On the Northern Annular Mode surface signal associated with stratospheric variability

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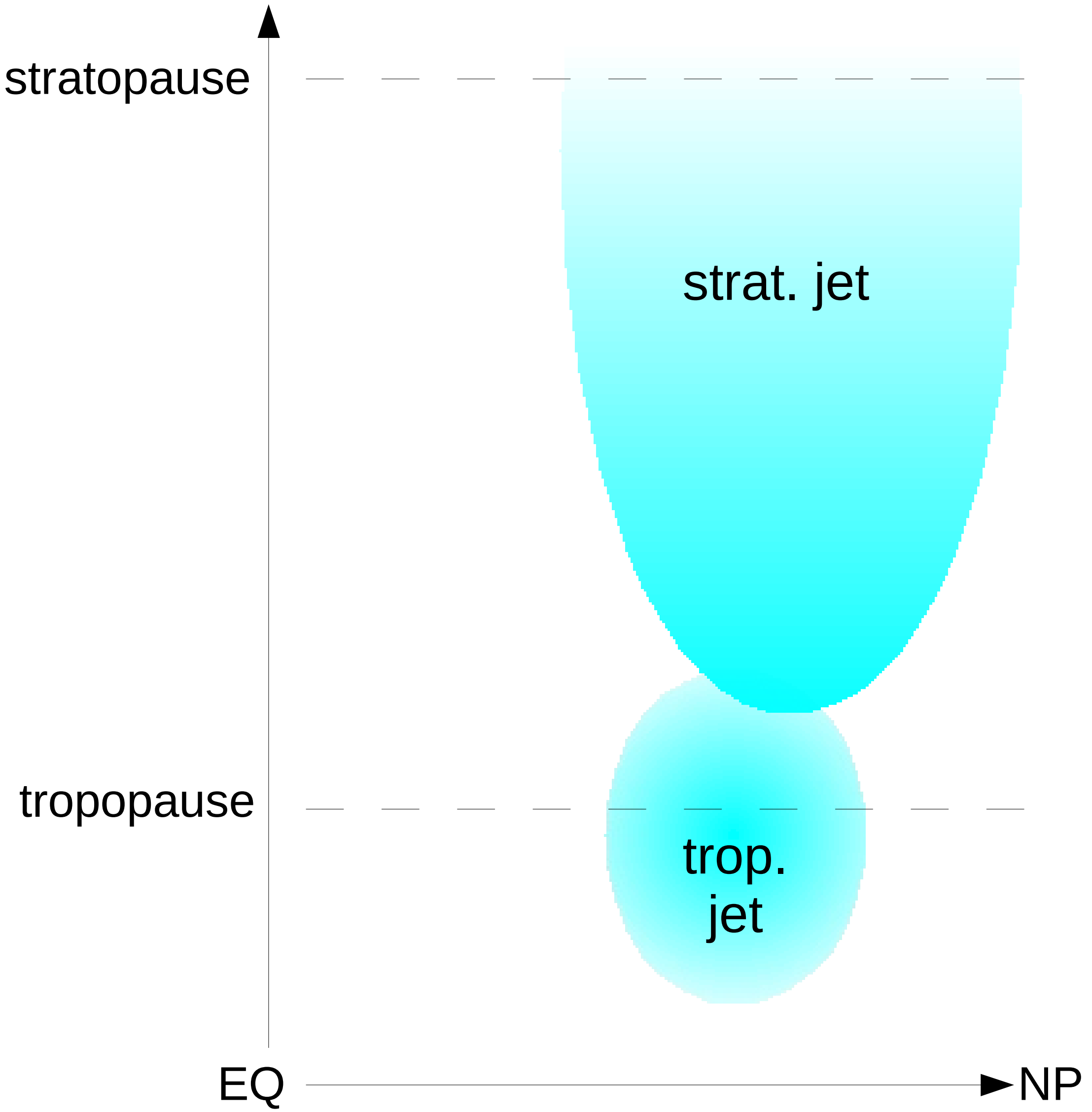
(Kunz and Greatbatch, 2013, JAS, accepted)

Motivation & Background

Dynamics of Strat-Trop coupling

- strat. polar night jet (PV gradient)



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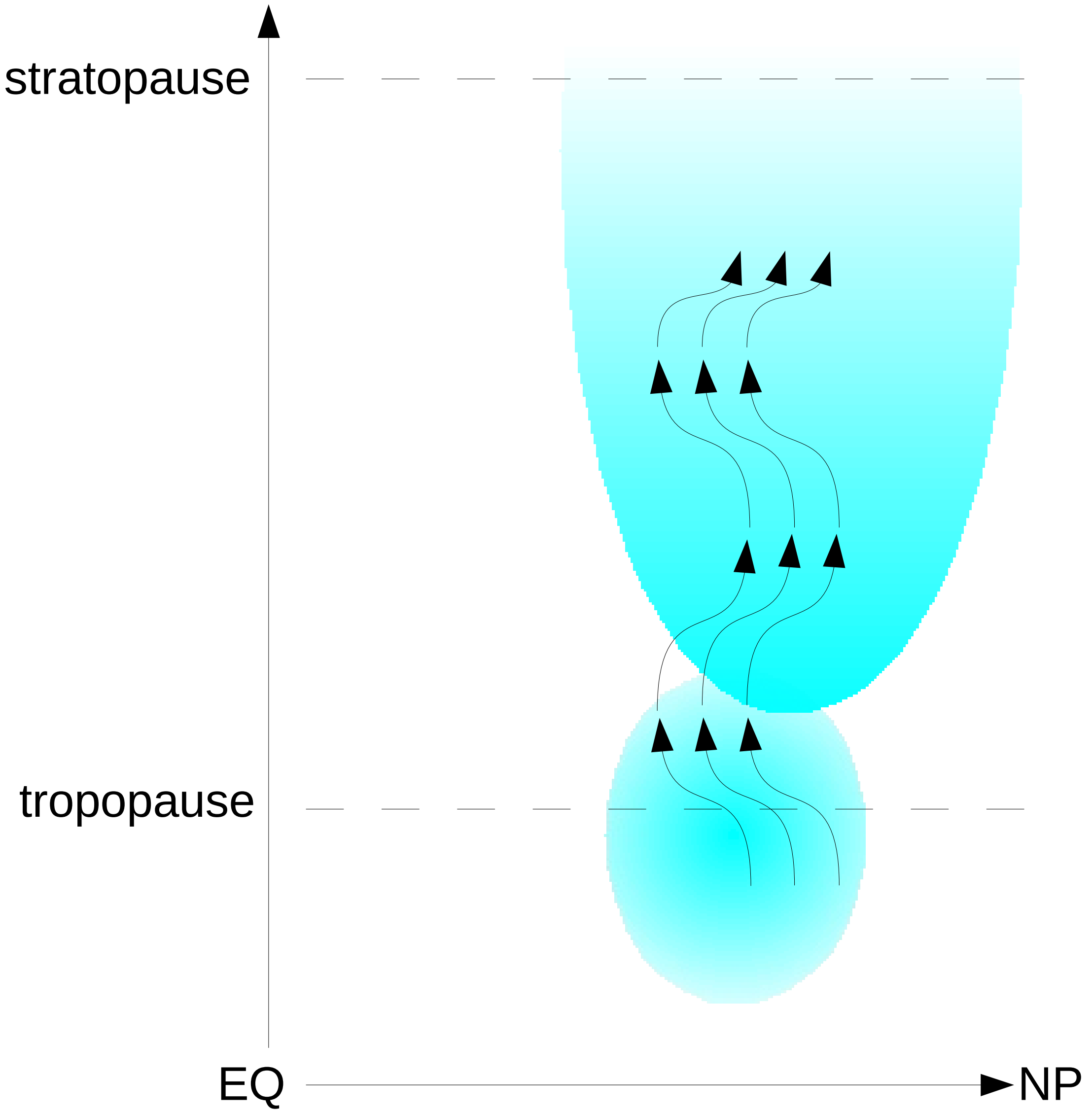
- strat. polar night jet (PV gradient) allows upward propagating planetary / gravity waves of trop. origin



