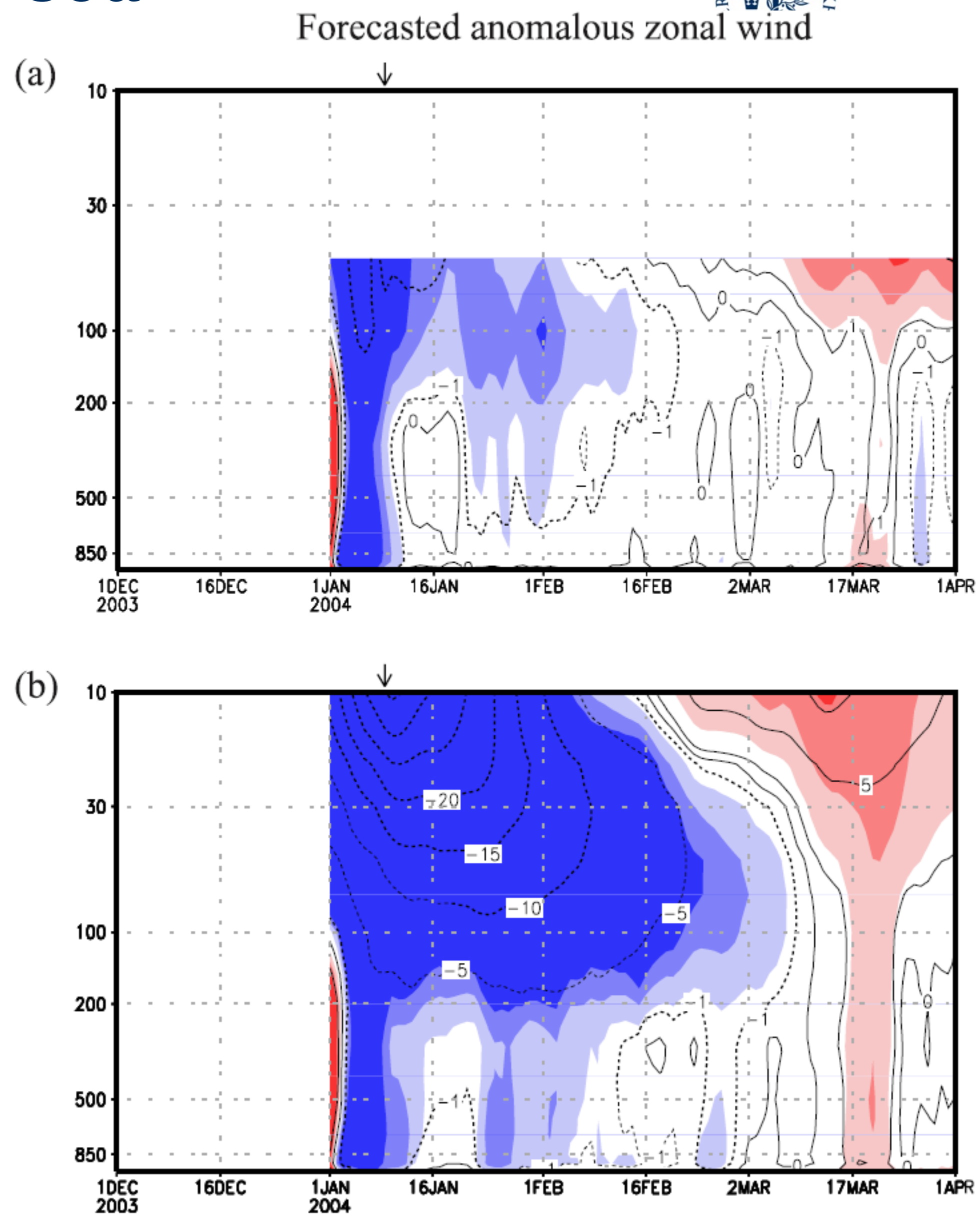
Role of model-top and sea surface temperatures

Low model-top

Tropospheric predictability strongly reduced.

Climatological SST

Stratospheric extension provides improved tropospheric predictability.

