The Role of Linear Interference in Troposphere-Stratosphere Interactions

Karen L. Smith (ksmith@atmosp.physics.utoronto.ca), Paul J. Kushner

Department of Physics, University of Toronto, Toronto, Canada,

Introduction

Linear interference can be described as the interaction between anomalous waves and the background climatological wave field. There has been recent interest in the role of linear interference in troposphere-stratosphere interactions (Nishii et al. 2009; Garfinkel et al. 2010; Kolstad and Charlton-Perez 2010; Smith et al. 2010; Nishii et al. 2010; Fletcher and Kushner 2011; Smith et al. 2011). With respect to the tropospheric variability, DeWeaver and Nigam (2000; hereafter DN2000) demonstrate that the linear interference component of the momentum flux is critical in maintaining tropospheric zonal mean zonal wind anomalies. This work provides a distinct perspective on the variability of the extratropical zonal-mean flow in the troposphere, which has been described by other authors in terms of feedbacks between the zonal-mean flow and transient, synoptic-scale waves (Robinson 2000; Lorenz and Hartmann 2003). In the stratosphere, vertical fluxes of Rossby wave activity from the troposphere correlate strongly and negatively with the Northern Annular Mode (NAM) index. Here we quantify the importance of this linear interference effect by performing a decomposition of the vertical wave activity flux in reanalysis. Like DN2000 we show that linear interference is the dominant process associated with stratospheric NAM variability and is also important in SAM variability, to a lesser extent.

Linear Interference Diagnostics

Following Smith et al. (2011), we employ a decomposition of heat flux anomalies, a proxy for the vertical component of the wave activity flux (see also Nishii et al. 2009). We define the zonally asymmetric fields, for a given day during year *j*, as

$$v^*_j = v^{*\prime}_j + v^*_c \text{ and } T^*_j = T^{*\prime}_j + T^*_c$$

where the prime indicates the deviation from the climatological time mean, the subscripts *j* and *c* indicate the year and the climatological mean, respectively. The anomalous wave heat flux in year *j*, $\{v^*T^*\}'_j = \{v^*_jT^*_j\}'$, becomes,

$$\{v^*T^*\}'_j = \{v^*_jT^*_j\}' = \{v^*_jT^*_j\} - \{v^*_cT^*_c\} = \textbf{NONLIN} + \textbf{LIN}$$

where

$$\textbf{NONLIN} = \{v^{*\prime}_jT^{*\prime}_j\} - \{v^{*\prime}_j\,T^{*\prime}_j\}_c = \{v^{*\prime}_jT^{*\prime}_j\}' \text{ and } \textbf{LIN} = \{v^{*\prime}_jT^*_c\} + \{v^*_cT^{*\prime}_j\}$$

and brackets indicate a zonal and 40°-80°N average. Under the zonal average, the sign and amplitude of the **LIN** term will depend in part on the degree of ***constructive or destructive interference*** between the climatological wave and the anomalous wave. The **NONLIN** term describes the component of the wave heat flux anomaly intrinsic to the anomalies themselves.

The interannual variance of the heat flux can then be written as

$$\begin{aligned} var(\{v^*T^*\}) &= var(\text{LIN} + \text{NONLIN}) \\ &= var(\text{LIN}) + var(\text{NONLIN}) + 2cov(\text{LIN,NONLIN})\ . \end{aligned}$$