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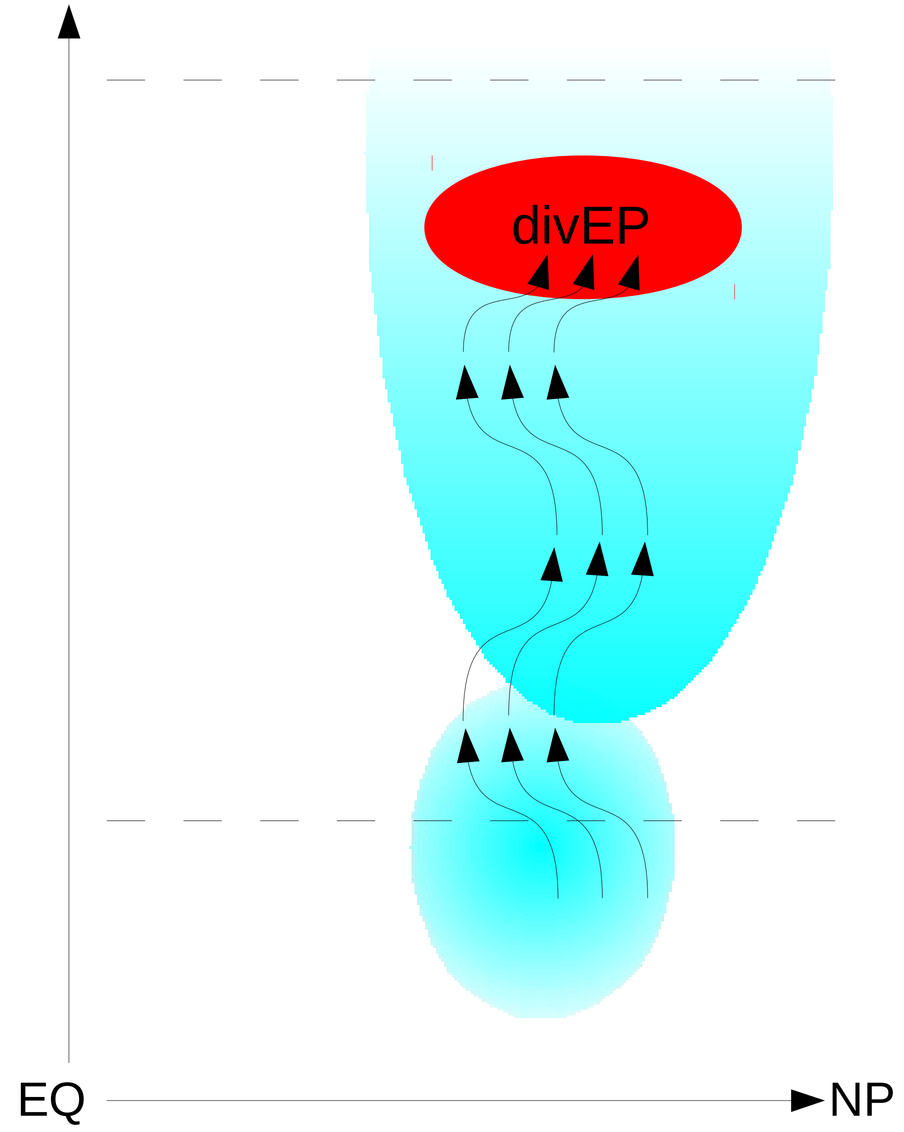
- strat. wave drag variability

  ➡ strat. NAM variability



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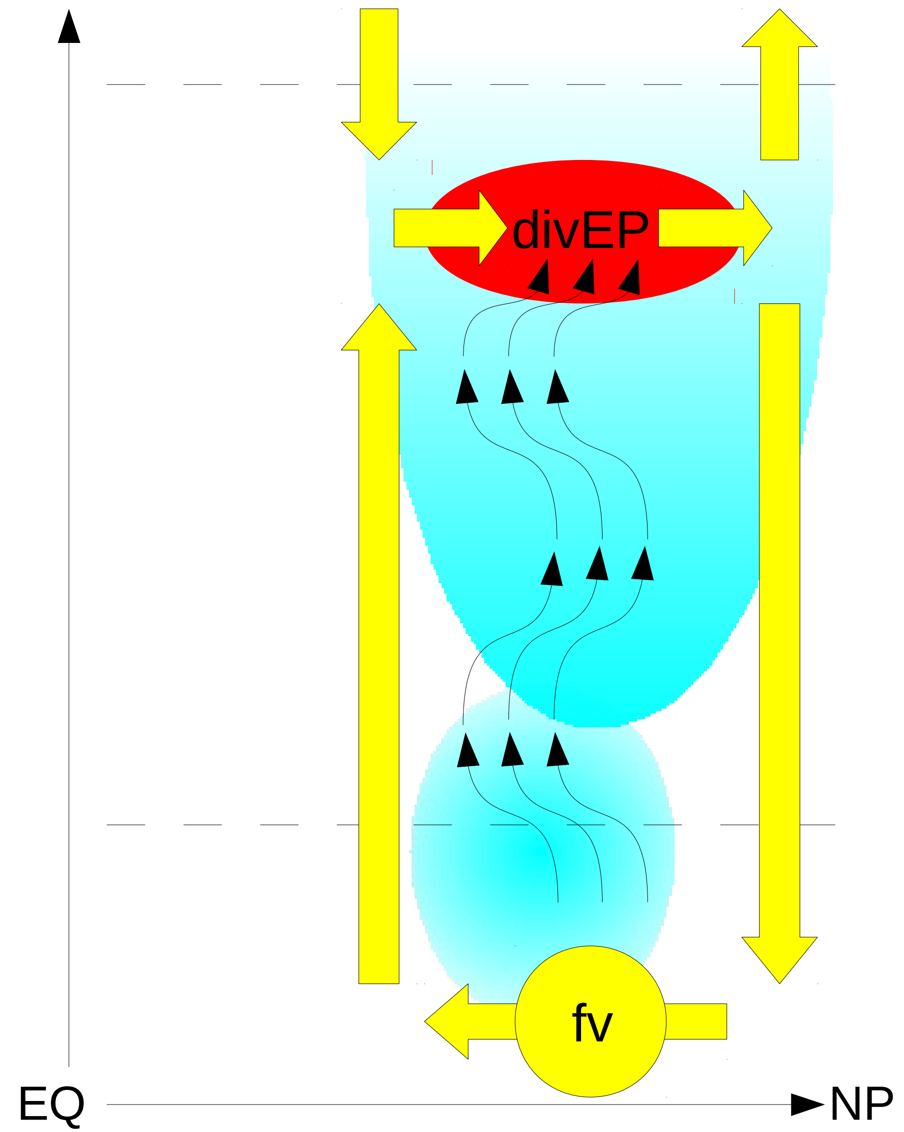
  → strat. NAM variability

- QG adjustment (to wave drag)
  → trop. NAM variability



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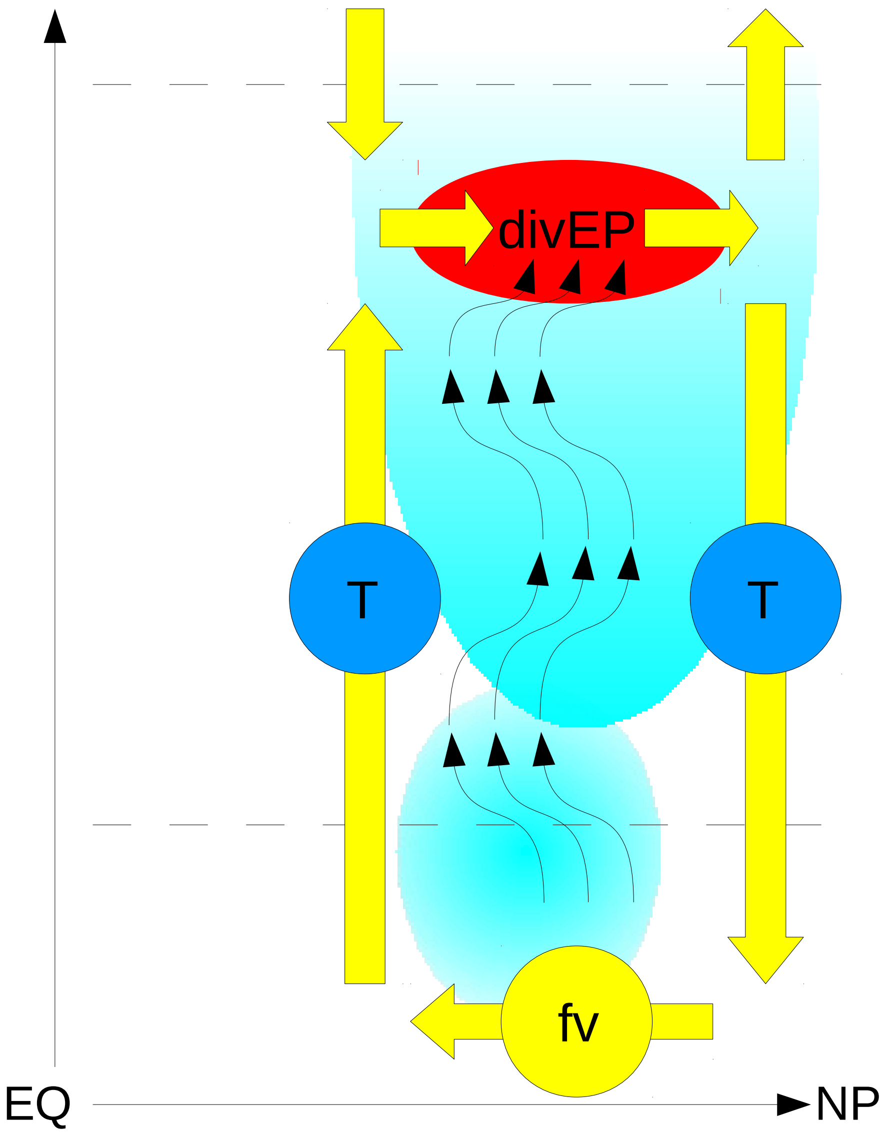

