STRATOSPHERE-TROPOSPHERE COUPLING:

A METHOD TO DIAGNOSE SOURCES OF ANNULAR MODE TIMESCALES

Lawrence Mudryk   Paul Kushner

SPARC DynVar

Abstract

Timescales derived from Annular Mode (AM) variability provide dynamical insight into stratosphere-troposphere coupling and are linked to the strength of AM responses to climate forcings. These timescales reflect decorrelation times of geopotential height in the stratosphere and troposphere. However, since geopotential height involves a vertical integral via the hypsometric equation, some aspects of the dependence of the timescales on vertical level are ambiguous.

We present a method for decomposing AM variability into contributions from surface pressure and temperature based on a linearization of the hypsometric equation. The decomposition is used to interpret stratosphere-troposphere coupling events and the seasonal variation of AM timescales. Surface pressure variations best account for AM variability in the troposphere and stratospheric temperature variations best account for AM variability in the stratosphere during coupling events, but AM timescales are not so readily separated. AM timescales involve strong coupling between the surface pressure and stratospheric temperature variations: the pressure-temperature cross correlation functions are small in magnitude but highly persistent and thus provide significant sources of AM persistence. These empirical results might serve as the basis for further theoretical analysis on the origins of zonal mean stratosphere-troposphere coupling.

Motivation and Background

The Northern and Southern Annular Modes (NAM, SAM) are defined as the dominant variability patterns in the extratropical circulation of each respective hemisphere.[1] The strength and polarity of the AM pattern fluctuates over time as indicated by the value of the AM index.

Stratospheric vs. Tropospheric Modes

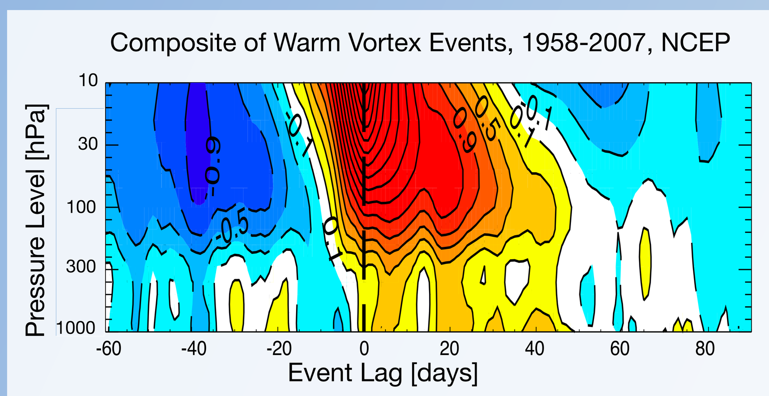
In the stratosphere, the AM index varies with the strength of the polar vortex which is strongly coupled to fluxes of vertical wave activity. In the troposphere it signals latitudinal vacillations in the mean position of the extratropical jet, connected with meridional fluxes of wave activity.

These distinctive dynamics are captured by simple mechanistic models of the two regions. The Holton and Mass[2] model in its simplest form is a prognostic model for the stratospheric zonal wind, which can be represented by stratospheric temperature. The Vallis et al.[3] model is a prognostic model for the barotropic stream function, which can be represented by surface pressure.

Stratosphere-Troposphere Coupling

The two mechanistic models would imply that these two fields are, to some extent, dynamically separate, but observations suggest that they couple under some conditions. For example, while the stratospheric AM is known to be more persistent than the tropospheric AM,[4,5] tropospheric AM persistence increases during seasons when the stratosphere itself is most active and persistent.[6]

Stratosphere-troposphere coupling is also implied by "dripping paint" type plots such as the one below. Stratospheric anomaly patterns propagate downwards from the upper and mid-stratosphere towards the lower stratosphere over 1-2 weeks. Once such anomalies reach the lower stratosphere, they rapidly descend throughout the entire troposphere, where like-signed anomaly patterns may exist for upwards of two months.



Composite of warm vortex events (NDJFM) based on northern hemisphere polar-cap averaged geopotential height anomalies. Contour intervals represent standard deviations of anomaly indices and are spaced by 0.2. Index values between -0.1 and 0.1 are unshaded. Composites for strong vortex events are similar except for the sign.

We begin by exploring the elementary idea suggested by the mechanistic models described above: that AM persistence in stratosphere is related to stratospheric temperature signals while throughout the troposphere it is related to surface pressure signals. We explicitly decompose AM variability into contributions from surface pressure and from temperature fields, based on a linearization of the geopotential height integral. This decomposition helps to separate stratospheric and tropospheric AM variability when applied to AM stratosphere-troposphere coupling events and highlights the role of coupling between surface pressure and temperature signals in determining AM timescales.