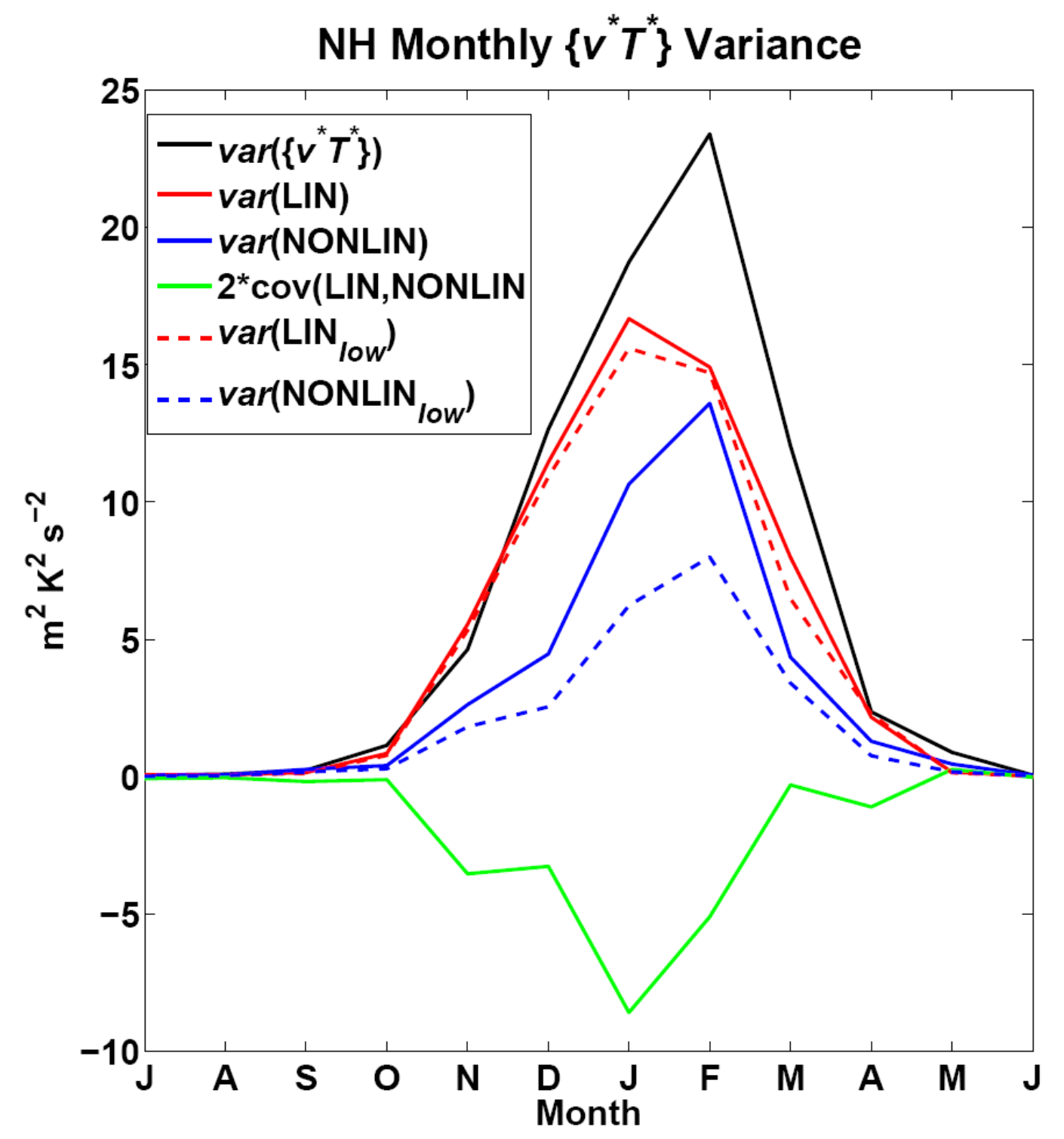

FIG.1. Monthly interannual heat flux variance decomposition. Subscript "low" indicates heat fluxes that were calculated using 11-day low pass filtered wave fields. Data is NCEP-NCAR Reanalysis 1979-2009.

NH winter, which is the season when strong stratosphere-troposphere interactions are observed, is also the season with the cleanest decomposition of the interannual variance of ({v^*T^*}) in terms of its frequency and its LIN and NONLIN components. During the winter season, the largest contribution to var({v^*T^*}) is from low-frequency LIN fluxes.