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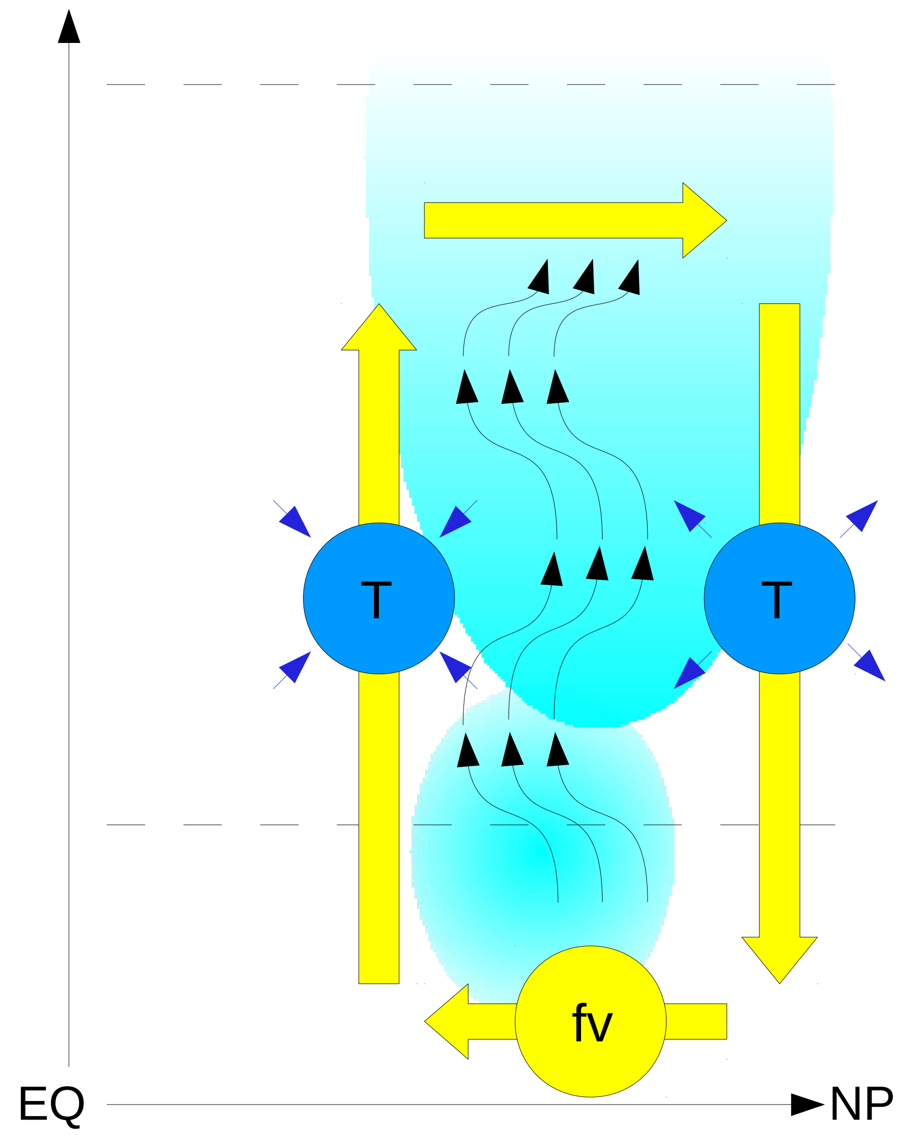

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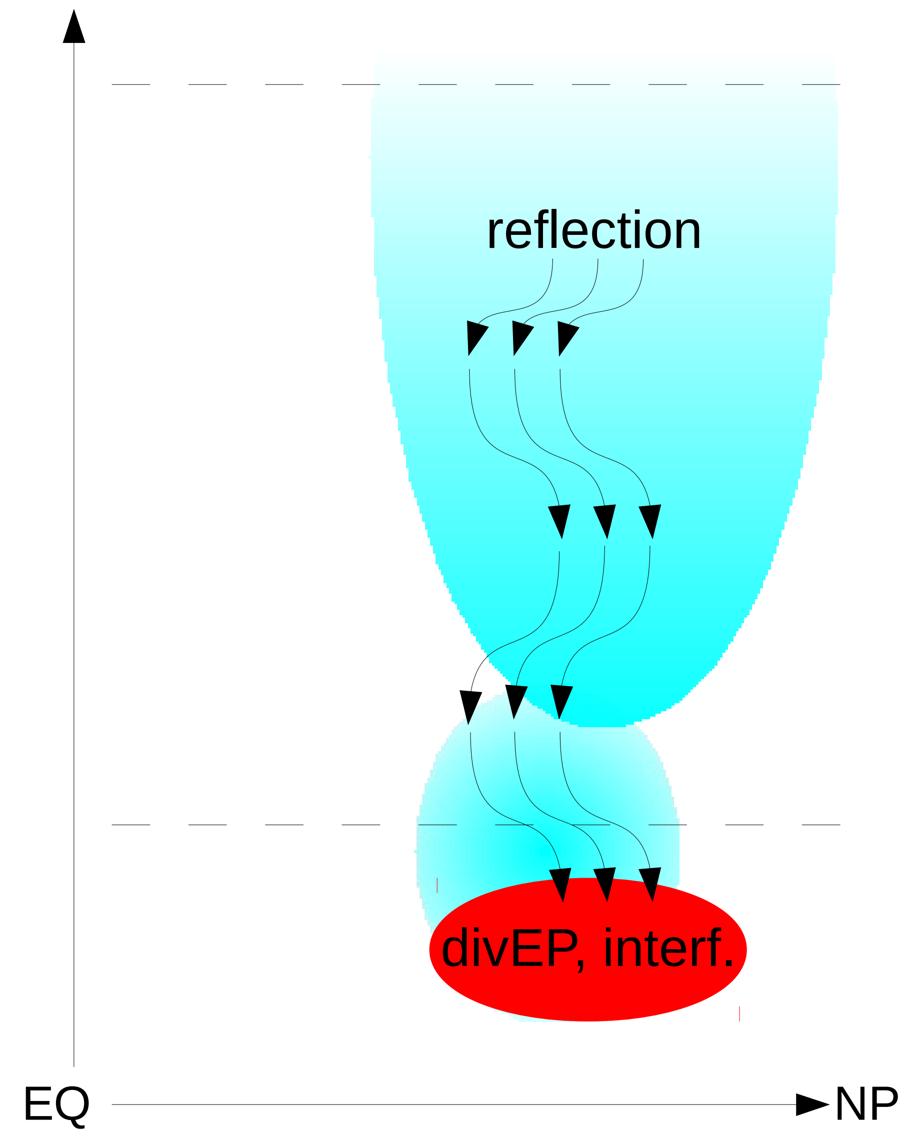
- wave reflection
- trop. wave drag/interference
  ➡ trop. NAM variability



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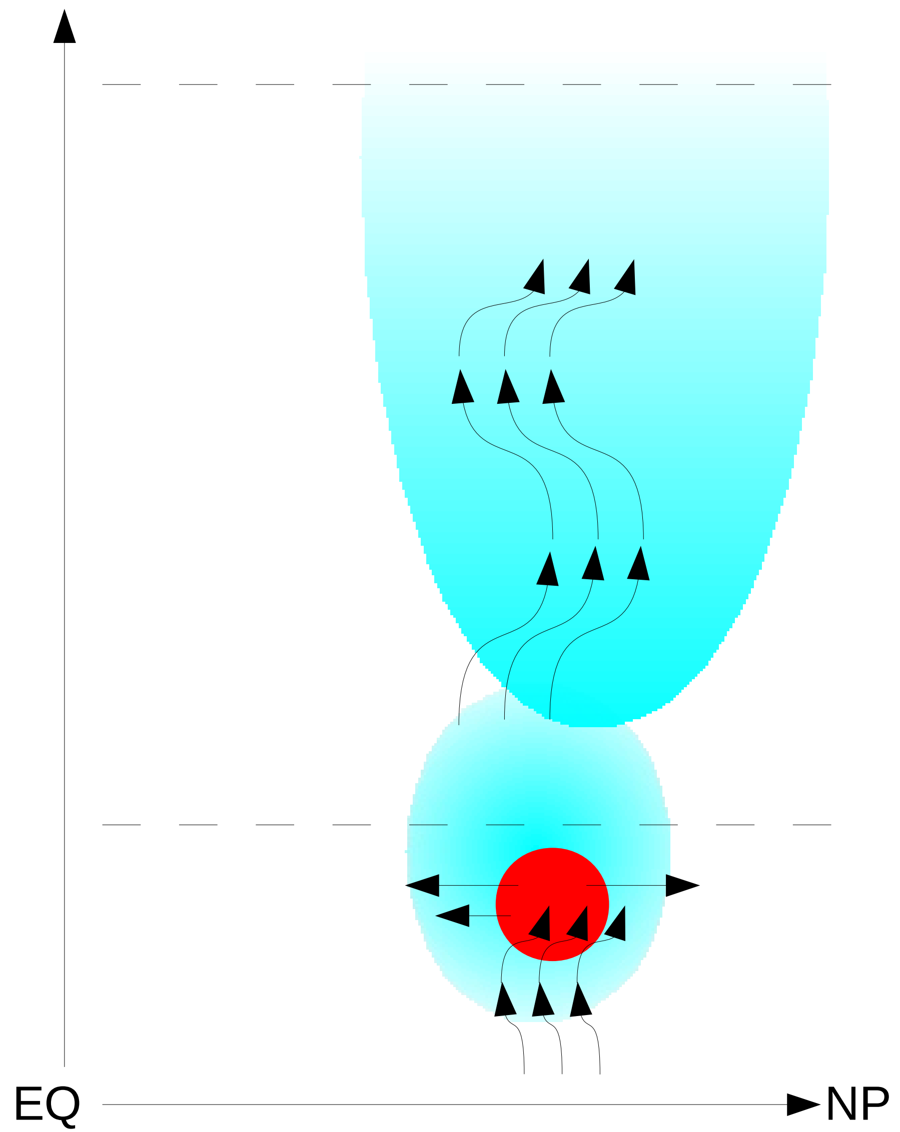

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} QG adjustment to strat. wave drag and strat. thermal damping

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} wave drag local to the troposphere

Motivation & Background

NAM surface signal associated with stratospheric variability

Key Question:

What are the relative roles of

(i) QG adjustment to stratospheric wave drag and thermal damping and

(ii) wave drag local to the troposphere?

