Stationary Wave Driving as a Potential Mechanism to Exploit for Extratropical S2S Prediction

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Dynamical Ideas for Improved S2S Prediction of AO/NAM*

• Describe driving of NAM anomalies by planetary waves.

• Main focus: stratosphere-troposphere, high latitudes.

• Highlight linear interference between planetary wave anomalies and the climatological stationary wave.

• Demonstrate that low-frequency standing waves (fixed node oscillations) are important in linear interference.

• Mention implications for S2S research.

*AO = Arctic Oscillation, NAM = Northern Annular Mode
Stratospheric Vacillation Cycles

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1. Introduction

The winter seasonal mean circulation of the Northern Hemisphere stratosphere consists primarily of planetary waves of zonal wavenumbers 1 and 2 superposed on a zonal westerly vortex. The planetary waves are quasi-stationary in phase but tend to fluctuate in amplitude. Occasionally the anomalous amplification of such waves leads to an enormous enhancement of the poleward eddy heat flux which in turn leads to a reversal of the normal pole-to-equator temperature gradient over a sufficient depth of the stratosphere so that the mean polar westerlies are replaced by easterlies. This sequence of events, known as a major stratospheric warming, has been the subject of many observational and theoretical studies [see Quiroz et al.].
Figure 2. Daily value of the NAM index at 10 hPa (red) and 40-day average of heat flux anomalies at 100 hPa (blue) and 300 hPa (black), for 1 January 1978 – 31 December 2002. Heat flux averaged over 40 days prior to the given day. The dashed vertical lines mark 1 January of each year.

It is interesting to note in Figure 1 that the averaged heat flux preceding ESEs (as defined in BD2001 on the basis of the NAM index at 10 hPa) is not symmetric. The histogram for the weak vortex (red) events is centered at roughly two standard deviations to the right of the PDF for all days, while the histogram from the strong vortex (blue) events is only about one standard deviation to the left. From the dynamical interpretation we have offered, one would not really expect symmetry. In some sense only the weak vortex ESEs are true “events,” insofar as something has in fact happened (notably, a much larger than average upward wave propagation followed by wave breaking, typical of a sudden warming). On the other hand, when the vortex is anomalously strong, not much actually happens, that is, the wave activity entering the stratosphere is weak and thus fewer waves are propagating upwards, breaking and decelerating the vortex.

This dynamical interpretation offered on the basis of the PDFs alone is much strengthened by inspection of the actual time series. These are plotted in Figure 2 for the last 24 yr of the record. Notice the extremely high anticorrelation ($-0.8$) between the NAM index at 10 hPa (red curve) and of the averaged heat flux at 100 hPa (blue curve). Such a high correlation lends strong support to our interpretation of upward wave activity fluxes as precursors to ESEs.

In Figure 3, we explore the dependence of the correlation between the averaged heat flux at 100 hPa and the NAM index at 10 hPa on two parameters: the time interval over which the heat flux is averaged (the integration period) and the time lag between the end of the integration period and the time of the 10 hPa NAM index. Figure 3 shows that the highest anticorrelations are found for integration periods of 20 days or more.

Rossby Wave Activity Flux (EP Flux) into Stratosphere

 Полвани & Waugh 2004
The correlation coefficient between the NAM index at 10 hPa and the averaged heat flux at 100 hPa, as a function of the integration period for the heat flux and time lag between the end of that integration period and the time of the NAM index. The contour interval is 0.05. Data for all winters (Dec–Feb) from 1958 to 2001 are used to compute these correlations.

**Figure 4.** (top) Composite so of height–time development of the NAM index for (a) 25 high heat flux events and (b) 24 low heat flux events. The horizontal line marks the 40-day period over which the averaged heat flux is anomalous. Values greater than 0.25 and smaller than 0.25 are shaded, and values greater (smaller) than 0.5 (20.5) contoured, with a contour interval of 0.5. (bottom) Temporal evolution of composite mean daily (bars) and 40-day averaged (curves) heat flux anomalies at 100 hPa.

With little sensitivity beyond that value. Note that high anticorrelations basically disappear for averaging periods over less than 10 days; this is why the anticorrelation using daily heat fluxes is much lower than that using heat fluxes averaged over 20 or more days [consistent with the Newman et al. (2001) theory]. This result holds even if a time lag is used between the daily heat fluxes at 100 hPa and the NAM index at 10 hPa. The maximum correlation with the daily heat flux occurs for a time lag of 5 days, but this correlation is only around 0.4.

In order to establish the tropospheric origin of ESEs, we have also explored how the correlation between the 10 hPa NAM index and the upward heat flux depends on the level at which the heat flux is measured. The time series of averaged heat flux at 300 hPa is actually shown in Fig. 2 (cf. the thin black line). There is, in general, good correspondence between anomalous events in the 100 and 300 hPa heat flux time series, and the correlation of the two heat flux time series exceeds 0.55 [an even closer relationship holds between 100 and 200 hPa (not shown) with correlation around 0.9]. These high correlations indicates that most of the variations in heat flux at 100 hPa originate at 300hPa and lower, that is, the wave activity at 100 hPa is of tropospheric origin.

The correlations between 200- or 300-hPa heat fluxes...
10-day Percent Variance Explained for NAM & AO

Surface anomalies 16-60 days after Stratospheric Sudden Warmings

Observations and CMAM Forecasts
Key Points

• Improved prediction of NAM/AO promises improved S2S prediction.

