Rainfall Variability at Decadal and Longer Time Scales: Signal or Noise?

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ABSTRACT

Rainfall variability occurs over a wide range of temporal scales. Knowledge and understanding of such variability can lead to improved risk management practices in agricultural and other industries. Analyses of temporal patterns in 100 yr of observed monthly global sea surface temperature and sea level pressure data show that the single most important cause of explainable, terrestrial rainfall variability resides within the El Niño–Southern Oscillation (ENSO) frequency domain (2.5–8.0 yr), followed by a slightly weaker but highly significant decadal signal (9–13 yr), with some evidence of lesser but significant rainfall variability at interdecadal time scales (15–18 yr). Most of the rainfall variability significantly linked to frequencies lower than ENSO occurs in the Australasian region, with smaller effects in North and South America, central and southern Africa, and western Europe. While low-frequency (LF) signals at a decadal frequency are dominant, the variability evident was ENSO-like in all the frequency domains considered. The extent to which such LF variability is (i) predictable and (ii) either part of the overall ENSO variability or caused by independent processes remains an as yet unanswered question. Further progress can only be made through mechanistic studies using a variety of models.

1. Introduction

Rainfall variability is one of the most important factors determining variability in agricultural production. This has severe consequences for individuals and societies, causing crop failures, loss of livestock, and associated loss of income and even famine. It also results in considerable environmental degradation particularly when combined with inappropriate management strategies (Hammer 2000; Allan 2000; Meinke et al. 2003). Economic pressure on farmers often exacerbates the downward spiral of land degradation via irreversible trade-offs between short-term economic gains and long-term sustainability. In this context Basher (2000), Hammer (2000), Hansen (2002), and Podestá et al. (2002) show that an understanding of rainfall variability is essential for appropriate agricultural risk management, and Nelson et al. (2002) describe how understanding of ENSO-related rainfall variability is becoming increasingly accepted in tactical risk management approaches to agriculture. However, there is also an increasing interest in understanding longer-term variability and associated strategic management and investment options (Meinke and Stone 2004).

Although research into ENSO-related rainfall variability (Ropelewski and Halpert 1989; Nicholls and Wong 1990; Zhang and Casey 1992) or secular climate change (Houghton et al. 2001; Hulme et al. 2002) has been predominant, Latif and Barnett (1996), Zhang et al. (1997), Folland et al. (1999), Meehl et al. (1998), Moron et al. (1998), Enfield and Mestas-Nuñez (1999), Power et al. (1999b), Allan (2000), and White and Tourre (2003) have described global low-frequency (LF) phenomena modulating climatic regimes and rainfall variability at time scales of decades and longer. Studies have also begun to focus on decadal to multidecadal variability in various ocean basins or specific regions of the globe (Andreoli and Kayano 2003; Chang et al. 1997; Chao et al. 2000; Peterson and Schwing 2003; Takahashi et al. 2003; Tourre et al. 1999, 2001; Tourre and White 2003). This has extended to investigations of correlations between global, LF sea surface temperature (SST) anomalies and seasonal rainfall and pressure patterns in the Tropics and subtropics (Folland et al. 1999), the North Atlantic region (Mysak and Venegas 1998), India (Annamalai et al. 1999; Krishnan and Sugi 2003), North America (Barlow

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et al. 2001), northern Africa (Ward 1998), and Australia (Allan 2000). There is also a growing body of research looking to disentangle possible interactions between, and resolve the physical mechanisms underlying, various biennial, interannual, decadal, and LF signals in the climate system (White and Cayan 2000; White and Allan 2001; White et al. 2003; Allan et al. 2003).

The consequences of LF rainfall variability on farming are also well documented (Allan 2000). Farming practices developed during periods of above-average rainfall are frequently suboptimal or even inappropriate during drier periods (Meinke and Hammer 1995), often leading to a rapid decline in productivity, environmental degradation, and increased farm abandonment (McKeon et al. 1990).

