Is Interannual Zonal Mean Flow Variability Simply Climate Noise?

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ABSTRACT

This study uses National Centers for Environmental Prediction–National Center for Atmospheric Research reanalysis data to investigate the extent to which interannual zonal index (ZI) fluctuations occur in the atmosphere and whether interannual ZI fluctuations can be accounted for by climate noise associated with the intraseasonal ZI. By using an empirical orthogonal function analysis, it is shown that the ZI is indeed a prominent form of interannual variability, because the interannual ZI corresponds to EOF1 (EOF2) for the winter (summer) seasons of both hemispheres. Also, by application of spectral, correlation, and χ^2 analyses, it is shown that interannual ZI variability can be interpreted as arising from climate noise.

1. Introduction

Zonal index (ZI) fluctuations are characterized by latitudinal movements of zonally averaged relative angular momentum within the subtropics and midlatitudes (e.g., Kidson 1985, 1986, 1988; Nigam 1990; Robinson 1991, 1996; Yu and Hartmann 1993; Hartmann 1995; Lee and Feldstein 1996; Feldstein and Lee 1996, 1998; Hartmann and Lo 1998). These studies typically identify the ZI as the first empirical orthogonal function (EOF1) of the zonally averaged, relative angular momentum or zonal wind, and find that EOF1 takes on a dipole latitudinal structure. This EOF1 structure corresponds to a latitudinal movement of the eddy-driven jet during the Northern Hemisphere (NH) and Southern Hemisphere (SH) summer, simultaneous latitudinal displacements of the eddy-driven and subtropical jets during the SH winter, and a strengthening and weakening of the subtropical jet during the NH winter (Feldstein and Lee 1998). While each of the above investigations of the ZI has dealt with intraseasonal ZI fluctuations, which normally persist for periods up to two weeks, the findings of van Loon and Rogers (1981), Hoerling et al. (1995), and Ting et al. (1996) show that ZI behavior is also a prominent form of interannual zonal mean flow variability. In these investigations of interannual variability, composite zonally averaged zonal flow anomalies take on a dipole latitudinal structure that closely resembles those found in most intraseasonal ZI studies.

The motivation for examining interannual ZI fluctuations received a recent boost by the companion studies of Hoerling et al. (1995) and Ting et al. (1996). Using a linear stationary wave model, these studies showed that interannual ZI fluctuations are closely related to the observed interannual variation of regional climate anomalies. Using data from a general circulation model (GCM) run, Feldstein and Robinson (1994) suggested that interannual ZI fluctuations can arise from climate noise (Leith 1973; Madden 1976; Madden and Shea 1978; Trenberth 1984, 1985; and Dole 1986), which involves much shorter timescale intraseasonal ZI fluctuations. However, as the sea surface temperature (SST) field in the model analyzed by Feldstein and Robinson (1994) was specified to undergo the same climatological seasonal cycle each year, it remains an open question as to whether climate noise can account for interannual ZI variability in the atmosphere.

The concept of climate noise addresses whether the variance of long time averages is due to sampling fluctuations associated with processes that take place on a timescale much less than the averaging time period. As an example of the climate noise concept, consider a time series represented by a red noise process, with a total length of T years and a timescale of τ days, where τ is defined to be the time over which the autocorrelation function of the time series decreases by a factor of e. For all periods much greater than τ, the power spectrum of such a process is white. Next, consider a new time series constructed by dividing the original time series into T/T_o number of segments, where $\tau \ll T_o \ll T$, and the data within each segment, whose length is T_o, are represented by a single value formed by a time average. It is the variance of this new time series that we refer to as resulting from climate noise. Because of the pres-

