Optimal nonmodal growth as a contributing cause to the Southern Hemisphere annular mode variability

Harun Rashid and Ian Simmonds
School of Earth Sciences, The University of Melbourne Melbourne, Victoria 3010, Australia
E-mail: harun@earthsci.unimelb.edu.au

The southern annular mode (SAM) is the leading mode of Southern Hemisphere (SH) circulation variability, the temporal evolution of which is characterized by large amplitudes and long persistence. Its spatial structure is dominated by a zonally-symmetric pattern, a see-saw meridional variation of zonal flow anomalies between 40°S and 60°S, and an equivalent barotropic structure in the vertical (e.g., Limpasuvan and Hartmann, 2000; Thompson and Wallace, 2000). Previous investigators have suggested a positive feedback mechanism that explains some of this low-frequency variance (Lorenz and Hartmann, 2001). Here, we propose another mechanism, involving transient nonmodal growths of the anomalies, that is at least as effective as the positive feedback mechanism in increasing the low-frequency variance of the SAM.

Using the *vector autoregressive modeling* (VAR) technique, we first derive a number of empirical models of SAM variability from a 22-year (1979–2000) record of NCEP/DOE Reanalysis 2. These models are then analyzed applying the ideas of the generalized stability theory (Farrell and Ioannou, 1996). Two VAR models, of order 1 and 3, are investigated in detail. The system matrices characterizing these models are found to be *nonnormal* (i.e., they do not commute with their respective transposes), indicating that these matrices have *nonorthogonal* sets of eigenvectors. Using a Schur decomposition, the system matrix **R** was separated into a normal matrix **N** and an asymmetric matrix **A**, which is related to the *departure from normality* of **R** (Golub and Loan, 1996). An examination of the elements of **A** shows that the main source of nonnormality of **R** is the strong forcing of the SAM provided by the high-frequency eddies (of periods 2–8 days). The above Schur decomposition also enabled us to determine the relative importance of the effects of nonnormality and of the positive feedback on SAM variability. This was done in two stages. First, SAM indexes were simulated using, in turn, the full coefficient matrix **R** the normal matrix **N**, and the matrix **R** with the element representing the zonal-wind feedback on the eddies set to zero. Then, the power spectra of the simulated SAM indexes were computed, which are displayed in Fig. 1. In each case, white-noise realizations having the same noise covariance matrix were used for driving the simulated processes. Therefore, the differences between the three spectra in Fig. 1 are solely due to the differences in deterministic contributions caused by the presence/absence of nonnormality and of feedback. The figure shows that both the nonnormality and the zonal-wind feedback have significant effects on the low-frequency variance of the SAM, with the former having a larger overall effect.

Because of the nonnormality of the system matrix **R**, the anomalies governed by this system may undergo *transient growths* due to modal interferences (Farrell and Ioannou, 1996), even though the system under consideration is stable. The *optimal* transient growth in such a system is associated with the right singular vector (V_1) corresponding to the largest singular value (σ_1) of **R**. If $\sigma_1 > 1$, then an initial field of anomalies projecting strongly on V_1 should experience optimal nonmodal growth before its ultimate decay. To determine whether this nonmodal growth can be detected in the temporal evolution of the observed SAM index, we constructed composites of the time-lagged SAM index corresponding to initial fields that project strongly on V_1, for the VAR(1) and VAR(3) models. The composites are presented in Fig. 2 separately for the positive anomaly growths and negative anomaly growths. The figure shows that the anomaly fields that have a significant projection on V_1 are indeed followed by the evolutions of the SAM index with growths of positive or negative anomalies. This result combined with

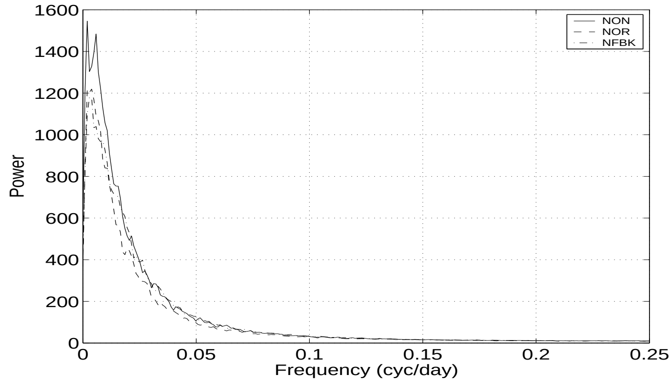

Figure 1: Power spectra of the simulated SAM indexes showing the effects of nonnormality and feedback on the SAM variability in the VAR(1) model.

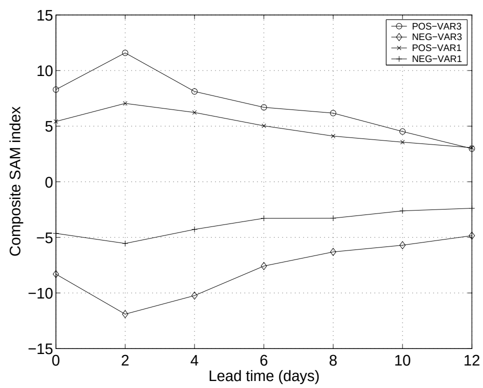

Figure 2: Composites of the time-lagged SAM index corresponding to initial perturbations that project strongly on the optimal perturbations of the VAR(1) and VAR(3) models.

that presented in Fig 1 show that a considerable fraction of the low-frequency variance of the SAM is caused by optimal nonmodal growths of the anomalies.

References

Farrell, B. F. and P. J. Ioannou: 1996, Generalized stability theory. Part 1: Autonomous operators. *J. Atmos. Sci.*, **53**, 2025–2040.

Golub, G. H. and C. F. V. Loan: 1996, *Matrix Computations. 3rd ed*. The Johns Hopkins University Press, Baltimore and London, 694 pp.

Limpasuvan, V. and D. L. Hartmann: 2000, Wave-maintained annular modes of climate variability. *J. Climate*, **13**, 4414–4429.

Lorenz, D. J. and D. L. Hartmann: 2001, Eddy–zonal flow feedback in the Southern Hemisphere. *J. Atmos. Sci.*, **58**, 3312–3327.

Thompson, D. W. J. and J. M. Wallace: 2000, Annular modes in the extratropical circulation. Part I: Month-to-month variability. *J. Climate*, **13**, 1000–1016.