Knowledge of the existence of LF oscillations in SST and sea level pressure (SLP) patterns that are associated with rainfall fluctuations attracts attention and generates interest in long-lead forecasting. Studies of the interdecadal Pacific oscillation (IPO; Power et al. 1999a) or the Pacific decadal oscillation (PDO; Mantua et al. 1997; Mantua and Hare 2002) have the potential to improve our ability to forecast climate anomalies, but key scientific questions remain unanswered. Until then the existing disquiet among scientists as to the use of these measures for operational forecasting appears justified (Meinke and Stone 2004).

Thus, our objective in this study is to document associations of LF variability in SST and SLP with terrestrial rainfall for five frequency domains from interannual to multidecadal (Fig. 1). While the work of Power et al. (1999a) and Allan (2000) shows the impact of these frequency domains on rainfall, we are looking to quantify the relative importance of each domain and assess the likelihood that rainfall variability at such time scales is caused by red noise (i.e., random) processes alone. We anticipate that this will assist in the future development of a better predictive capacity at longer time scales. Predictability at decadal and longer time scales would considerably improve decision making and risk management in agriculture and therefore make an important contribution toward sustainable development. This could relate to short-term decisions on the levels of inputs, types of crops, planting options, and marketing at the farm level as well as to the long-term design of land-use options at the policy level. Cropping systems based on traditional risk management strategies, such as long fallows for water storage as practiced in eastern Australia, could have undesired environmental consequences via increased drainage and runoff in wetter years (Keating et al. 2003). Such unintended consequences of production can lead to substantial degradation of the resource base via erosion and increased salinity. Strategically intensifying crop rotations during

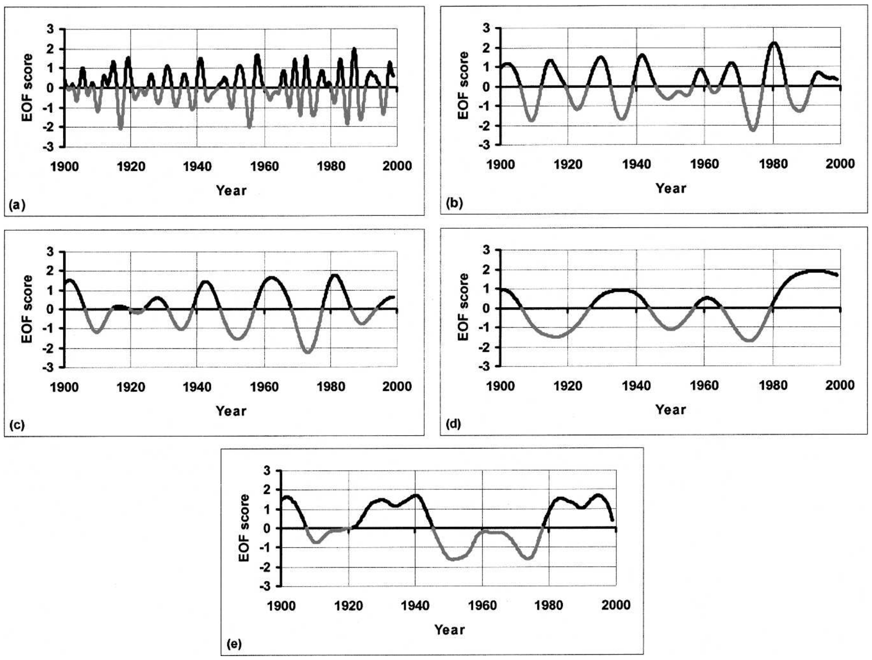

FIG. 1. Factor scores of EOF analyses of near-global SST and SLP data and Pacific SST data alone. The combined SST–SLP analysis contains four series, each bandpass filtered to domains of (a) 2.5–8.0 yr: ENSO time scale; (b) 9–13 yr: decadal time scale; (c) 13–18 yr: interdecadal time scale; and (d) 18–39 yr: multidecadal time scale. The Pacific analysis defines the IPO (e) with high-frequency components removed by using a low-pass filter with a 13-yr cutoff, and thus includes both the (c) 13–18- and (d) 18–39-yr time scales. The resultant EOF factor scores for each time series are split into groups of analog years, namely, years with a high (or positive) or a low (or negative) EOF component score.

likely wetter decades would not only alleviate such undesired effects, it would also increase the economic potential of cropping. At regional scales such forecasting ability would also assist with the implementation of flood and drought mitigation strategies and programs.