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Strategy:

***** spectral QG zonal mean zonal wind equation (tidal theory)

Step-1: feed obs. NAM to model ➡ obtain mechanical NAM forcing

Step-2: integrate eq. in time forced only at

strat. levels ➡ NAM surf. signal due to strat. QG adjustment

trop. levels ➡ NAM surf. signal due to local trop. wave drag

***** linear regression analysis of trop. NAM against mid-strat. NAM

Outline

(1) Methodology

ERA-40 NAM, QG model equations

(2) Results

Decompose NAM surface signal (Strat vs. Trop)

(3) Conclusions & Discussion

Summary of results, Limitations of approach

(1) Methodology

Daily NAM index (separately for each pressure level)

(1) subtract seasonal cycle from daily zonally averaged Z fields (ERA40, 1957-2002, 00 UTC, 23 levels from 1000 to 1 hPa)

(2) EOF-1 from DJFM monthly mean anomalies north of 20°N

(3) project NDJFMA daily anomalies onto EOF-1, and norm. ($\mu = 0$, $\sigma^2 = 1$)

➡ **daily NAM index time series**

(4) regress daily anomaly fields onto NAM time series

➡ **NAM pattern**

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daily variance explained by NAM:	troposphere	~50 %
	stratosphere	~80 %

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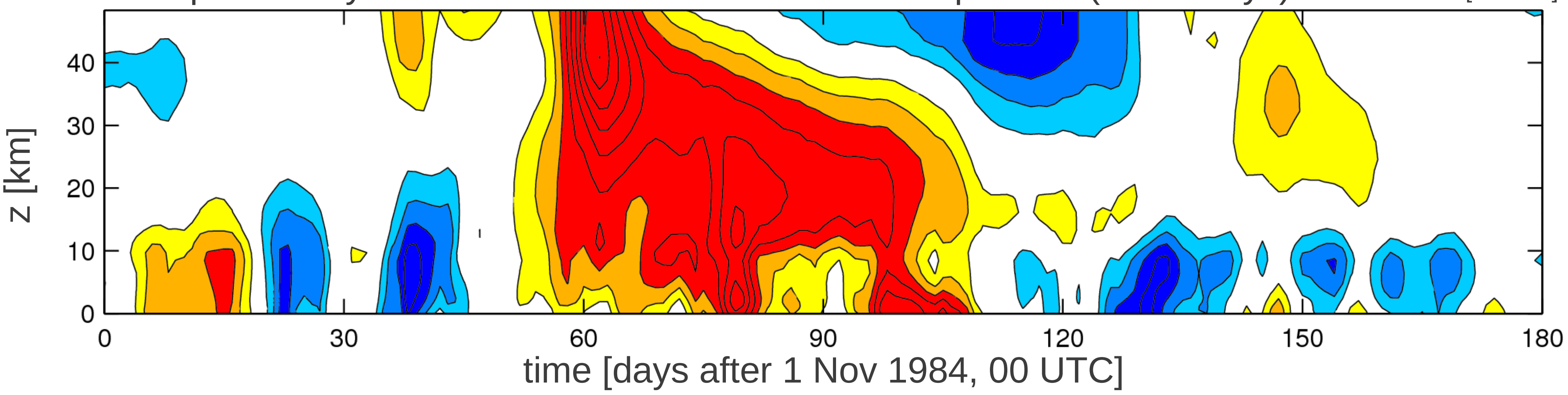
sample of daily NAM index from 1 Nov 1984 to 30 Apr 1985 (= 181 days) [Δ=0.5σ]



(1) Methodology

QG TEM equations, in spherical and log-pressure coordinates:

$$\bar{u}_t - f\bar{v}^* = \bar{F} - \kappa\bar{u}$$
$$f\bar{u} + a^{-1}\bar{\Phi}_\phi = 0$$
$$-RH^{-1}\bar{T} + \bar{\Phi}_z = 0$$
$$\bar{T}_t + N^2HR^{-1}\bar{w}^* = \bar{Q} - \alpha\bar{T}$$
$$(a\cos\phi)^{-1}(\bar{v}^*\cos\phi)_\phi + \rho_0^{-1}(\rho_0\bar{w}^*)_z = 0,$$

Zonal mean anomalies from climatological mean seasonal cycle

$\alpha(z)$: Newtonian cooling coefficient
$\kappa(z)$: Rayleigh drag coefficient

$\bar{Q}$: External thermal forcing
$\bar{F}$: External mechanical forcing

(1) Methodology

Combine Eqs. into elliptic PDE (analog. to QGPV tend. Eq.):

$$\frac{1}{4\Omega^2 a^2}\mathcal{L}_2^\phi \mathcal{L}_1^\phi u_t + \mathcal{L}_1^z \mathcal{L}_2^z u_t = \frac{1}{4\Omega^2 a^2}\,\mathcal{L}_2^\phi \mathcal{L}_1^\phi (F - \kappa u) + \mathcal{L}_1^z \mathcal{L}_2^z (Q_* - \alpha u)$$

---

with the linear differential operators

$$\mathcal{L}_1^\phi(\,\cdot\,) \equiv \frac{1}{\sqrt{\cos\phi}}\frac{\partial}{\partial\phi}\left[\frac{\sqrt{\cos\phi}}{\sin\phi}(\,\cdot\,)\right], \quad \mathcal{L}_2^\phi(\,\cdot\,) \equiv \frac{\sqrt{\cos\phi}}{\sin\phi}\frac{\partial}{\partial\phi}\left[\frac{1}{\sqrt{\cos\phi}}(\,\cdot\,)\right],$$

$$\mathcal{L}_1^z(\,\cdot\,) \equiv \frac{1}{\sqrt{\rho_0}}\frac{\partial}{\partial z}\left[\frac{\sqrt{\rho_0}}{N}(\,\cdot\,)\right], \quad \mathcal{L}_2^z(\,\cdot\,) \equiv \frac{\sqrt{\rho_0}}{N}\frac{\partial}{\partial z}\left[\frac{1}{\sqrt{\rho_0}}(\,\cdot\,)\right],$$

and the modified variables

$$u = \mu\bar{u}, \qquad F = \mu\bar{F}, \qquad Q_* = \mu\bar{Q}_*,$$

where $\mu = \sqrt{\cos\phi\;\rho_0}$ and $\bar{Q}_*(\phi, z) = -R/(Hfa)\int_0^z \bar{Q}_\phi(\phi, z')dz'$.

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Set $F = Q_* = 0$ and $\alpha =$ const, $\kappa =$ const

Separate ϕ- from z-dependence (tidal theory), according to

$$u(\phi, z, t) \propto \exp(-\sigma t) U(\phi) Z(z)$$

➡ two eigenvalue equations:

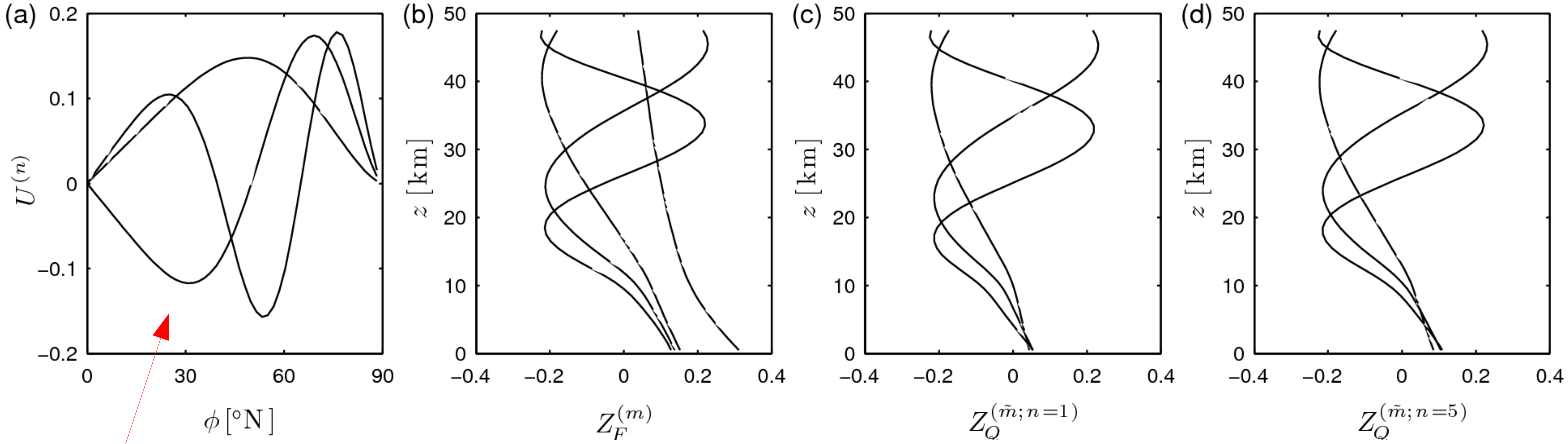
HSE: $\mathcal{L}_2^\phi \mathcal{L}_1^\phi U - \epsilon U = 0$