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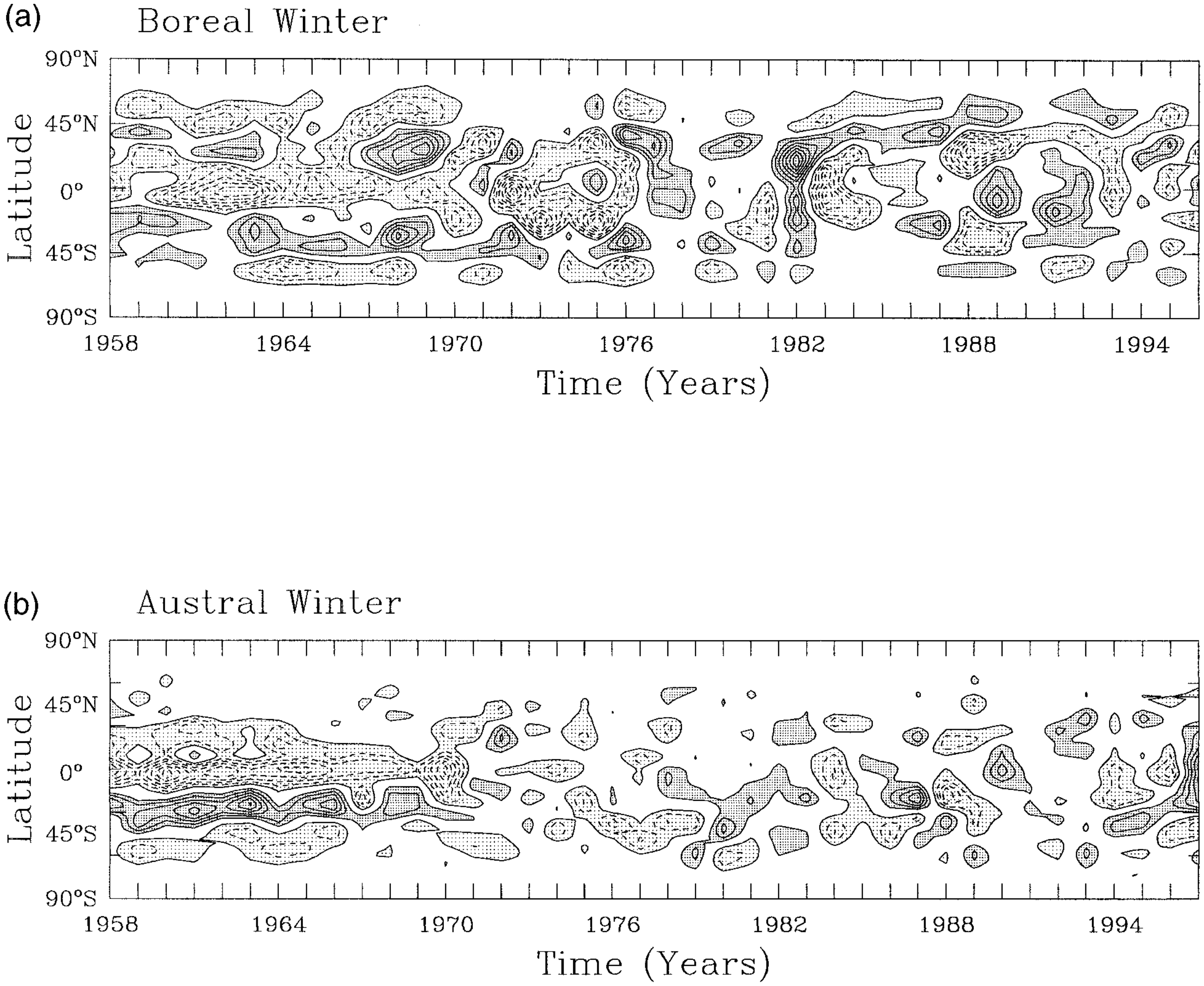

FIG. 1. Latitude–time diagram of the seasonal averaged anomalous $M_R/(1.0 \times 10^{24})$. The contour interval is 0.2 kg m^2 s^{-1}. Solid contours are positive, dashed contours are negative, and the zero contour is omitted. Shaded values exceed a magnitude of 0.2 kg m^2 s^{-1}, with dark (light) shading denoting positive (negative) values.

ence of power at all periods, the variance of this new time series must have a nonzero value, no matter how large T_o is. However, as shown by Nitsche (1996), the variance of such a time series declines as the averaging period T_o increases. Within the context of the ZI, τ is approximately 2 weeks, and we specify T_o to correspond to one season. We then address the question of whether interannual ZI fluctuations, which are generated from seasonally averaged data, arise from climate noise caused by the much shorter timescale intraseasonal ZI fluctuations.