Heat Flux Composites

Polvani and Waugh (2004) demonstrate that high (low) index NAM events are highly correlated with anomalously low (high) extratropical meridional wave heat fluxes in the lower stratosphere. Time-pressure composite plots of the NAM index based on these low/high heat flux anomalies show remarkably similar features to those based on high/low NAM events themselves.

We generate similar composites by selecting the maximum or minimum 40-day averaged standardized {v^*T^*}' for each year from November-March in the NH and June-December in the SH for the years 1979-2009 (NCEP-NCAR Reanalysis). Maximum and minimum composites are denoted weak and strong vortex composites.

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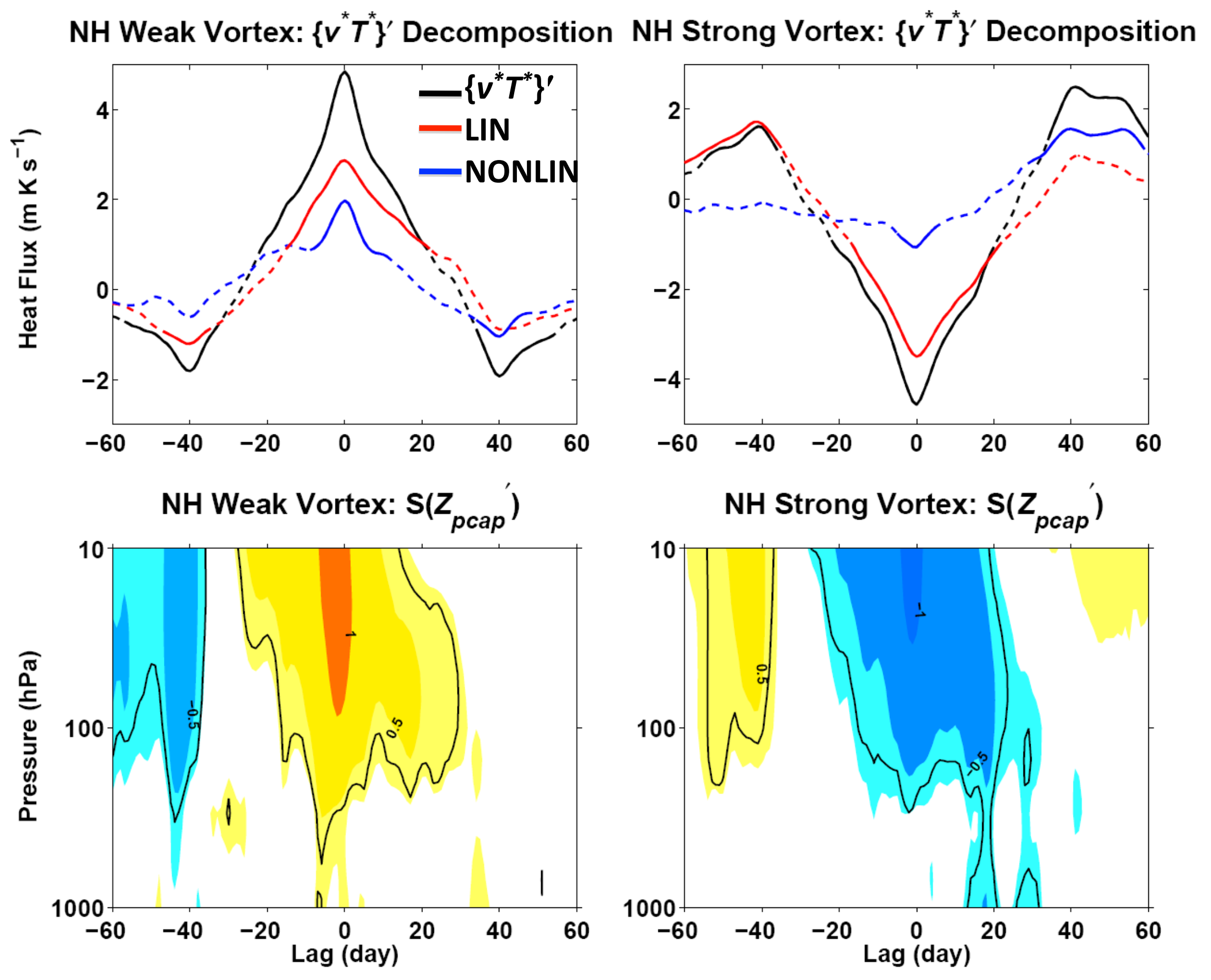