VSE: $\mathcal{L}_1^z \mathcal{L}_2^z Z - \gamma Z = 0$

BCs ➡ eigenmodes $U^{(n)}(\phi)$, $Z_F^{(m)}(z)$, $Z_Q^{(\tilde{m};n)}$, eigenval. $\epsilon < 0$, $\gamma < 0$

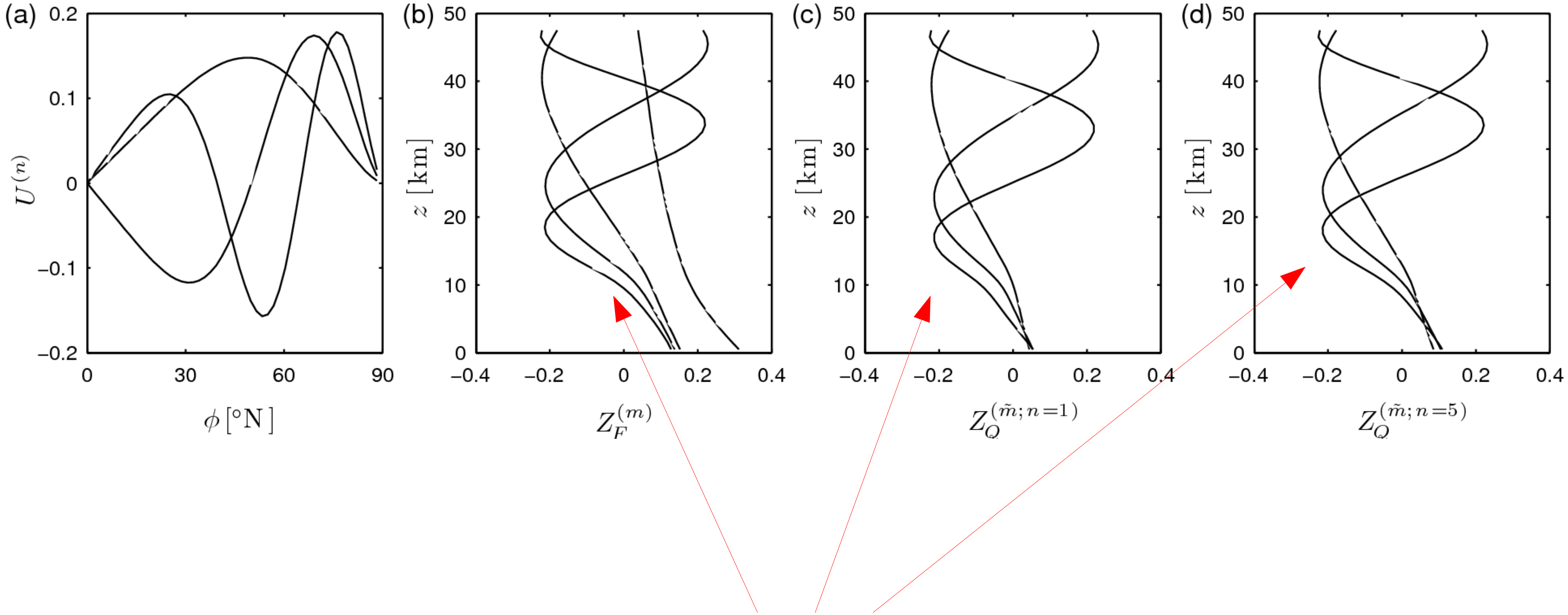
Diff. LBC for mech. / therm. damping ➡ n-dep. for therm. damp.

(1) Methodology



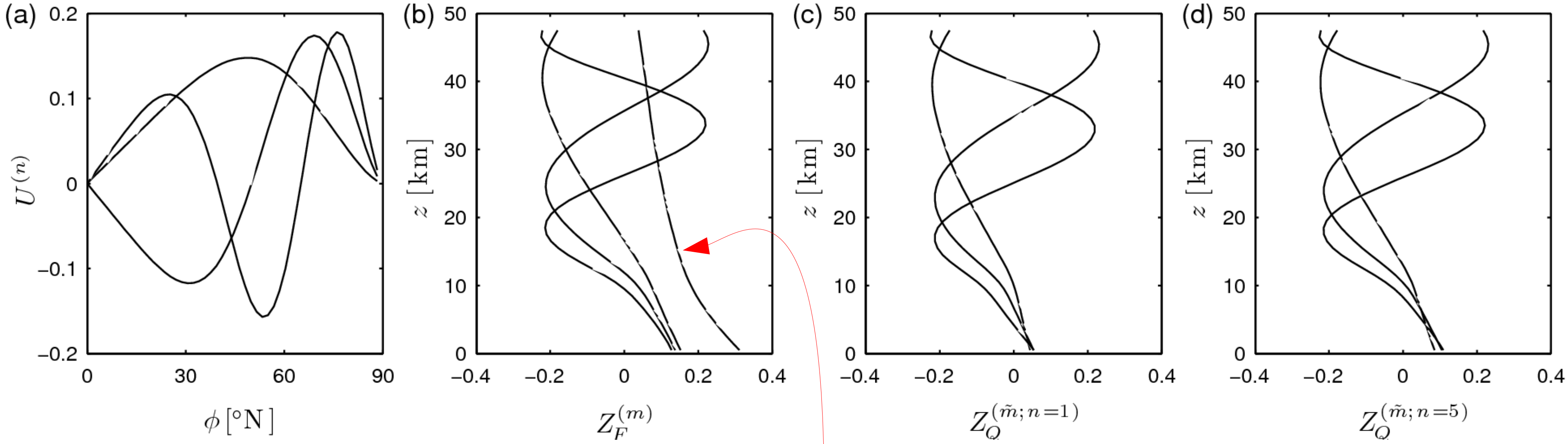
Hough functions

(1) Methodology



Vertical structure functions

(1) Methodology



Lamb mode (external)

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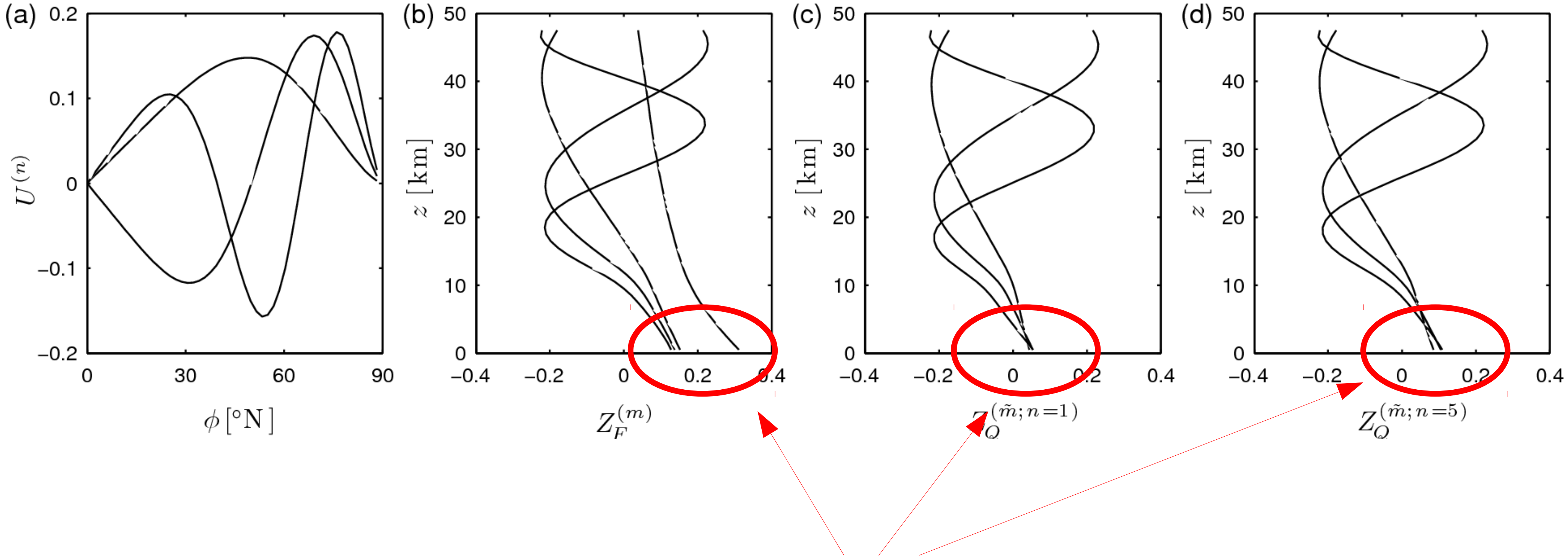

- LBC takes different forms (depend. on type of forcing)