Thus, the aim of this study is to investigate whether large amplitude, interannual ZI fluctuations do take place, and if so, to examine whether the occurrence of the observed interannual ZI can be interpreted as being due to climate noise. In section 2, the data and methodology are presented, followed by the results in section 3, and concluding remarks in section 4.

2. Data and methodology

The relative angular momentum data used in this study are derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis dataset, for the interval of 1 January 1974 to 31 December 1997. Relative angular momentum, $M_R(\theta, t)$, is expressed as

$$M_R(\theta, t) = \frac{a^2}{g} \int_0^{2\pi} \int_0^1 p_s u \cos^2\theta \, d\sigma \, d\lambda, \qquad (1)$$

where u and p_s denote the zonal wind and surface pressure, respectively; σ, λ, and θ are the vertical, longitudinal, and latitudinal coordinates, respectively; t is time; a is the earth's radius; and g is the gravitational acceleration. In this study, we will be examining the properties of M_R anomalies, where an anomaly is defined as the deviation from the seasonal cycle. The seasonal

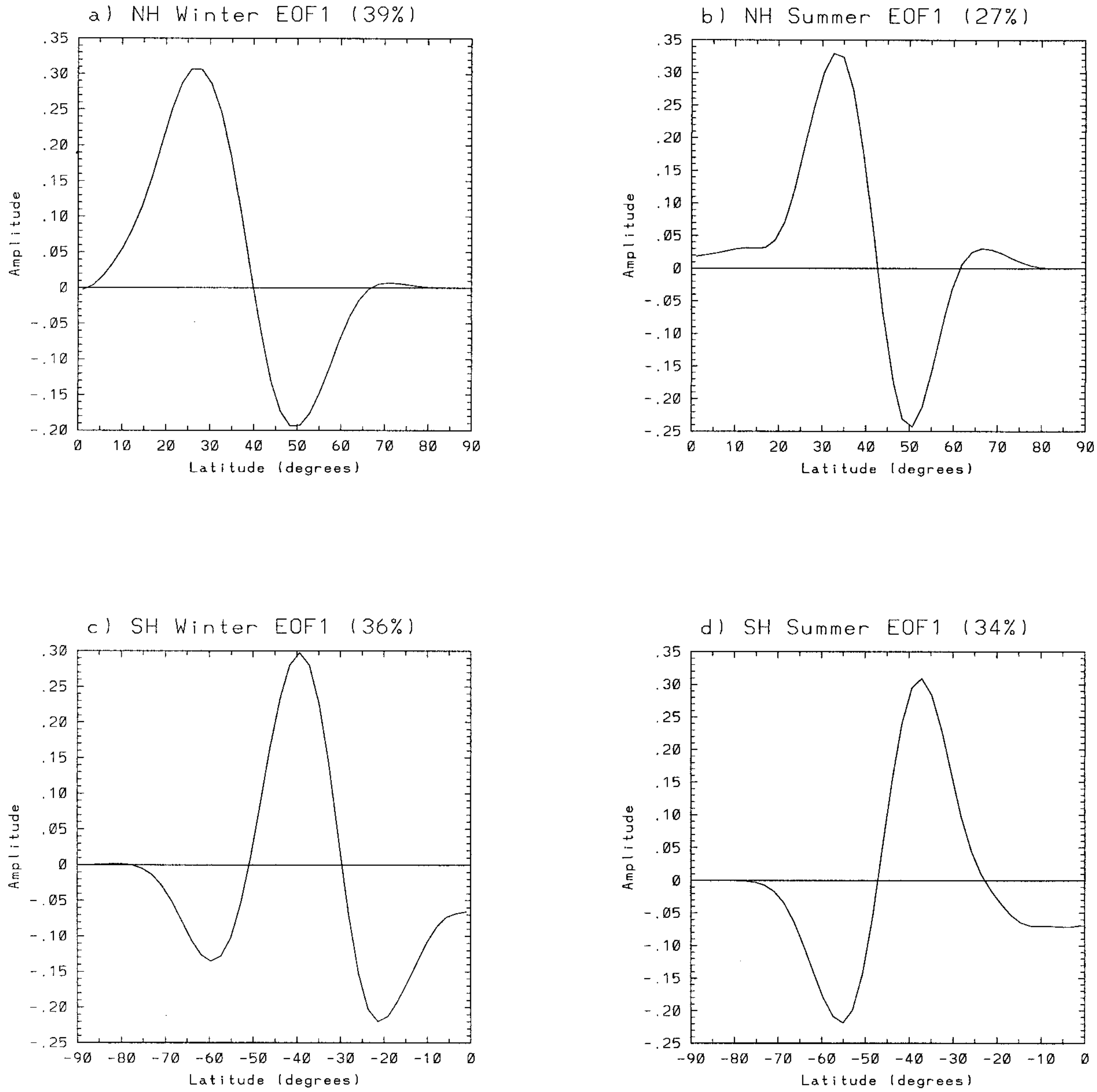

FIG. 2. EOF1 for (a) the NH winter, (b) the NH summer, (c) the SH winter, and (d) the SH summer, based on the daily M_R. The fractional variance is indicated at the top of each frame.

cycle is calculated by taking the time mean M_R for each calendar day followed by smoothing with a 20-day lowpass digital filter. The anomalous M_R is separated into equally spaced 2.25° latitudinal bands, and the vertical integral extends from $\sigma = 0.995$ to $\sigma = 0.0027$. [Feldstein and Lee (1998), who define the ZI using the same range of sigma levels, find essentially identical results if the vertical integral in (1) is restricted to the troposphere.]