• Planetary wave events lead the tropospheric NAM/AO on S2S timescales.
NH Winter Stationary Wave, 60N

O. Watt-Meyer

ERA-Interim \( Z_c^* \), NDJFM, 1979-2012
$Z^*$ composite on vertical wave activity flux anomalies

Upper tropospheric wintertime streamflow anomaly composite on Zonal Index

(Contours: Climatological streamflow; Shading: Anomalies)
Key Points (cont.)

• Improved prediction of NAM/AO promises improved S2S prediction.

• Planetary wave events lead the tropospheric NAM/AO on S2S timescales.

• Wave anomalies tend to amplify or reduce the climatological stationary wave: a linear interference effect.

• We now quantify and study this linear interference effect.
• Zonal mean/wave decomposition:

\[ \psi = [\psi] + \psi^*. \]

• Rossby/EP wave activity flux into stratosphere:

\[ \vec{F} \sim [v^*\theta^*] \hat{z}. \]

• Climatology/anomaly decomposition:

\[ \psi^* = \psi^*_c + \psi^*'. \]

\( \psi^*_c \) is the stationary wave field.

• Wave activity flux anomaly from climatology:

\[ [v^*\theta^*]' = \text{LIN} + \text{NONLIN} \]

\[ \text{LIN} = [v_c'\theta^*] + [v_c^*\theta'], \quad \text{NONLIN} = [v^*\theta^*]' \]
• Zonal mean/wave decomposition:

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• Wave activity flux anomaly from climatology:

\[ [v^*\theta^*]' = \text{LIN} + \text{NONLIN} \]

**LIN: Interference term**

\[ \text{LIN} = [v'_c \theta^*] + [v^* \theta'_c], \quad \text{NONLIN} = [v^* \theta'']' \]
Linear Interference Is a Big Effect

Wintertime Budget of Heat Flux Variance, ERA-Interim

Linear Interference Is Predictable, in Principle

Spatial Correlation of \( Z^*_c \) and \( Z^*_l \)

Stratosphere, High Heat Flux Events

Stratosphere, Low Heat Flux Events

Troposphere, High Heat Flux Events

Troposphere, Low Heat Flux Events

Wave anomalies are phase locked to the stationary wave in weeks prior to a strong heat flux event.
Linear Interference Is “Tunable”

[$Z$] Response to Wintertime Tropical SST Warming, GFDL AM2

- In TPO, the forced wave and stationary wave are in phase.
  - **Constructive interference, negative NAM.**
- In TIO, the waves are out of phase.
  - **Destructive interference, positive NAM.**

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Fletcher and Kushner (2010)
Linear interference controls NAM/AO for different tropical forcings, GCMs, resolutions, stratospheric representation.
Key Points (cont.)

• Improved prediction of NAM/AO promises improved S2S prediction.

• Planetary wave events lead the tropospheric NAM/AO on S2S timescales.

• Wave anomalies tend to amplify or reduce the climatological stationary wave: a linear interference effect.

• Linear interference is, in principle, predictable.

• It is sensitive to model details.
Which Waves Drive Linear Interference?
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100 hPa, ERA-Interim

Wave-1 Z*'

Wave-1 LIN

Min and Max of $Z_c^*$

Heat Flux [K m s$^{-1}$]
Which Waves Drive Linear Interference?

Winter 1990–1991
“Standing Wave” Season

Winter 1979–1980
“Propagating Wave” Season

Standing/Propagating Wave Spectra

Cosine DFT

\[ q(\lambda, t) = \frac{2}{NT} \sum_{k=1}^{N_2} \sum_{j=-T_2}^{T_2} Q_{k,j} \cos (k\lambda + \omega_j t + \phi_{k,j}) \]

Counter propagating pairs

\[ q_{k,\pm j}(\lambda, t) = \frac{2}{NT} Q_{k,j} \cos (k\lambda + \omega_j t + \phi_{k,j}) \]
\[ + \frac{2}{NT} Q_{k,-j} \cos (k\lambda - \omega_j t + \phi_{k,-j}) \]

\[ Q_{k,j}^{St} = \min(Q_{k,j}, Q_{k,-j}) \]
\[ Q_{k,j}^{Tr} = Q_{k,j} - Q_{k,j}^{St} \]

Amplitude of the Standing Wave Field

Standing Wave Amplitude and Stationary Waves: Standing Wave Interference

Shading: standing wave amplitude; contours: stationary wave

Standing-Wave Linear Interference is a Big Effect

Heat flux variance $[K^2 m^2 s^{-2}]$

- $\text{var(\{\nu T^*\})}$
- $\text{var(LIN)}$
- $\text{var(LIN}_{\text{St}}$
- $\text{var(LIN}_{\text{Tr}}$
- $\text{2cov(L_{St}, L_{Tr}}$

Standing Wave Linear Interference Is Predictable, in Principle
Conclusion

- Planetary-wave interference is a robust predictor of tropospheric AO/NAM.

- Linear wave activity fluxes are dominated by low-frequency, persistent standing oscillations.

- Planetary wave metrics (stationary waves, phasing of waves, standing waves) are worth exploiting for S2S research:
  - Predictors in statistical forecast systems.
  - Constraint on dynamical forecast systems.
  - Ideas should generalize beyond stratosphere-troposphere interactions.


Fletcher, C. G. and P. J. Kushner, 2011: The role of linear interference in the annular mode response to tropical SST forcing. J. Climate, 24, 778-794. DOI: 10.1175/2010JCLI3735.1