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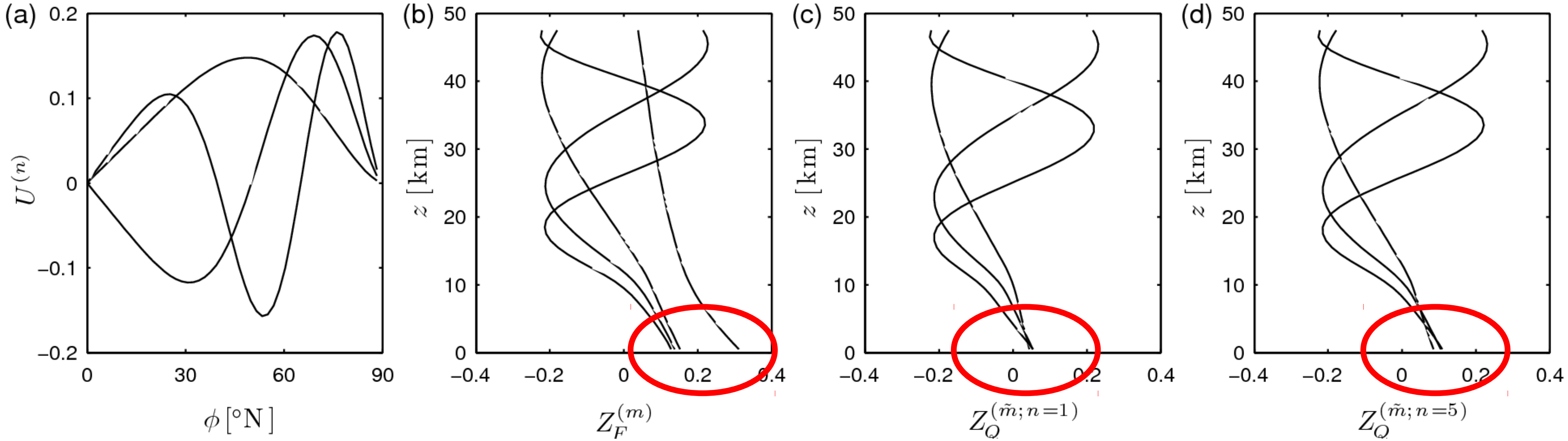

- LBC takes different forms (depend. on type of forcing)
- simplified LBC ➡ neglect surface eddy heat fluxes

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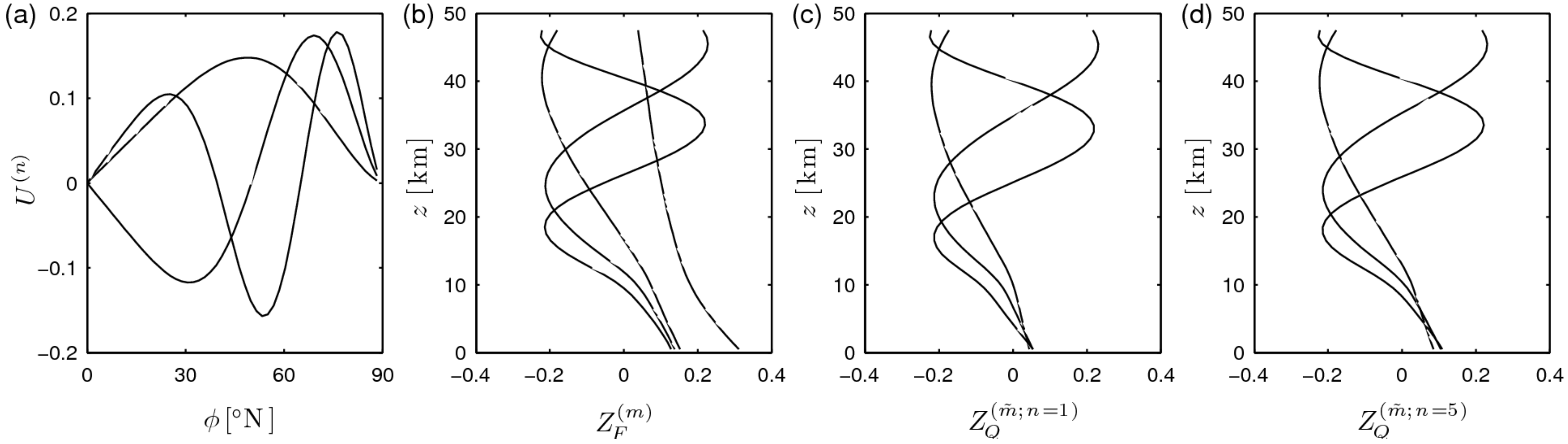

Expansions:

$$X(\phi, z, t) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \hat{X}^{(m,n)}(t) U^{(n)}(\phi) Z_F^{(m)}(z)$$

$$X(\phi, z, t) = \sum_{\tilde{m}=1}^{\infty} \sum_{n=1}^{\infty} \hat{X}^{(\tilde{m},n)}(t) U^{(n)}(\phi) Z_Q^{(\tilde{m};n)}(z)$$

Project elliptic PDE onto modes $UZ(\phi, z)$ ➡ spectral u tend. equation

(1) Methodology

Spectral zonal wind tendency equation (arbitr. $\alpha(z)$, $\kappa(z)$, neglect Q_*):

$$\hat{u}_t^{(m,n)} = \left(\hat{F}^{(m,n)} - \widehat{\kappa u}^{(m,n)}\right) r_F^{(m,n)} - \mathcal{B}^{(m,n)}\left(\widehat{\alpha u}^{(\tilde{m},n)} r_Q^{(\tilde{m},n)}\right)$$

---

with the operator

$$\mathcal{B}^{(m,n)}(\,\cdot\,) \equiv \int_0^{z_t} \left(\sum_{\tilde{m}=1}^{\infty} (\,\cdot\,) Z_Q^{(\tilde{m};n)}\right) Z_F^{(m)} dz$$

and the QG adjustment terms (where $\lambda = -4\Omega^2 a^2 \gamma$)

$$r_F^{(m,n)} = (1 - \lambda_F^{(m)}/\epsilon^{(n)})^{-1} \quad \text{and} \quad r_Q^{(\tilde{m},n)} = (1 - \epsilon^{(n)}/\lambda_Q^{(\tilde{m};n)})^{-1}$$

$$\hat{F}^{(m,n)} = \left[\hat{u}_t^{(m,n)} + \mathcal{B}^{(m,n)}\left(\widehat{\alpha u}^{(\tilde{m},n)} r_Q^{(\tilde{m},n)}\right)\right] / r_F^{(m,n)} + \widehat{\kappa u}^{(m,n)}$$

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Step-1: obtain *F* from NAM (u_{NAM})

- *F* represents wave drag
- but also incl. non-QG eff., negl. *Q*

Step-2: obtain NAM from *F*

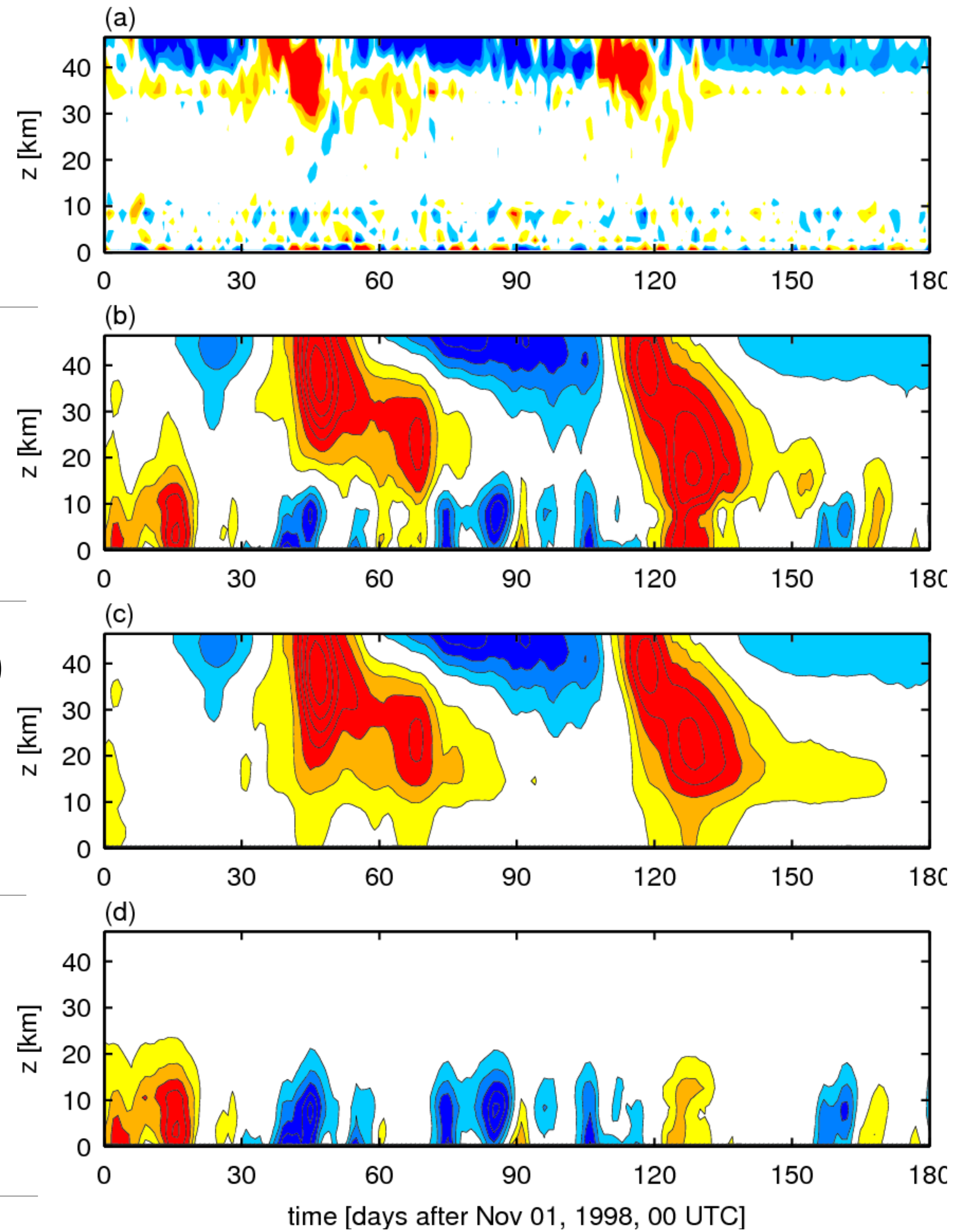
- by constr. ident. to ERA-40 NAM
- two major SSWs during 1998/99