The intraseasonal ZIs are defined as the EOF1 of the daily anomalous M_R field. The interannual ZIs are then identified with the particular EOF of the seasonal mean anomalous M_R field, which has a spatial structure that closely resembles the intraseasonal EOF1, as long as such an EOF does indeed exist. The corresponding principal component time series associated with these EOFs is defined as the ZI time series, as in Feldstein and Lee (1998). For these calculations, the boreal (austral) winter season is specified as the months of November–March (May–September). When discussing the ZI for a particular hemisphere, we will refer to these seasons as the NH winter and SH summer, and the NH summer and SH winter, respectively.

The seasonal mean anomalous M_R for the period of 1 January 1958 to 31 December 1997 is shown in Fig. 1. As can be seen, the M_R anomalies are much more persistent prior to 1973, when compared with the following years. Because of this change in the properties of the interannual M_R anomalies (whether this change in the interannual M_R anomalies is related to any data deficiencies in the early part of the NCEP–NCAR reanalysis period is not examined), we limit our analysis to the period of 1 January 1974–31 December 1997, as indicated above.

3. Results

The EOF1 of daily anomalous M_R, for each of the two hemispheres and two seasons, are shown in Fig. 2. The shape and fractional variance of these EOF1 are extremely similar to those found in the intraseasonal ZI study of Feldstein and Lee (1998), which used NCEP–NCAR reanalysis data covering the shorter period of 1 January 1979–31 December 1995.

One issue that has not been addressed in previous intraseasonal ZI studies is the question whether the ZI represents a zonally symmetric signal or if it is simply a small zonal mean residual of many regional zonal wind anomalies of both signs. To address this question, the 300-mb relative angular momentum field $u(\lambda, \theta, t)a \cos\theta$ was calculated at each longitude, and this quantity was projected onto the EOF1 spatial pattern. These projections were performed for each of the high and low ZI events presented in Feldstein and Lee (1998). On average, depending upon the season, hemisphere, and phase of the ZI, it was found that between 65% and 70% of the longitudes had a positive projection onto the corresponding EOF1 pattern. These results show that the ZI can indeed be understood as representing a zonal mean signal.