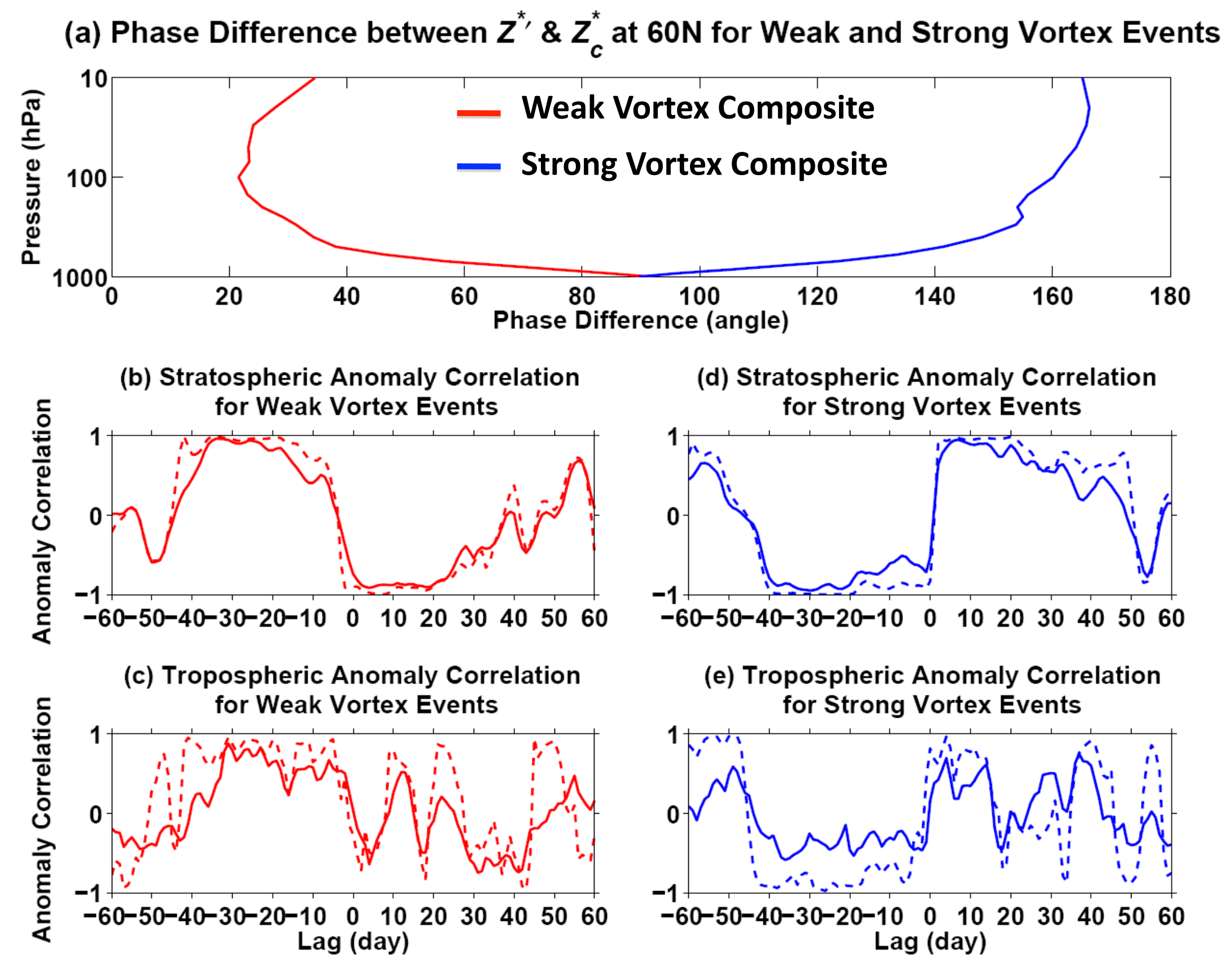
FIG. 2. (top) Composite mean 40-day averaged heat flux anomaly decomposition at 100 hPa; {v^*T^*}$'$, LIN and NONLIN for NH weak and strong vortex events. Solid sections of the curves indicate 95% significance. (bottom) Composite mean standardized GPH anomaly, S(Z_{pcap}') for NH weak and strong vortex events. Black contour indicates 95% significance.