- *F* restricted to strat. (abv. 100 hPa)

➡ trop. NAM due to strat. QG adjustment

- *F* restricted to trop. (bel. 100 hPa)

➡ trop. NAM due to local trop. wave drag



(USSA N^2, surface drag, varying therm. damping)

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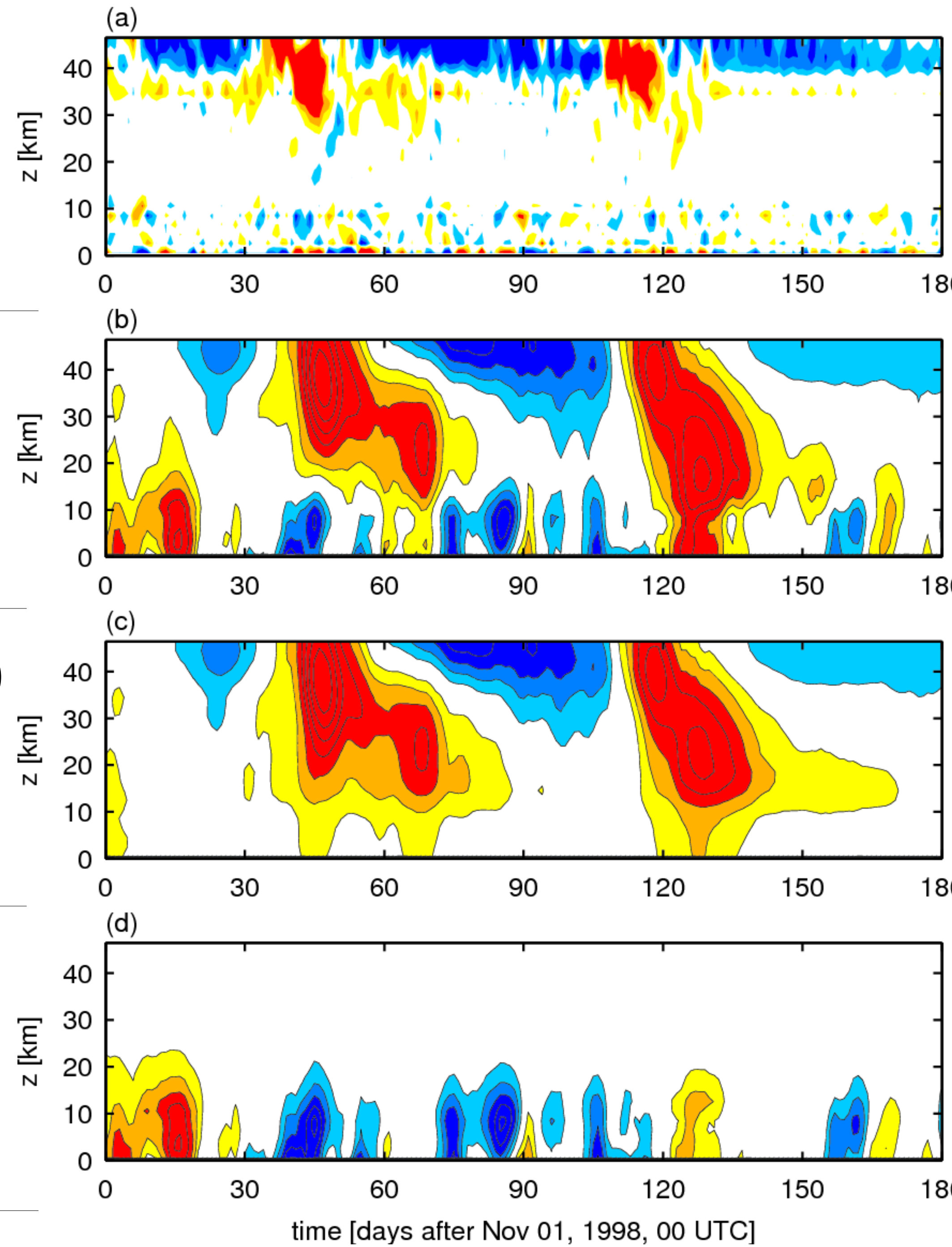


Three NAM surf. signals: full, strat, trop

(2) Results

Lagged linear regression analysis

of NAM at each level

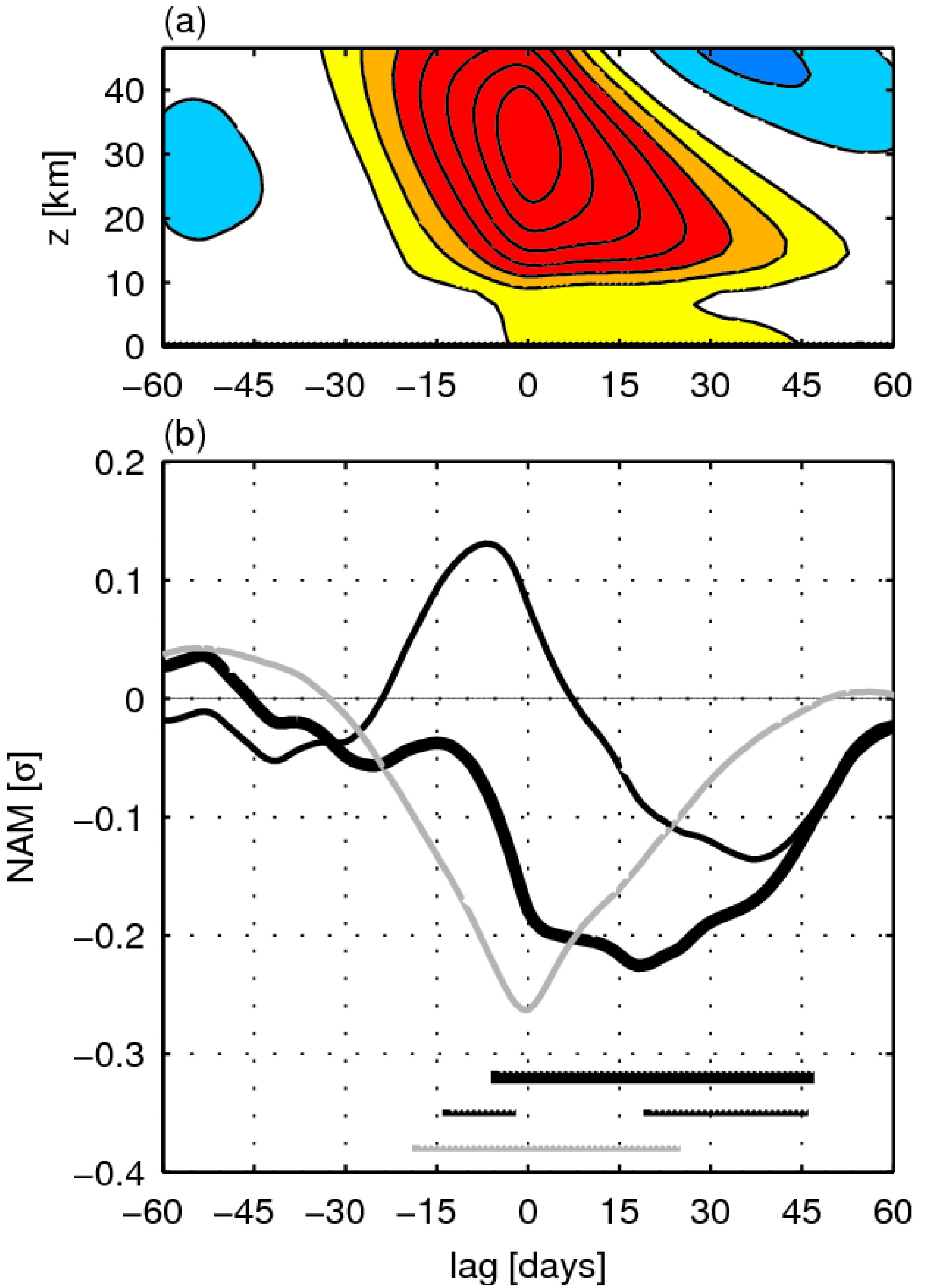
onto mid-strat. NAM (10 hPa)

Stratosphere

- slowly downward migrating signal
- most presistent in lower strat.
- vortex recovery from above

Troposphere

- signal max. at surf. (thick black)
- persists for ~8 weeks
- lags mid-strat. by ~3 weeks
- expl. 5% surf. NAM variance (10% of LFV, T > 30 days)
- lin. regr. mixes types of events (strong/weak vort., SSW, ...) and incl. small amplitudes



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Surface signal due to...