To examine the longitudinal variation of the flow associated with the ZI, we plot the frequency (as a percentage) of ZI events for which the relative angular momentum at a particular longitude projects positively onto the EOF1 pattern (see Fig. 3). As can be seen, for the NH winter, the vast majority of ZI events are characterized by positive relative angular momentum projections from both the Pacific and Atlantic Oceans. On the other hand, the SH summer exhibits much less longitudinal variation in the projections. A similar lack of longitudinal variation is also found in the NH summer and SH winter projections (not shown). Thus, the NH winter ZI appears to be distinct in that there is a strong preference for certain longitudes to contribute toward the ZI. Also, one-point correlation maps were generated that show that the North Atlantic and North Pacific relative angular momentum is essentially uncorrelated (the largest correlations between the two oceans had a value of -0.2). This implies that the NH winter ZI must result from the random coincidence of North Atlantic and North Pacific relative angular momentum anomalies with an EOF1 spatial pattern. This same characteristic was found by Ting et al. (1996) for the interannual ZI.

The power spectra for each of the four intraseasonal

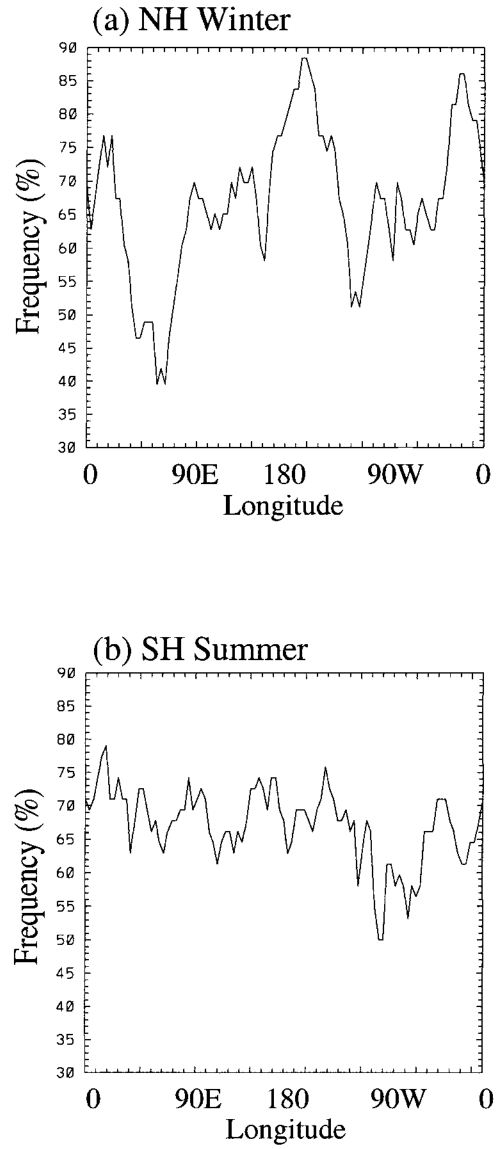

FIG. 3. The frequency of ZI events for which the relative angular momentum at each longitude projects positively onto the intraseasonal EOF1 spatial pattern.