Observed Data and Model Output

Reanalysis Data

NCEP, 1958-2007, daily resolution
ERA40 1961-2001, daily resolution

Canadian Middle Atmosphere Model (CMAM) Data[5]

LOWERED: 41 vertical levels, lid at 10 hPa
HIGH: 71 vertical levels, model lid at 0.0006 hPa
both configurations conserve momentum by depositing gravity wave momentum in the uppermost layer.

Geopotential Height Decomposition

For a hydrostatic fluid, geopotential height may be described as a function of time, pressure level and horizontal position as a temperature integral from the Earth's surface to a given pressure level:

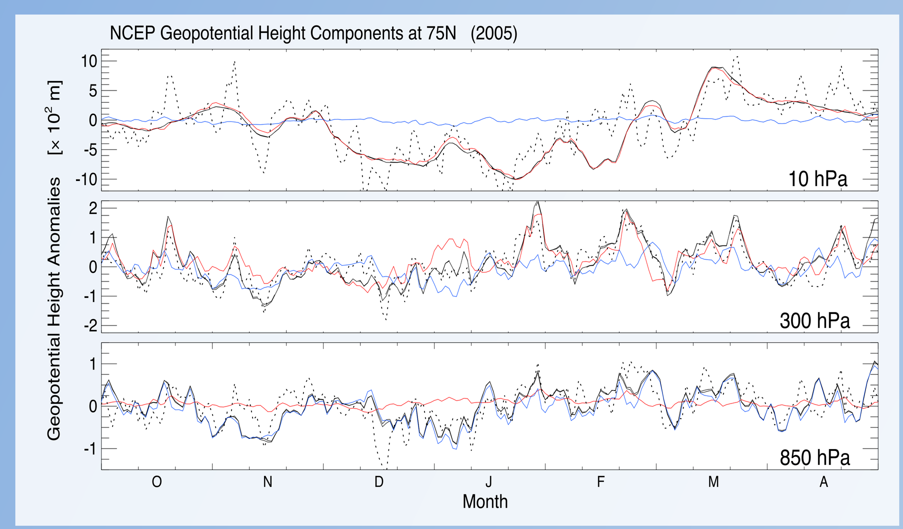
$$Z(\boldsymbol{x},p,t) = -\frac{R}{g}\int_{p_s(\boldsymbol{x},t)}^{p} T(\boldsymbol{x},p',t)\,d\ln p'$$

We can decompose the above time varying geopotential into a climatology and anomalies, $Z(\boldsymbol{x},p,t) = \overline{Z}(\boldsymbol{x},p) + \delta Z(\boldsymbol{x},p,t)$. Decomposing the temperature and surface pressure in the same way, to first order we can approximate the geopotential anomalies as two terms for which the temperature and surface pressure variability is decoupled:

$$\delta Z_L(\boldsymbol{x},p,t) \approx -\frac{R}{g}\int_{\overline{p}_s(\boldsymbol{x})}^{p} \delta T(\boldsymbol{x},p,t)\,d\ln p + \frac{R}{g}\overline{T}(\boldsymbol{x},p)\frac{\delta p_s(\boldsymbol{x},t)}{\overline{p}_s(\boldsymbol{x})} \quad (1)$$

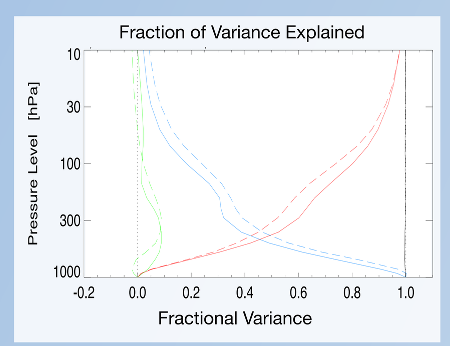
$$\delta Z_L = \delta Z_T + \delta Z_{p_s}$$

"linearized geopotential height"   "temperature component"   "surface pressure component"



Components of geopotential height anomalies based on NCEP data for the year 2005, with climatologies defined over the years 1958-2007. The solid black curve shows the full non-linear geopotential height anomalies. The dotted curve shows scaled differences between the non-linear anomalies and the linear anomalies reconstructed using Eq. 1. Differences in the top panel are plotted as 100x the actual difference; those in the bottom two panels are plotted as 20x the actual difference. The red and blue curves show the respective contributions from the temperature and surface pressure components.