...strat. QG adjustment (thin gray)

- amplitude similar to full signal
- but peaks already at lag 0

➡ initiates surface signal

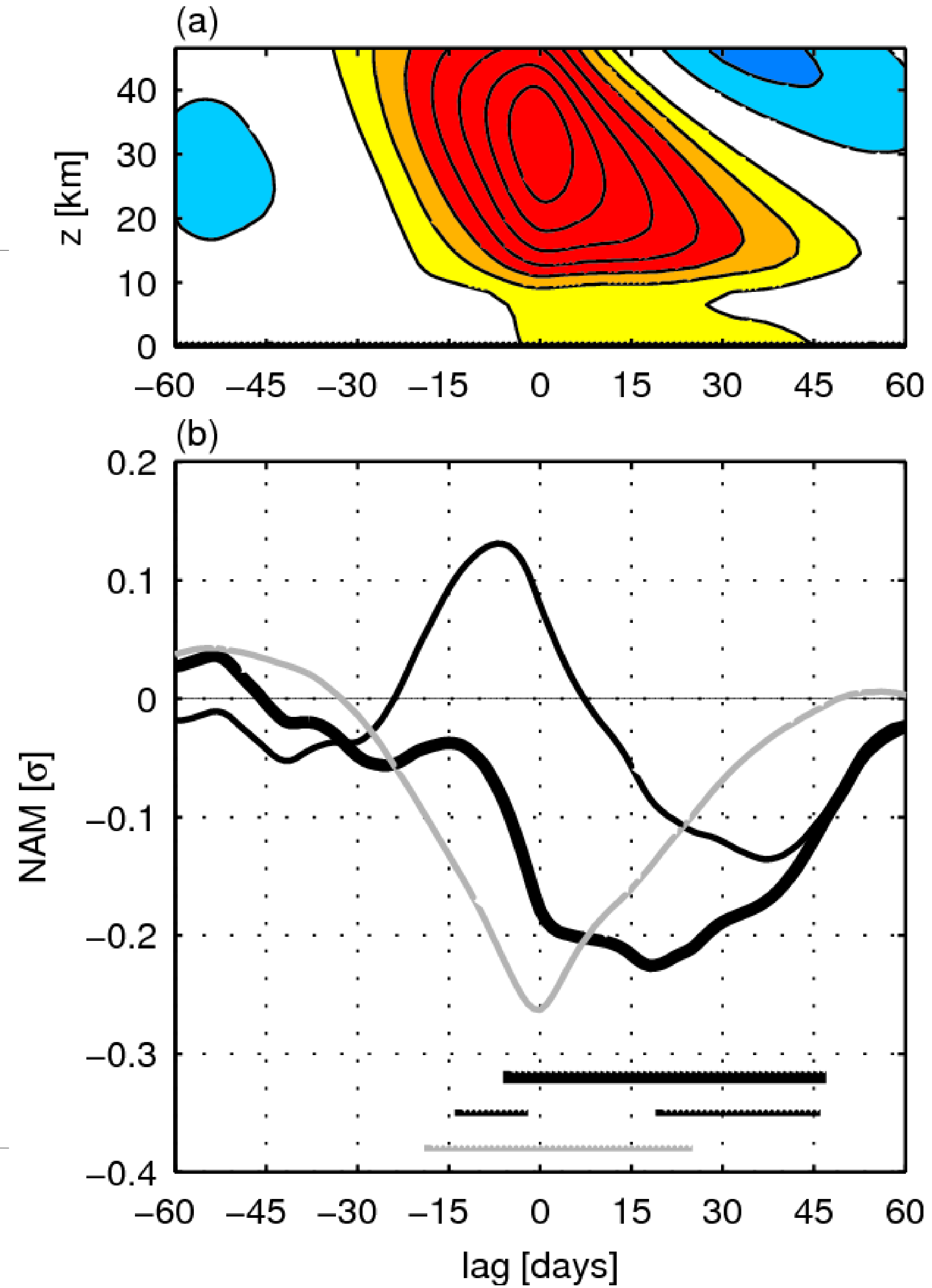
...local trop. wave drag (thin black)

- two-phase character
- neg. lags: delay of surf. signal
- pos. lags: persists surf. signal

➡ maintains surface signal

Noticable sensitivity to N^2, damp. coeff.

...but qualitative conclusions robust



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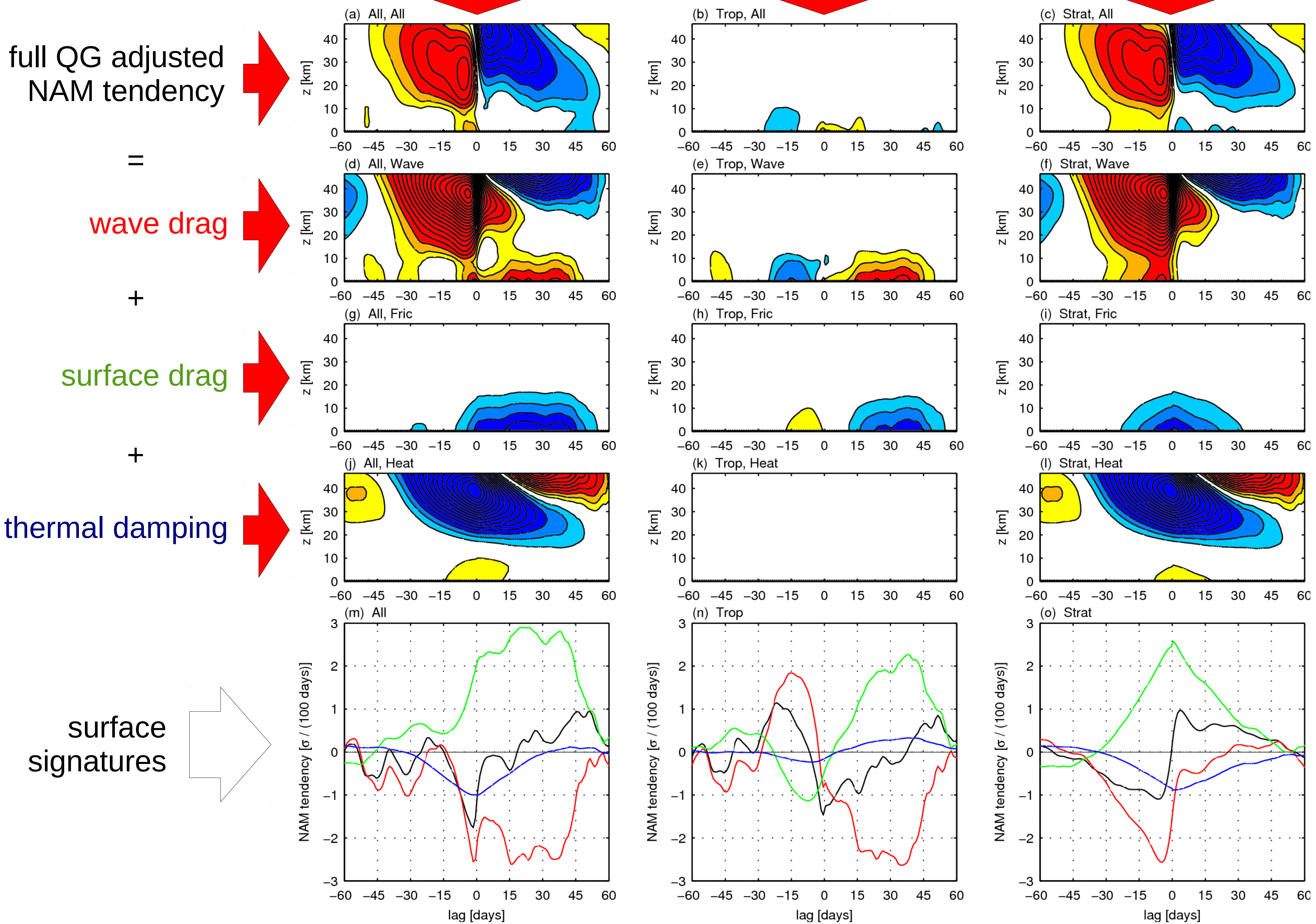
full forcing = trop forcing + strat forcing



(3) Conclusions & Discussion

Reconcile conclusions from previous studies

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Results indicate that

- both types of mechanisms are of similar quantitative importance
- but their roles differ in a qualitative sense
- strat. QG adjustment initiates NAM surface signal (but no lag rel. to strat.)
- whereas local trop. wave drag
  - first delays the build-up of the surface signal
    (possibly trop. tail end of strat. wave drag)
  - later persists the surface signal over several weeks
    (internal trop. wave dynamics, or waves reflected from strat.)

  - trop. wave drag actively maintains signal against dissipation

    ...suggests the need for trop. eddy-feedbacks for lagged surf. signal

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Further possible applications of method

(1) SSW composites or even individual events

(2) dynamical origin of NAM auto-correlation structure, NAM timescales

(3) and the SAM

(3) Conclusions & Discussion

Limitations of approach

- QG scaling, although ERA-40 is output from PE model
- external diabatic heating neglected,
  but pos. vortex-ozone feedb. and volc. erup. involve diabatic heating anoms.
- LBC simplified (neglect surface eddy heat fluxes)
  reduces possibility to further investigate trop. wave drag
- implicitness of wave effects: distinction between diff. wave classes not possible
- ERA-40 at upper strat. is uncertain, particularly during pre-satellite era,
  (however, here: only NAM and linear relationship to surface considered)

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Relation to other approaches (PV perspective)

- based on inversion of strat. PV anomalies
  (e.g., Hartley et al., 1998, Black 2002, Ambaum & Hoskins 2002)

QGPV tendency equation:

$$q_t = -f(2\Omega a)^{-1}\mathcal{L}_1^{\phi}(F - \kappa u) - fRH^{-1}\mathcal{L}_1^{z}(\alpha T)$$

strat. q-tendencies generated by: strat. wave drag and most of therm. damp.,
...but only marginally trop. thermal damp., no surf. drag (weak indirect eff.)

- largely neglects trop. dissipation:
  ...trop./strat. always in phase, no sep. phases of initiation and maintenance