ZI time series, along with red noise spectra and 95% confidence levels based on the lag 1-day autocorrelation, are illustrated in Fig. 4. These ZI power spectra were obtained by averaging each of the 24 individual winter or summer periodograms, and the 95% confidence levels are based on the approximation of 48 degrees of freedom (2 degrees of freedom for each periodogram value). As can be seen, all four ZIs are well described by a first-order Markov (red noise) process. Also, an estimate of the *e*-folding timescale associated with the four intraseasonal ZI time series can be obtained from the autocorrelation function. For NH winter, NH summer, SH winter, and SH summer, these *e*-folding timescales are found to be 18, 8, 10, and 14 days, respectively, veri-

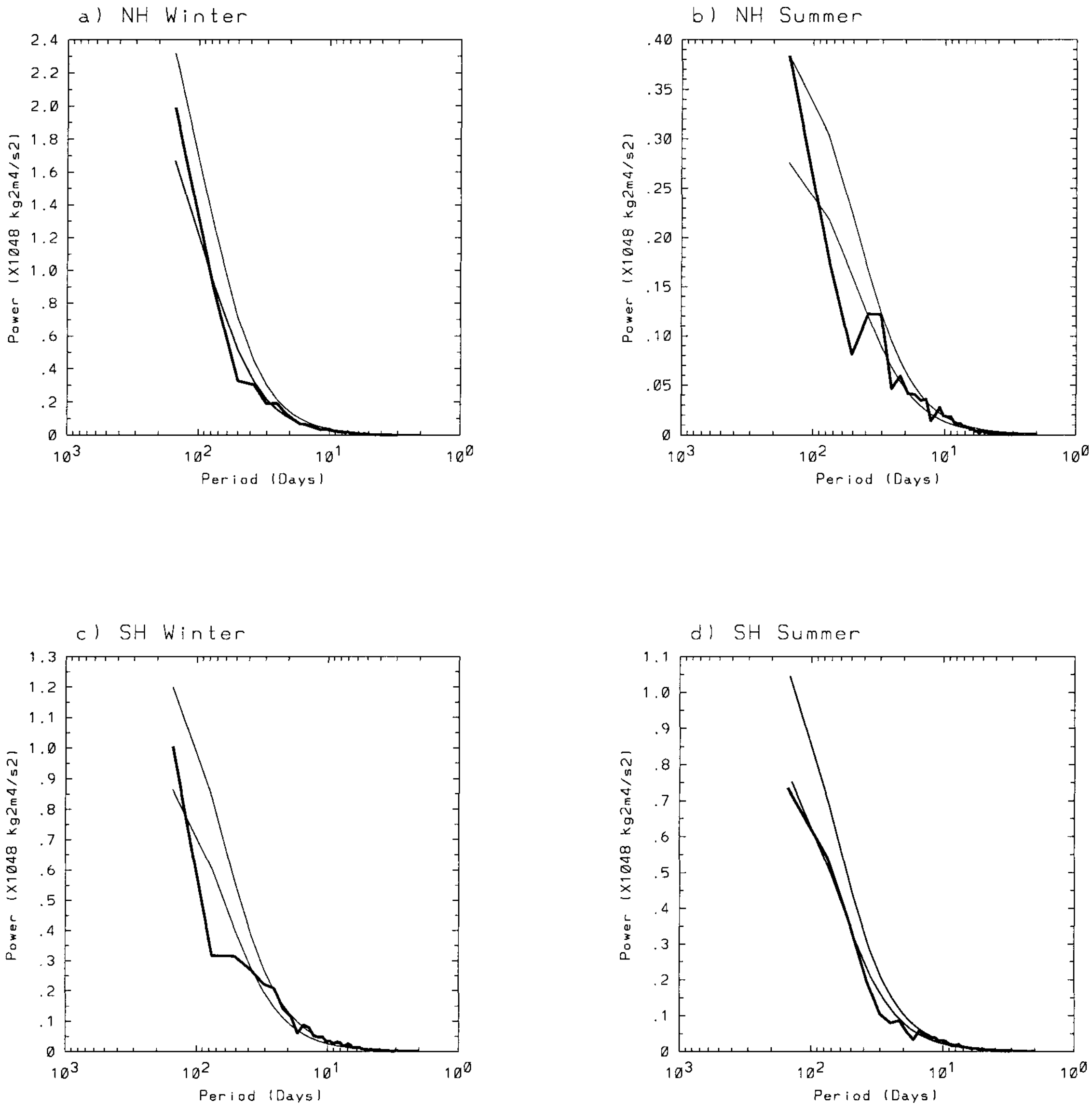

FIG. 4. Power spectra for the intraseasonal ZI time series for (a) the NH winter, (b) the NH summer, (c) the SH winter, and (d) the SH summer. The corresponding red noise spectra and 95% confidence levels are also shown.

fying that the timescale for the ZI is indeed just a small fraction of the length of a single season.