The graph on the right shows the fraction of the total variance (normalized relative to the fully nonlinear anomalies) captured by the linearized anomalies (black curve), the temperature component (red curve), the surface pressure component (blue curve), and by the covariance of the two components (green curve). NH: solid curves. SH: dashed curves. The green curves measure the coupling between the two contributions, which is important for understanding AM timescales in the upper troposphere/lower stratosphere.



δZ_T variability dominates in stratosphere
δZ_{p_s} variability dominates in troposphere

We can define separate AM indices for both the temperature and surface pressure components above by projecting their respective anomalies onto the AM spatial pattern just as for the total geopotential. We normalize their sum so that it has unit variance.

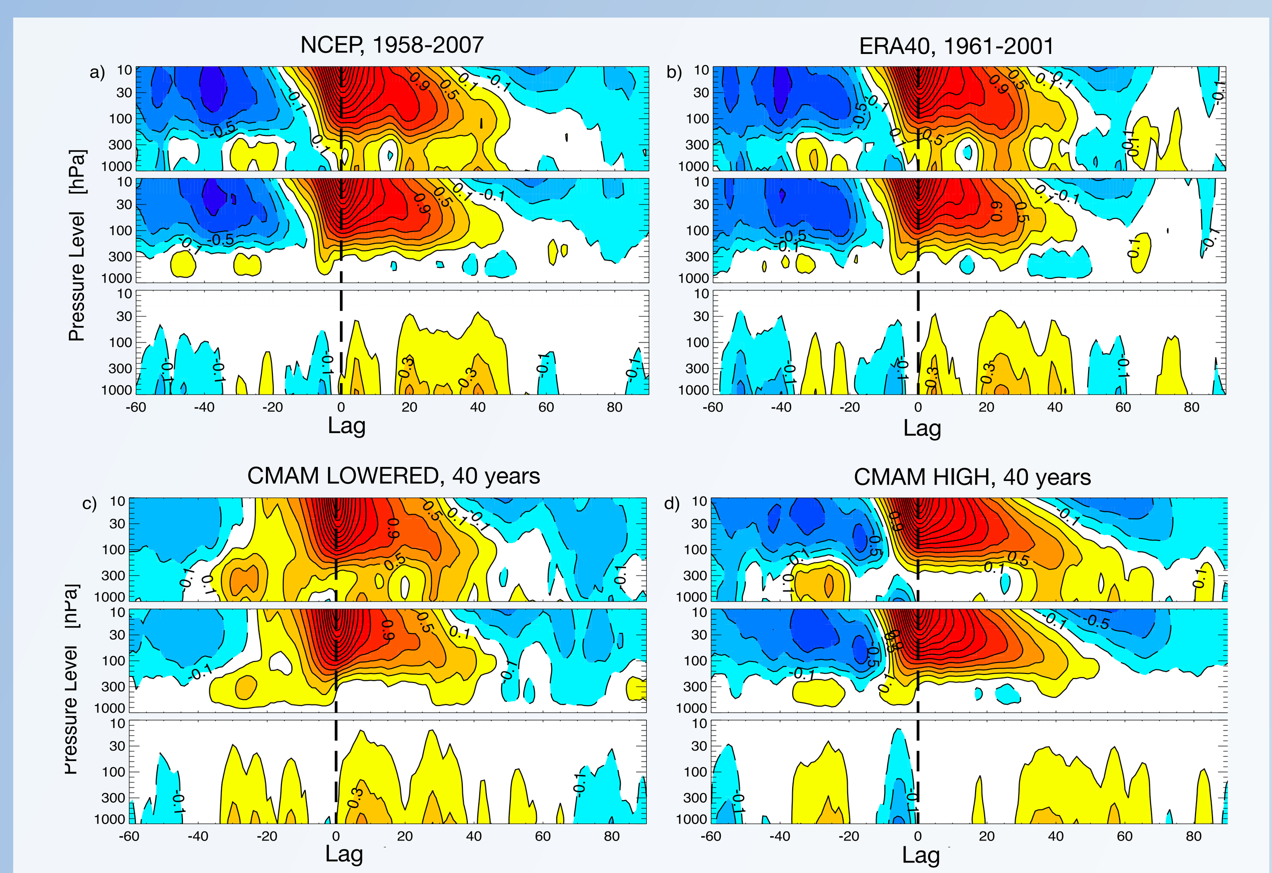
$$y_L = \delta Z_L \cdot e_L = \underbrace{\delta Z_T \cdot e_L}_{y_T} + \underbrace{\delta Z_{p_s} \cdot e_L}_{y_{p_s}}$$