S(Z_{pcap}') is used as a measure of the NAM index.

The weak and strong vortex composites consist of primarily LIN fluxes, particularly the strong composite. For the weak (strong) vortex composite the LIN fluxes are characterized by a steady linear increase (decrease) while the NONLIN fluxes increase (decrease) much more rapidly.

Composite mean differences in the LIN contribution to the weak and strong vortex composites illustrate that the frequency distributions of these fluxes differ. The distribution of 40-day averaged {v^*T^*}$'$ is t positively skewed (skew = 0.34), stemming from the distribution of NONLIN fluxes (skew = 1.66) while the distribution of LIN fluxes is slightly negative (skew = -0.19).

FIG. 3. (a) Phase difference between the composite mean $Z^{*\prime}$ and Z^*_c at 60°N averaged over days [-30,-1] for the weak and strong vortex composites. (b) and (d) stratospheric (≥ 100 hPa) anomaly correlation between the composite mean $Z^{*\prime}$ and Z^*_c at 60°N for the full wave field (solid curve) and the wave-1 component (dashed curve) for the weak and strong vortex composites, respectively. (c) and (e) same as (b) and (d) but for the tropospheric (< 100 hPa) anomaly correlation.



Weak (strong) vortex composites exhibit persistent constructive (destructive) linear interference of $Z^{*\prime}$ and Z^*_c preceding the zero lag giving rise to the steady positive (negative) LIN flux tendencies illustrated in Fig. 2. The sudden switch in the sign of the anomaly correlation at the zero lag implies a sudden weakening (strengthening) of the part of the wave anomaly that projects onto the background climatological wave. After the zero lag, the anomaly correlations in the troposphere and stratosphere in Fig. 3 become uncoupled for both composites and the magnitude of the LIN flux weakens.

The persistence of the phasing of $Z^{*\prime}$ and Z^*_c is further illustrated in Fig. 4 which shows that the winter decorrelation function of the phase is much greater than the amplitude.