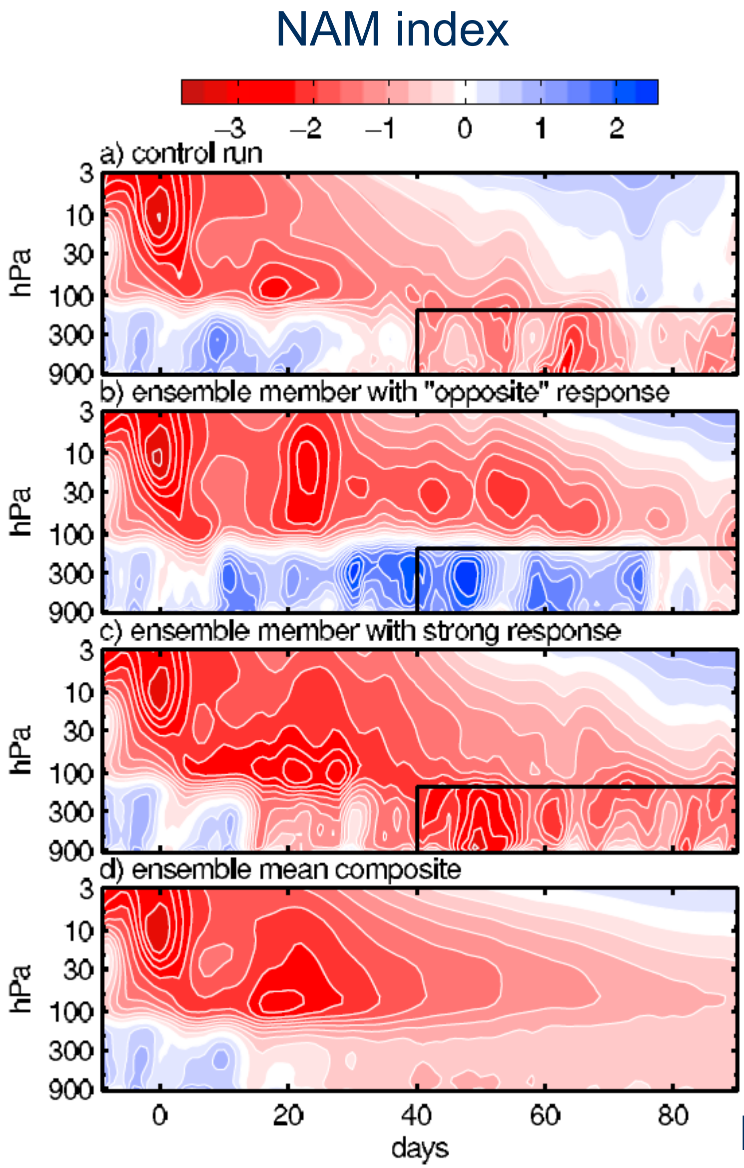


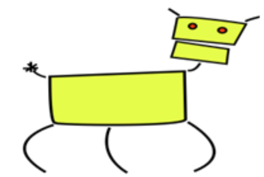
From Kuroda (GRL 2008)

Tropospheric persistence?

Cases:
12

88





- Idealized GCM
- T42, 40 levels up to 0.7 hPa

- Initialize forecast 10 days before major warming with perturbed tropospheres.

- Tropospheric response depends on ”deepness” of stratospheric warming.

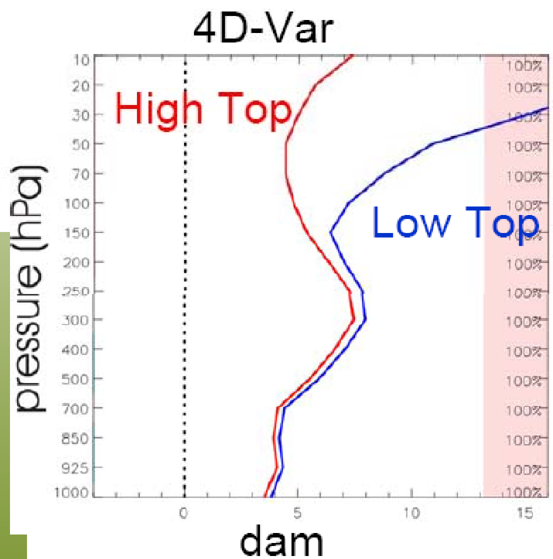
- Downward propagation to troposphere only, if tropospheric NAM is neutral or positive; otherwise troposphere responds simultaneously.