2. Data and methods

For this study we used factor scores from time series based on empirical orthogonal function (EOF) analyses of (i) near-global SST and mean SLP (MSLP) data (four time series bandpass filtered for significant frequencies) and (ii) Pacific SST data alone (one time series). The four frequencies resolved from the combined SST and MSLP analysis were (a) 2.5–8.0 yr, representing the ENSO time scale, (b) 9–13 yr for the decadal time scale, (c) 13–18 yr for the interdecadal time scale, and (d) 18–39 yr for multidecadal time scales (Allan 2000). Bandpass filters were used to isolate these specific frequency domains, which were identified through the spectral analysis component of a Multitaper Method singular value decomposition technique (Mann and Park 1999).

The Pacific SST time series results from the work of Power et al. (1999a), who found that many of the Pacific LF SST-based indices are similar. Power et al. (1999a) coined the term IPO to refer to the ENSO-like pattern, which Folland et al. (1999) obtained from their EOF analysis of low-pass-filtered near-global SST. Following Power et al. (1999a), we use a low-pass filter with a 13-yr cutoff, which includes both the 13–18 and 18–39 yr time scales.

The resultant five EOF time series (subsequently referred to as the five frequency domains) were split into two approximately equal sized categories, namely, years with a "high" (or positive) or "low" (or negative) EOF time series (Fig. 1). Thus all years are uniquely categorized. Although several of the Allan (2000) frequency domains are likely to be manifestations of the broader IPO phenomenon (Mantua et al. 1997; Folland et al. 2002; McPhaden and Zhang 2002; Mantua and Hare 2002), we will only refer to IPO in this paper as the phenomenon based on the analysis by Power et al. (1999a).

Here we analyze monthly rainfall over land. The global dataset covers the years 1900–99 and is an augmented version of a dataset compiled earlier (Hulme and Jones 1993). We calculated normalized[1] annual rainfall (June–May; this time period was chosen because it is better aligned with ENSO-related rainfall patterns; a January–December analysis yielded similar results and would not have altered our conclusions; data not presented) for each grid cell (2.5° latitude by 3.75° longitude resolution) for years when EOF scores were either high or low. For each frequency domain we then tested the two cumulative frequency distributions of rainfall for significant differences using a conventional Student's *t* test.

To distinguish the real signal from background (red) noise, we conducted a field significance analysis using the approach described by Livezey and Chen (1983). For this purpose we fitted autoregressive models to each EOF time series to allow the generation of red noise time series that exhibit the same statistical properties as the original EOF series. The significant area ratio (SAR), defined as the ratio of the number of significant grid cells divided by all grid cells between the latitude 45°S and 55°N, was recorded for 1000 randomly generated red noise time series and compared against the SAR from the analysis of the original EOF time series.

Previous studies have used correlations to show relationships between ocean and/or atmospheric patterns and rainfall (e.g., Power et al. 1999a,b). However, such relationships can be nonlinear and, hence, we deliberately chose a simple, two-way division for each time series based on the sign of the associated EOF score at that time. This is one of the simplest approaches possible and therefore signals that are at the extremes or even outside the randomly generated SAR distributions are likely to be the consequence of underlying mechanisms rather than just red noise variability. However, the opposite does not necessarily hold: a SAR value that cannot be differentiated from that obtained from a random process can either mean that the variability at that frequency is random (red noise) or that the method employed is not sensitive enough to detect a true (but weak) signal. Analyses were conducted assuming a zero lag between EOF score and rainfall (concurrent analysis). We acknowledge the problems associated with filtered data and therefore discourage the use of our findings in any predictive mode.