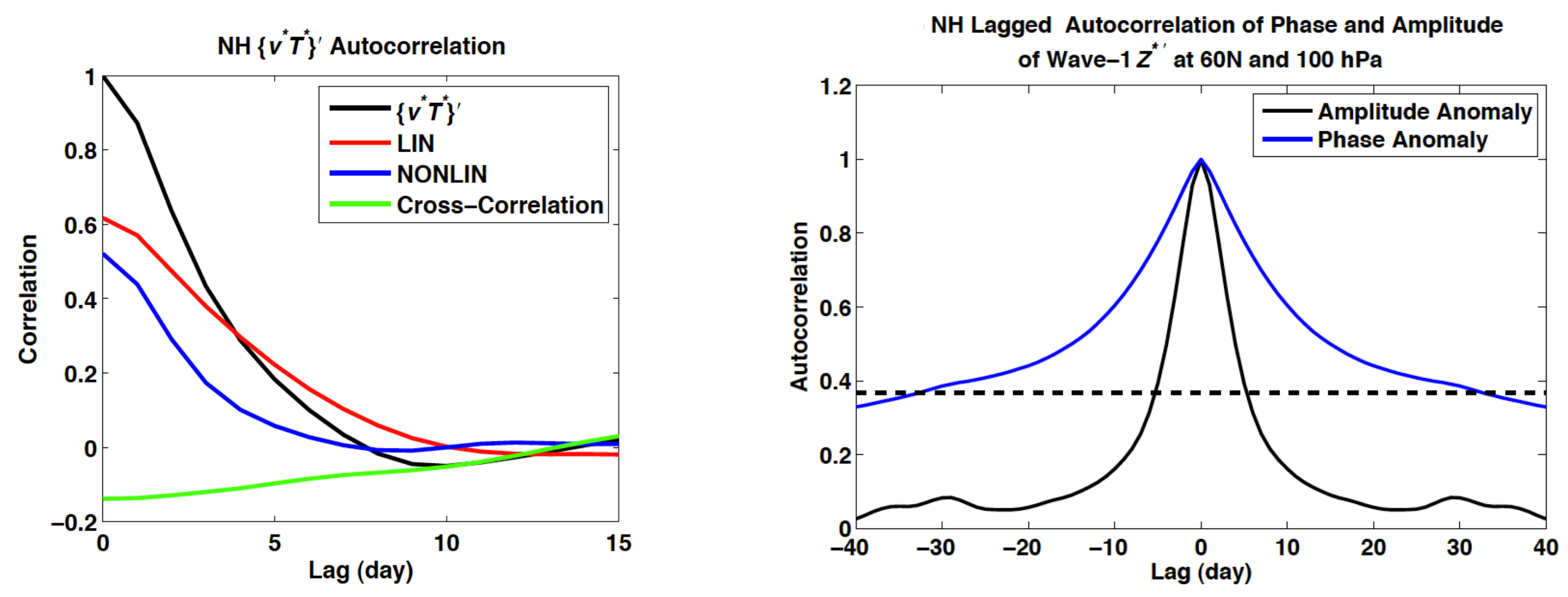


FIG. 4. (left) Heat flux anomaly lagged autocorrelations for {v^*T^*}$'$, LIN and NONLIN and the cross-correlation of LIN and NONLIN. (right) Lagged Autocorrelation of the phase and amplitude of the wave-1 $Z^{*\prime}$ at 60°N and 100 hPa. The dashed line is 1/e.

Stratospheric Sudden Warmings

The heat flux anomaly decomposition also provides evidence for differing processes preceding displacement (D) and split (S) stratospheric sudden warming (SSW) events (NCEP-NCAR Reanalysis from 1958-2009). D events are preceded by a persistent enhancement of wave-1 LIN fluxes while S events are preceded by a pulse of wave-2 NONLIN fluxes (Fig. 5).