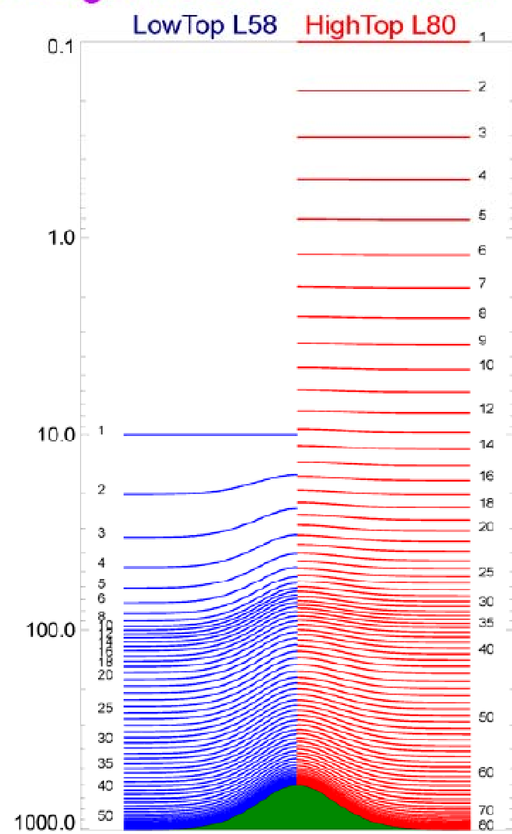
From Gerber (GRL 2009)

Improving the stratosphere improves 5-day forecasts in the troposphere

On June 22, 2009 Canadian Meteorological Centre implemented operationally a global stratospheric model (0.1 hPa) for medium range weather forecasts

O-F(5 day) against NH sondes for GZ





Winter

Dec. 20 – Jan. 26, 2006 (75 cases)

Environment Canada Environnement Canada

Canada

From S. Polavarapu (SPARC-DA workshop 2010)

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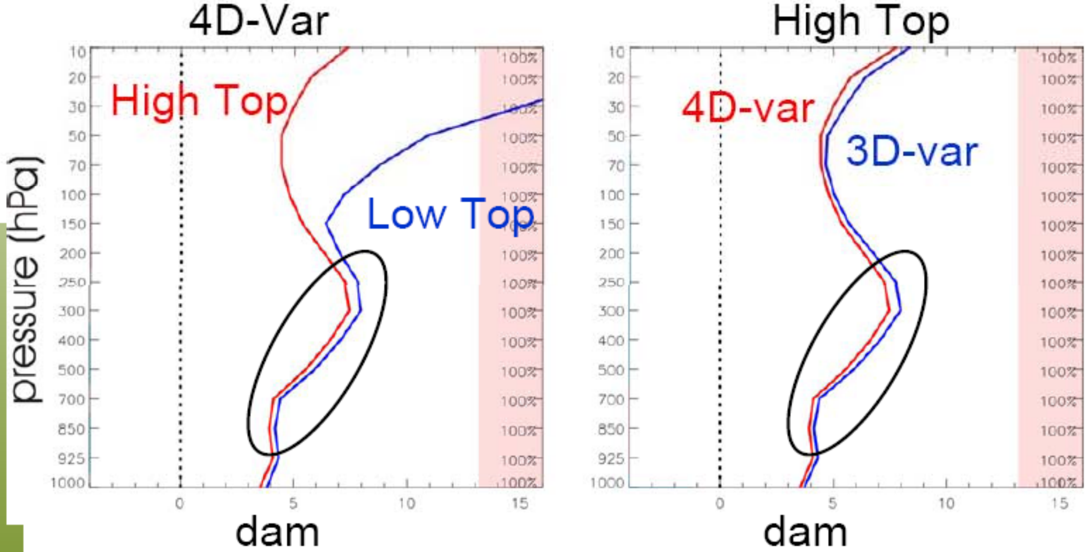