3. Results and comparison with previous studies

For the ENSO, decadal, and interdecadal frequency domains, SAR values differ significantly from those obtained from randomly generated populations (Table 1 and Fig. 2). Specifically, results for the traditional ENSO frequency domain (2.5–8.0 yr) showed the ENSO impact on global, annual rainfall to be large and nonrandom (Figs. 2a and 3a). This finding was expected, and we have included it to demonstrate the validity of our approach. It shows significant negative and positive rainfall anomalies (negative EOF versus positive EOF) in all the "classical" ENSO-affected regions, for example, Australia and Southeast Asia, South Africa, South America, parts of the United States, and even some parts of central Asia and Europe, as identified by Ropelewski and Halpert (1989), Tren-

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[1] The notoriously skewed nature of rainfall data violates homocedasticity assumptions, which are a prerequisite for many statistical tests. Hence, normalization is essential before parametric tests can be conducted.

TABLE 1. SAR, the ratio of the number of significant grid cells ($p \leq 0.05$) divided by all grid cells between lat 45°S and 55°N, and their associated significance levels (p values) for all frequency domains and for annual (Jul–Jun as in Fig. 2) as well as for 3-monthly, seasonal rainfall. SARs with associated p values of 0.05 or lower are shown in italic.

Rainfall period	ENSO		Decadal		Interdecadal		Multidecadal		IPO	
	P	SAR	*p*	SAR	*p*	SAR	*p*	SAR	*p*	SAR
Jul–Jun	0.01	*0.27*	0.01	*0.16*	0.03	*0.11*	0.21	0.12	0.22	0.11
JFM	0.01	*0.18*	0.01	*0.14*	0.05	*0.10*	0.22	0.09	0.02	*0.13*
AMJ	0.01	*0.13*	0.04	*0.08*	0.38	0.06	0.05	*0.09*	0.23	0.07
JAS	0.01	*0.19*	0.01	*0.10*	0.10	0.07	0.29	0.08	0.29	0.07
OND	0.01	*0.27*	0.03	*0.10*	0.17	0.07	0.08	0.09	0.27	0.07

berth and Caron (2000), and van Oldenborgh and Burgers (2001). The corresponding SAR is 0.27; that is, 27% of all grid cells exhibited significant difference in annual rainfall on this ENSO time scale (Table 1; Fig. 2a). Analyses of 3-monthly, seasonal rainfall patterns shows that ENSO impacts occur throughout the year, but the global impact is strongest during the October–December period (Table 1). These findings confirm that the method employed is suitable for detecting rainfall anomalies associated with key drivers of the climate system.

For the decadal frequency domain (Figs. 2b and 3b)