We next compare the EOFs associated with the interannual ZI (Fig. 5) with those for the intraseasonal ZI (Fig. 2). Excellent agreement in spatial structure can be seen for the NH and SH winter seasons, and also for the NH and SH summer seasons outside of the deep Tropics. Furthermore, as the interannual ZI corresponds to EOF1 (EOF2) in the two winter (summer) seasons, it is clear that the ZI is indeed a very prominent form of interannual zonal mean flow variability. (The summer season EOF1 are primarily monopole structures with largest amplitude in the Tropics.)

Further support for the relationship between the intraseasonal and interannual ZI is obtained by linearly correlating the interannual ZI time series with the time series constructed by taking nonoverlapping, seasonal-averaged segments of the intraseasonal ZI time series. The resulting linear correlations for the NH winter, NH summer, SH winter, and SH summer, are 0.89, 0.69, 0.98, and 0.91, respectively, which are high for three of the four seasons, and marginal for the NH summer. The large values for these linear correlations indicates that the interannual ZI time series simply corresponds to interannual fluctuations of the intraseasonal ZI time series. Furthermore, this result implies that the essential features of the interannual ZI are captured by the intraseasonal ZI analysis.

Because of the above link between the intraseasonal and interannual ZI analyses, we can use each of the

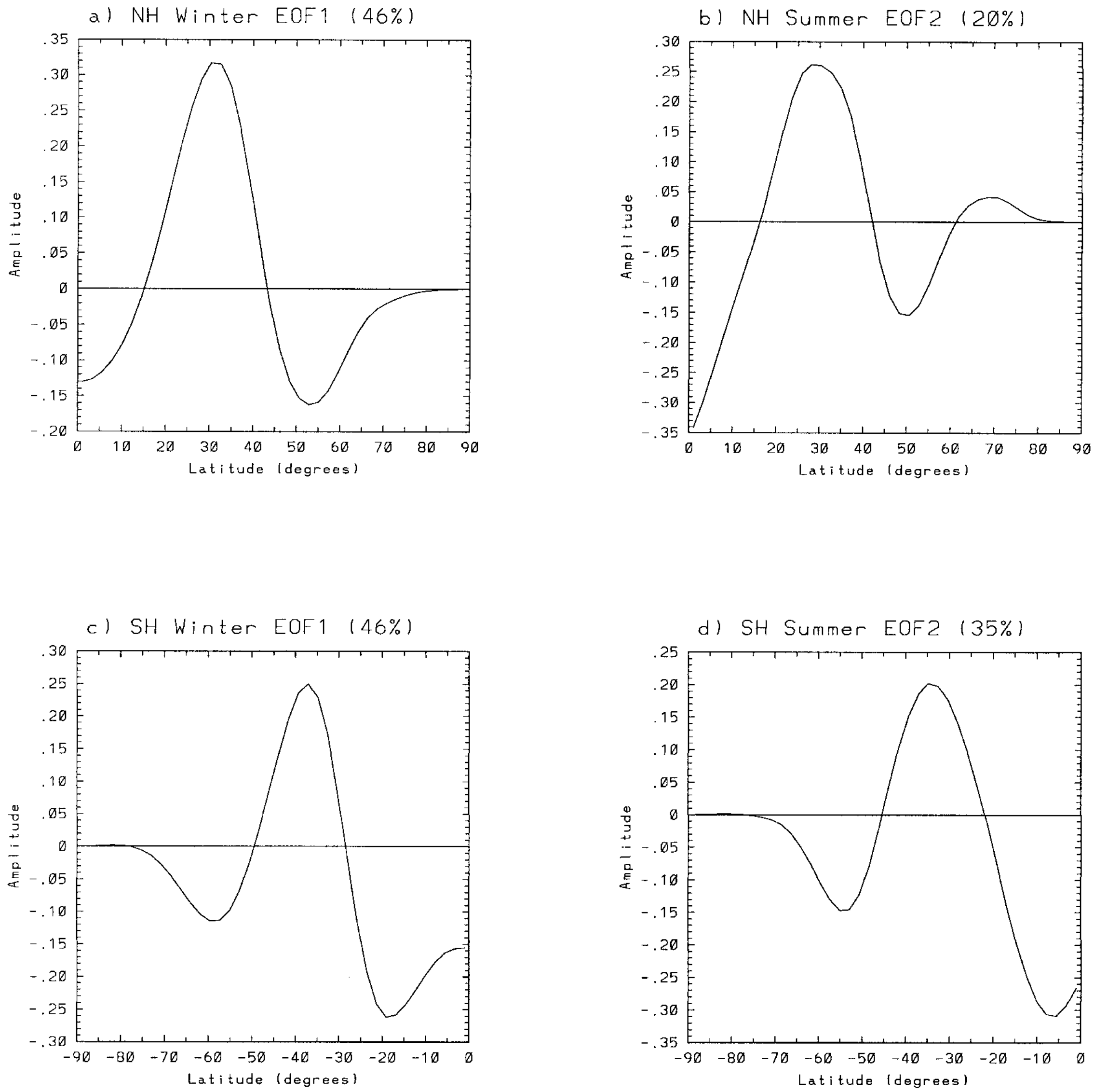

FIG. 5. The EOFs corresponding to the interannual ZI for (a) the NH winter, (b) the NH summer, (c) the SH winter, and (d) the SH summer. The fractional variance and ranking are indicated at the top of each frame.

intraseasonal ZI time series to examine whether interannual ZI fluctuations arise from climate noise. Following the procedure in Dole (1986) and Feldstein and Robinson (1994), we calculate $\chi^2 = NS_z^2/S^2$, where N is the number of degrees of freedom ($N = 23$, one less than the number of years in the time series), S_z^2 