A good stratosphere impacts troposphere forecasts as much as 4D-Var

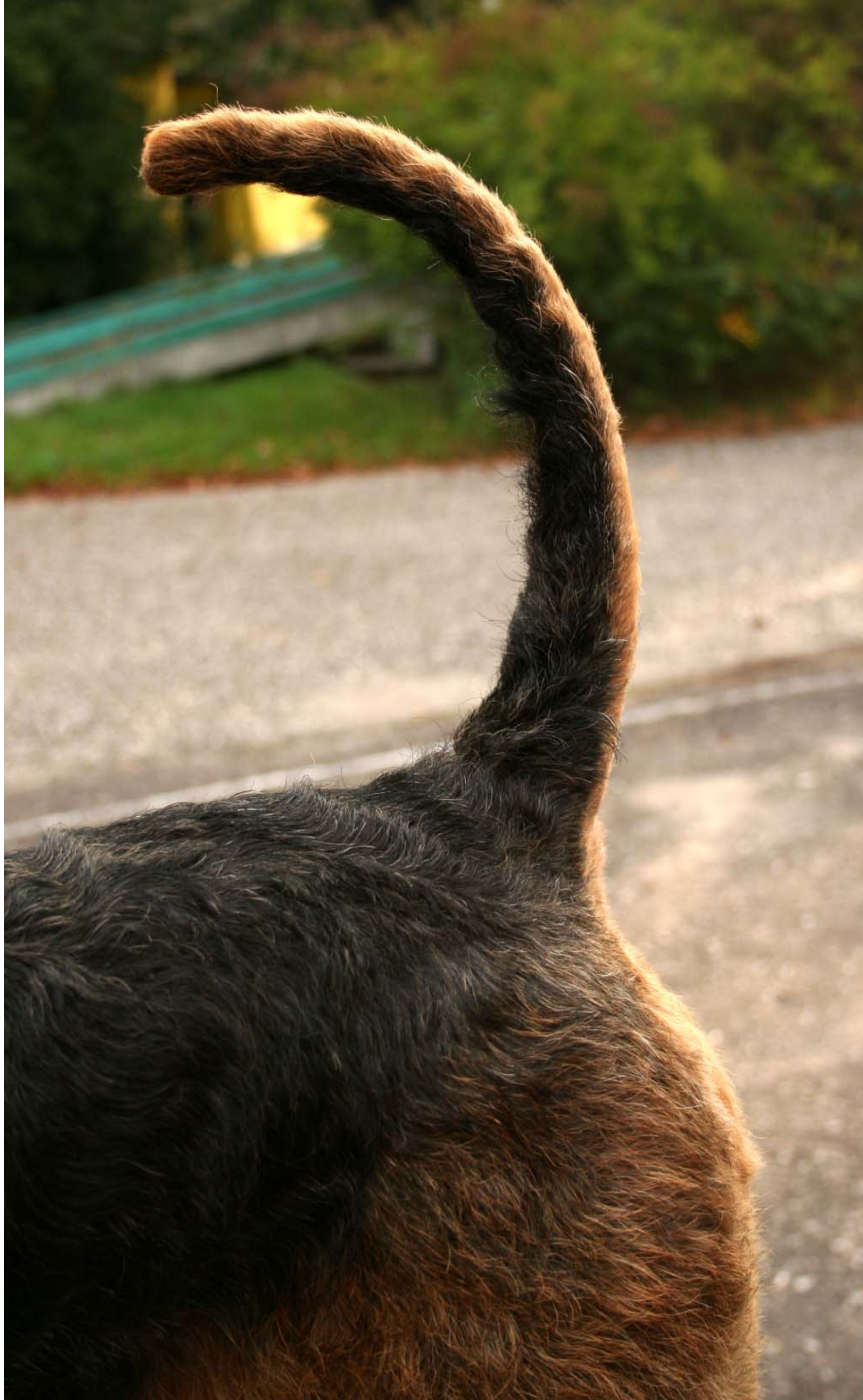
Winter

Dec. 20 – Jan. 26, 2006 (75 cases)

From S. Polavarapu (SPARC-DA workshop 2010)

Conclusions

- Impact bottom-up:
  - Planetary waves propagate upwards.
  - Predictability limited by troposphere to 20 days.
- Impact top-down:
  - Downward propagation of stratospheric wind anomaly.
  - It provides tropospheric predictability of 2-3 months.



Things not covered

- Gravity waves
- Stratospheric chemistry
- Climate change
- …

Acknowledgements

- Adam Scaife
- Andrew Charlton-Perez
- Saroja Polavarapu