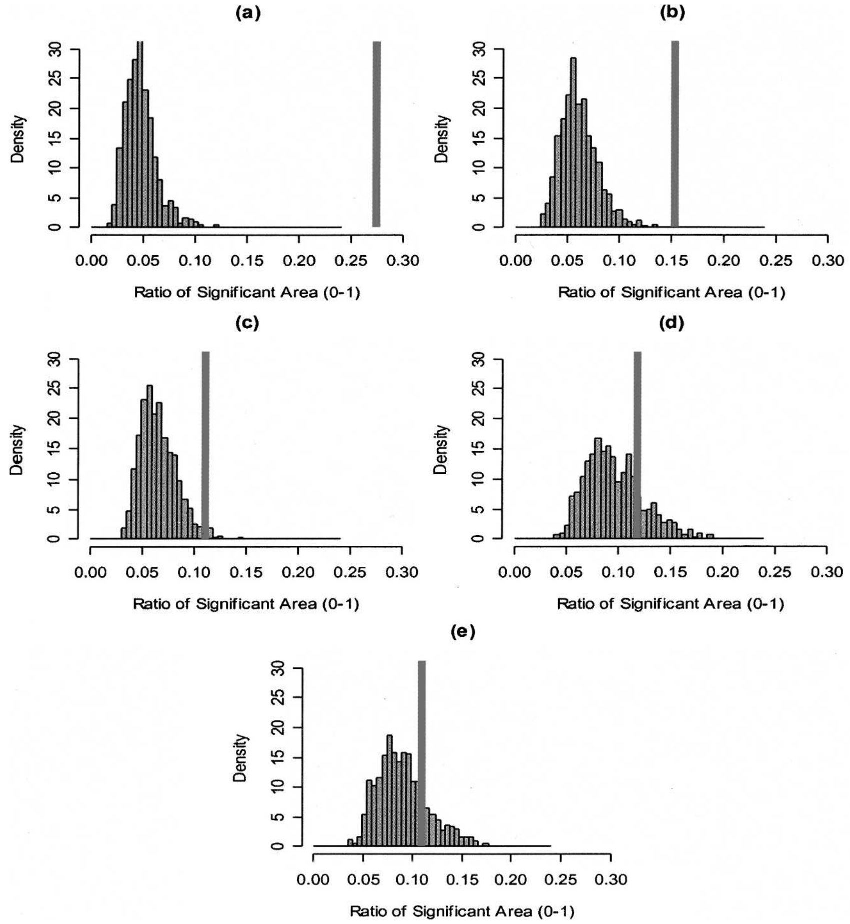

FIG. 2. Field significance analysis using a Monte Carlo approach; an autoregressive model is developed for each LF domain allowing the generation of random red noise signals that exhibit the same statistical properties as the original time series. SARs (as described in Table 1) calculated from 1000 random series are shown as histograms, and the value for the actual EOF time series from Fig. 1 is shown as a vertical bar. The LF domains shown are (a) ENSO, (b) 9–13 yr, (c) 13–18 yr, (d) 18–39 yr, and (e) IPO. The median value of the red noise distribution can be regarded as the likely level of "background noise."