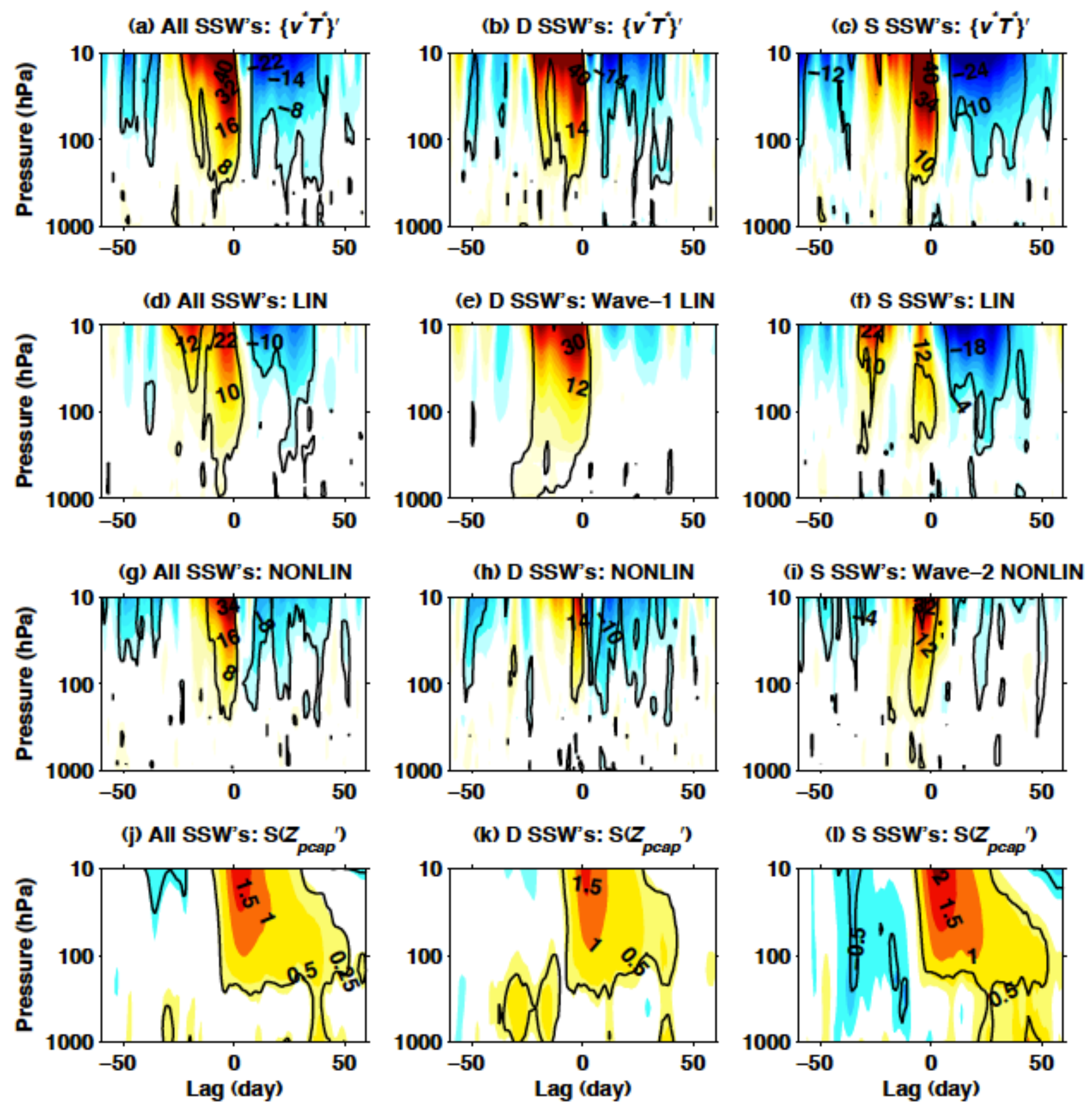


FIG. 5. SSW composite mean daily heat flux anomaly decomposition for (a) {v^*T^*}$'$, (d) LIN and (g) NONLIN. (b), (e) and (h) and (c), (f) and (i) same as (a), (d) and (g) but for D SSWs (LIN fluxes are wave-1 only) and S SSWs (NONLIN fluxes are wave-2 only). (j)-(l) shows the composite mean S(Z_{pcap}') for SSWs, displacement (D) SSWs and split (S) SSWs, respectively. Black contour indicates 95% significance.

Southern Hemisphere

Although the climatological waves are weaker in the SH, the interannual variance of {v^*T^*} is dominated by the low-frequency LIN component during the season of stratosphere-troposphere interactions, spring. The composites reveal that the NONLIN fluxes contribute slightly more to weak and strong vortex events. The LIN fluxes remain considerable, contributing ~ 40% to the composite mean.

Conclusions

In summary, as DN2000 demonstrate for momentum fluxes and tropospheric variability, we demonstrate that linear interference effects are an integral part of heat flux variability and, consequently the coupled variability of the stratosphere and troposphere. Collectively, this work demonstrates that interactions between wave anomalies and the climatological waves appear to be vitally important to Annular Mode dynamics in both the troposphere and stratosphere.

The persistence of the anomalous wave patterns associated with the LIN fluxes suggests that the identification of multiple week trends in the phase structure of these patterns may improve seasonal prediction.