AM index (y_L); linearized anomalies (δZ_L); AM spatial pattern (e_L)

Linearized anomalies are an excellent approximation to nonlinear anomalies
Linearized AM time series components are additive: $y_L = y_T + y_{p_s}$

Decomposition of Coupling Events

For each winter (NDJFM) we define a single weak vortex event as the day with the largest negative NAM index based on the 10 hPa AM time series for the linearized geopotential, y_L.

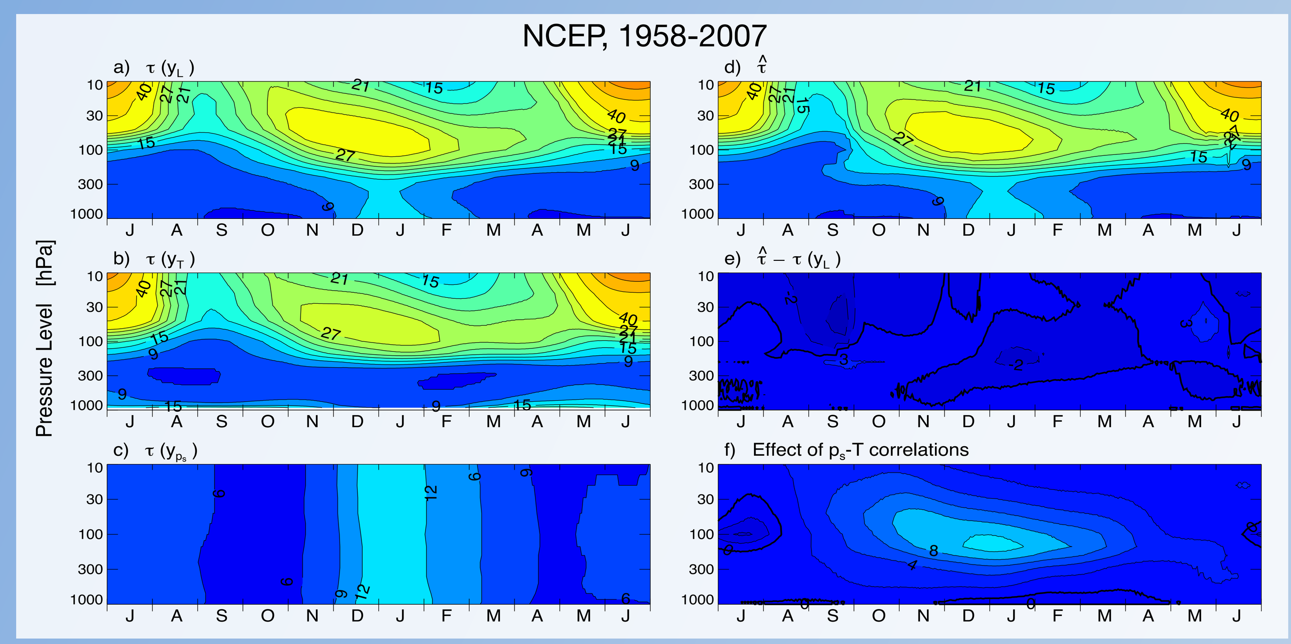


Each plot shows composites for warm vortex events for each of the data sets. Within each plot, from top to bottom, panels show composites of linearized geopotential, temperature component and surface pressure component, respectively. Contour intervals are spaced by 0.2. Index values between -0.1 and 0.1 are unshaded.

For both reanalysis data and model runs, the surface pressure component of the geopotential height dominates the pattern in the troposphere, while the temperature component dominates in the stratosphere. Models display an extended or delayed surface pressure anomaly compared to observations as well as a stronger warm/positive anomaly in both temperature and surface pressure in the troposphere prior to the stratospheric event.

Separation of AM Timescales

AM timescales track seasonal variations in the AM index's decorrelation time[6,7].