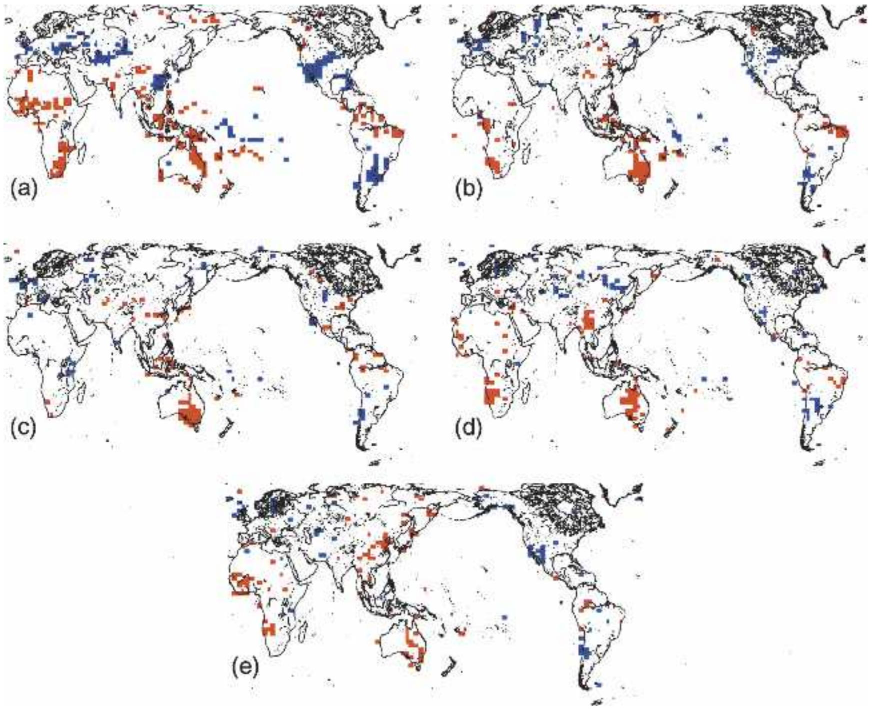

Fig. 3. Significant differences (t test, $p \leq 0.05$) between paired, cumulative distributions of normalized, annual rainfall (Jun–May) at each grid cell. Red indicates negative anomalies (distributions based on negative EOF scores vs those based on positive EOF scores), while blue indicates the inverse. Shown are the five different frequency domains: (a) ENSO, (b) 9–13 yr, (c) 13–18 yr, (d) 18–39 yr, and (e) IPO. Normalized annual rainfall for each cell is calculated from a monthly, global terrestrial rainfall dataset for the years 1900–99. At each frequency domain, two cumulative frequency distributions are developed from years when EOF scores were either high or low. We then test these distributions for significant differences using a conventional Student's t test.

the annual SAR value is 0.16 ($p \leq 0.01$). We also observe significant differences for all 3-monthly intervals, with the highest SAR values being for the January–March period (Table 1).

Although annual rainfall exhibits significant differences associated with the interdecadal frequency domain (Figs. 2c and 3c), most of the effect is associated with variability observed during the austral summer (January–March; Table 1). In Australia, where rainfall variability is amongst the highest in the world (Hammer 2000; Allan 2000; Meinke et al. 2003), ENSO affects mainly the northeast of the country, the decadal frequency domain affects much of central-eastern Australia, and the interdecadal frequency domain affects mainly southeastern Australia. These patterns are similar to the ENSO footprints identified by principal component analysis (PCA) of Australia-wide simulated wheat yields (Potgieter et al. 2005). Neither the multidecadal (Figs. 2d and 3d) nor the IPO (Figs. 2e and 3e) frequency domains result in significant annual rainfall differences, although at seasonal time scales the former shows some significance for the April–May–June (AMJ) period (albeit without an associated increase in SAR compared to the other seasons), while the IPO shows strong significance for January–February–March (JFM) with a corresponding SAR value of 0.13. These results further suggest that the IPO is a climatic phenomena that has spectral energy spread across a broad band of frequencies on interdecadal to multidecadal time scales (McPhaden and Zhang 2002; Hoerling and Kumar 2003).

Many authors have suggested that the main LF influence on global rainfall is via modulations of the frequency and/or amplitude of interannual ENSO events (Gershunov and Barnett 1998; Power et al. 1999a; Power et al. 1999b). Globally distributed proxy records have also indicated considerable ENSO variability at decadal, multidecadal, and century time scales (Mann et al. 2000; Cobb et al. 2003). However, a question remains as to whether LF variability is an inherent feature of ENSO itself, or a manifestation of a partially independent processes. The latter is strongly supported by analyses based on coral and tree-ring proxy data, which reveal strong decadal/multidecadal variability distinguishable from the decadal modulation of ENSO (Cole et al. 2000; Cobb et al. 2001, 2003; D'Arrigo et al. 2001; Evans et al. 2001; Linsley et al. 2000a,b, 2004;

Villalba et al. 2001), implying that the dynamics of decadal-like variability is distinct from ENSO.

Previous work indicates that a delayed action oscillator (e.g., Battisti and Hirst 1989; Suarez and Schopf 1988), operating up to around (but not beyond) decadal time scales (Tourre et al. 2001; White et al. 2003) may be a key driver of interannual ENSO events. This further suggests that the physics driving the decadal (9–13 yr) signal could be different from that underlying the IPO phenomenon. Further, "protracted" ENSO episodes have been shown to result from interactions between the quasi-biennial, classical interannual ENSO, and decadal signals (Allan et al. 2003). Low-frequency variability at IPO time scales may play a part in again providing a broad modulation of the climatic regime in which such higher frequencies operate. However, these protracted ENSO episodes, which are evident in both historical instrumental and proxy records, have only lasted up to about 7–8 yr and are thus important distinct entities in themselves (Allan and D'Arrigo 1999). Hence, the physical mechanism evidence, and the nature of protracted ENSO episodes further support the theory that the decadal signal is not simply part of LF variability measured via the IPO.