is the interannual variance of the intraseasonal ZI time series (i.e., the variance of the ZI time series of the previous paragraph, generated from nonoverlapping seasonally averaged segments), and S^2 is the interannual variance of the first-order Markov process corresponding to the appropriate red noise spectra in Fig. 4. For the purpose of calculating S^2, a 10 000-day synthetically generated time series was obtained that has the same variance and lag 1-day autocorrelation as the corresponding ZI time series. We then specify a null hypothesis that S_z^2 is not greater than S^2 and then examine the statistical significance of χ^2. The resulting χ^2 for the NH winter, NH summer, SH winter, and SH summer, are 25.2, 24.3, 26.6, and 27.6. As each of these χ^2 values is close to that expected for the null hypothesis, that is, $\chi^2 = 23$, which is well below the 95% confidence level value of $\chi^2 = 35.2$, we cannot reject the null hypothesis, and we interpret the interannual ZI fluctuations as arising from climate noise.

4. Concluding remarks

The results of this study show that there are prominent interannual ZI fluctuations in both the winter and summer seasons of both hemispheres. Furthermore, it is also demonstrated that these interannual ZI fluctuations arise to a large degree from climate noise associated with intraseasonal ZI fluctuations.

The results of this study are also consistent with Hoerling et al. (1995), who show with an ensemble of GCM runs that the interannual variance in the zonally averaged zonal flow can be attributed to internal (external) processes in the midlatitudes (deep Tropics). In their study, the external variance is attributed to interannual changes in the SST. To the extent that these model results apply to the atmosphere, these findings are consistent with the interannual ZI being climate noise, because the intraseasonal ZI has its largest amplitude where internal processes dominate and the SST anomalies have little influence.

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