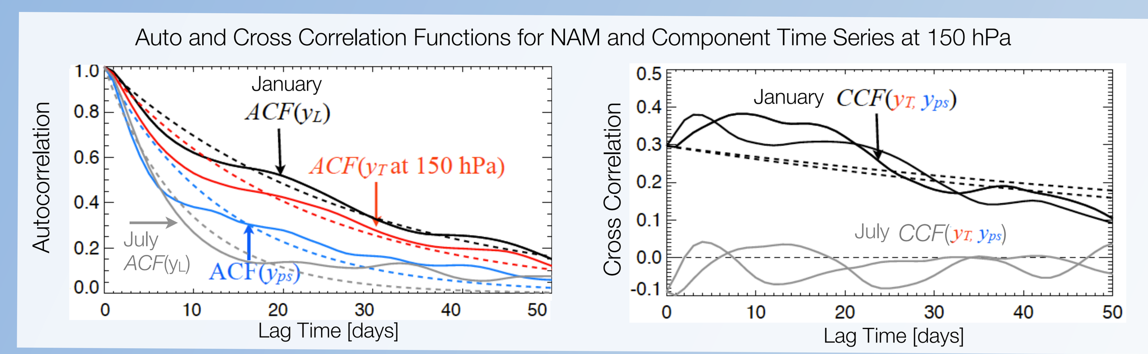


Left panels show the seasonality of the NAM time scale calculated for the a) linearized geopotential, b) temperature component and c) surface pressure component.

Right panels show d) effective timescale estimate (see below) e) difference of d-a and f) cross correlation timescale due to T-p_s correlations.

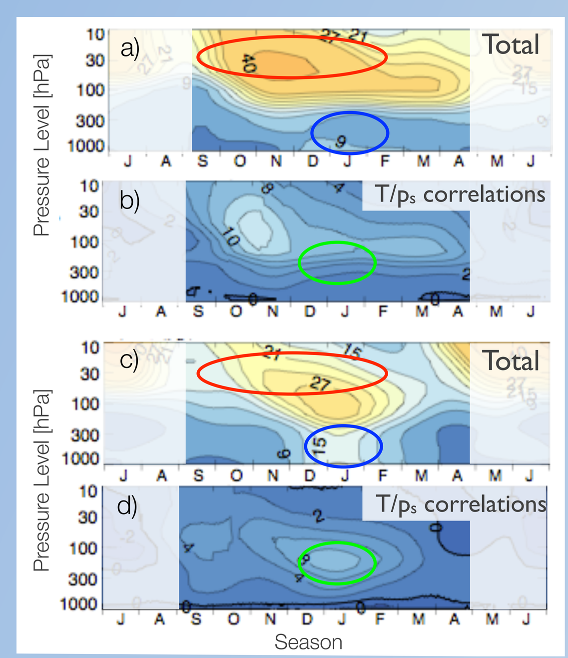
AM timescales are not a simple combination (e.g., sum, average, harmonic mean) of the surface pressure and temperature timescales: $\tau(y_L) \neq \tau(y_T) + \tau(y_{p_s})$

We develop a procedure to estimate a timescale, $\hat{\tau}$ for y_L which is consistent with the timescales of y_T, y_{p_s} and their cross-correlations. The procedure allows us to estimate the seasonal contribution from T-p_s cross-correlations to the NAM timescale. This estimate is shown in panel f) of the above figure. Although such cross correlations are weak, they are extremely persistent during active vortex seasons as shown in the figure below.



Correlations between y_T and y_{p_s}, although weak, can decay very slowly, enhancing NAM persistence by as much as 10 days in the lower stratosphere and upper troposphere.

Effect of Sudden Stratospheric Warmings on Timescales



Years Without SSWs

- longer decorrelation times in stratosphere
- shorter decorrelation times in troposphere
- no increase observed in timescale in upper troposphere

Only Years With SSWs

- shorter decorrelation times in stratosphere
- longer decorrelation times in troposphere
- increased timescale in upper troposphere

Panels show NAM timescale and cross correlation timescales calculated from time series composed only of years without SSW events (a, b) or only of years with SSW events (c,d). The selection criteria leads to non-adjacent years being spliced together. These splices are aligned during NH summer to curtail their effect during the active vortex season.

Conclusions

The linear decomposition diagnostic we present has several advantageous properties:

- Empirical, relatively easy to do,motivated by basic dynamical ideas
- Cleanly separates stratospheric and tropospheric contributions to AM variability
- Quantifies effect of coupling in UTLS on persistence
- Provides additional views of GCM performance

In addition, weak but persistent cross correlations between T and p_s suggest dynamical ideas to test about eddy driving in UTLS.

References

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Affiliation

Department of Physics, University of Toronto   email: mudryk@atmosp.physics.utoronto.ca