In this study we use a 100-yr time series of reconstructed SST, SLP, and rainfall data, which is strongly based on direct observations rather than proxy data. Although a longer time series (if available) may have revealed significance at multidecadal and even lower frequencies, our results for the twentieth-century dataset indicate that after the traditional ENSO frequency domain of 2.5–8.0 yr, variability at the decadal scale contributes most to the observed variance in global rainfall. Regardless of whether the decadal frequency domain is simply the LF component of ENSO or an independent, ENSO modulating process, our findings suggest that the traditional means of identifying the IPO as an LF phenomenon of >13 yr might actually remove that part of the spectrum generating the greatest contribution to global rainfall variability after ENSO.

4. Forecasting potential

Understanding the mechanisms responsible for LF rainfall variability is desirable before any credible climate forecasting scheme that incorporates decadal or interdecadal modes can be developed or applied. Work in this field has been guided by the caution that predictability might never be achieved if the source of LF variability turned out to be either chaotic or the random, LF residual of ENSO (Power et al. 1999b). Other studies show some evidence of LF variability emerging from simulations with coupled climate models and some scientists have suggested that a degree of predictability may be achievable (Latif et al. 1997); however, the extent to which decadal/interdecadal changes in ENSO statistics are predictable is less clear. Two major mechanisms have been suggested (Kleeman and Power 2000) that could result in such decadal modulation of ENSO signals, namely, an internal equatorial Pacific influence or external, midlatitude variability forcing. In addition, McPhaden and Zhang (2002) describe a slowdown of the meridional overturning circulation over the last half century, raising decadal SST fluctuations in the Pacific. This corresponds well to a change from a negative state of the IPO before the late 1970s to the recent positive one that extended to about 1998. This slowdown could be consistent with expected consequences of global warming (McPhaden and Zhang 2002). Our observational dataset is too short to investigate such nonstationary impacts. However, our finding that variability at decadal and possibly interdecadal time scales is more than just red noise is at least consistent with the possibility of genuine mechanisms leading to LF variability that is not simply a manifestation of ENSO alone.

Low-frequency variability is a feature of agricultural systems. A simulation study of 101 yr of wheat yields for all wheat-producing shires in Australia found three distinctly different spatial "El Niño footprints" (Potgieter et al. 2005). Type-1 El Niño events mainly reduced wheat yield in eastern Australia, type 2 reduced yields in northeastern Australia, and type 3 reduced yield across all wheat-growing regions (including western Australia). Most of these El Niño events, but particularly types 2 and 3, occurred at times when the EOF score for the decadal frequency domain was high (Fig. 1b). This is further evidence of ENSO frequency and impact modulation at LF time scales and supports other studies (Power et al. 1999b) that find ENSO signals to be inconsistent during certain periods particularly in southeastern Australia.

5. Conclusions

In this study, we have highlighted the need to better understand the physical causes of low-frequency rainfall variability as a means to progress the development of a predictive capability of such climate variation. We stress the importance of segregating temporal scales on the basis of coherent variation, thus ensuring that the decadal frequency is specifically considered. Finally, we have discussed the importance of connecting such scientific developments with approaches to influencing decision makers, particularly in agriculture.

Our work does not constitute a climate prediction system. However, we expect that this study will lead to better-targeted research efforts into the underlying mechanisms of LF rainfall variability in a manner that will allow new insights to positively influence agricultural decision making. This is most likely to be achieved through analyses of long runs from the emerging generation of coupled climate models with high tropical oceanic resolution. These are needed to help develop improved prediction schemes that are mechanistically sound, skillful, valuable for decision makers, and scientifically defensible. This will require investigating possible interactions between LF rainfall variability and climate change.

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