ENSO and Climatic Variability in the Past 150 Years

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Abstract

Efforts to improve our understanding of the various types of natural variability inherent in the global climate system have included a growing focus on interactions between the El Niño/Southern Oscillation (ENSO) phenomenon and lower frequency decadal- to secular-scale fluctuations in climate. New global historical instrumental data compilations are being analyzed by increasingly more sophisticated objective analysis techniques that are beginning to resolve important physical links and modulations involving dominant climatic signals. This chapter details the current historical observational evidence for interactions between ENSO and decadal- to secular-scale fluctuations in the climate system.

Spectral analyses of global historical sea surface temperature (SST) and mean sea level pressure (MSLP) anomalies reveal significant climatic signals at about 2-2.5, 2.5-7, 11-13, 15-20, 20-30, and 60-80 years and a long-term secular trend. The spatial and temporal characteristics of the SST and MSLP signals in these bands are resolved and examined by using joint empirical orthogonal function (EOF) and singular value decomposition (SVD) analyses. The ENSO signal is seen to consist of quasi-biennial (QB) (1.5- to 2.5-year) and lower frequency (LF) (2.5- to 7-year) components that interact to produce important modulations of the phenomenon. However, longer duration ENSO characteristics and climatic fluctuations are the result of decadal- to secular-scale influences. Protracted El Niño and La Niña phases are found to be a consequence of the “phasing” of quasi-decadal (1- to 13-year) and interdecadal (15- to 20-year) ENSO-like signals with higher frequency QB and LF ENSO components. Lower frequency ENSO-like patterns in global SST and MSLP anomalies extend through to multidecadal timescales and can be seen in the 60- to 80-year Sahelian rainfall/interhemispheric
temperature contrast signal. The secular trend, reflecting the observed global warming signal, reveals SST and MSLP anomalies with neutral to slightly La Niña–like conditions in the Pacific sector.

Something of the impact of decadal- to secular-scale signals on the environment, relative to that caused by QB and LF ENSO components, can be seen in the patterns of correlations with global precipitation. Significant contributions to rainfall variability arising from these low-frequency components are evident not just in known ENSO-sensitive regions. However, it is the “phasing” of the various signals that dictates the bulk of the overall precipitation response. El Niño and La Niña episodes of the ENSO phenomenon can be both synchronous and asynchronous with El Niño–like and La Niña–like signals on various decadal to multidecadal timescales, resulting in permutations that lead to either enhanced or suppressed regional rainfall regimes.

Perhaps the major challenge in developing the above concepts further is the resolution of a more unified understanding of climatic variability and change involving features such as ENSO with the North Atlantic Oscillation (NAO), the Arctic Oscillation (AO), the North Pacific Oscillation (NPO), and the Antarctic Circumpolar Wave (ACW).

Introduction

The El Niño/Southern Oscillation (ENSO) phenomenon is a natural part of the global climate system and results from large-scale interactions between the oceans and the atmosphere that occur chiefly across its core region in the tropical–subtropical Pacific to Indian Ocean basins. As a consequence, the most direct climatic shifts and environmental impacts are found over, and in countries bordering, the Indo-Pacific sector of the planet (Ropelewski and Halpert 1987, 1989; Kiladis and Diaz 1989; Halpert and Ropelewski 1992; Allan et al. 1996; Glantz 1996). The importance of this phenomenon in the global climate system can be quantified to the extent that it is the next feature that explains a large amount of climatic variability after the seasonal cycle and the monsoon system.

El Niño/Southern Oscillation is an irregular/aperiodic phenomenon that tends to reoccur in the range of 2–7 years and is manifest by alternations between its two phases or extremes, often called El Niño and La Niña events. Once it begins, the “average” event tends to last for 18–24 months and shows characteristics of being locked to the seasonal cycle (Philander 1985, 1989, 1990; Yasunari 1985, 1987a,b; Allan et al. 1996; Glantz 1996). However, seasonal persistence is weakest in the boreal spring (austral autumn), the time of the so-called predictability barrier or spring frailty, when new events are likely to develop and existing conditions collapse (Torrence and Compo 1998; Torrence and Webster 1998, 1999).

Although composites of climatic patterns and impacts during El Niño and La Niña events tend to be of the opposite sign to one another, individual El Niño or La Niña events are never exactly the same and can vary in magnitude, spatial extent, onset, duration, cessation, etc. (Philander 1985, 1989, 1990; Ropelewski and Halpert 1987, 1989; Kiladis and Diaz 1989; Allan et al. 1996). In reality, the phenomenon encompasses events that cover a wide range, or “family,” of types and signatures (Allan et al. 1999).

During El Niño events, warming of tropical regions of the Pacific and Indian Oceans leads to the displacement of major rainfall-producing systems from the continents to the previously mentioned oceanic areas, causing massive redistributions of climatic regimes. The opposite tendency with regard to continental and oceanic rainfall regimes occurs during La Niña episodes. As tropical regions are linked to mid- to high latitudes in both hemispheres via teleconnection patterns, any major variations in mass, energy, and momentum resulting from a redistribution of equatorial rainfall regimes are communicated into more temperate regions of the globe (Webster 1994). This effect has the potential to extend ENSO influence beyond the tropics and cause near-global modulations of climate (Glantz et al. 1991; Allan et al. 1996).

Within the tropical–subtropical regime, the ENSO phenomenon has shown a degree of interaction with the Indo-Asian monsoon system. This relationship is described as being “selectively interactive,” in that during the boreal autumn to winter (austral spring to summer) ENSO is strong and the Indo-Asian monsoon is weak, with the opposite situation in the boreal spring to summer (austral autumn to winter) (Webster and Yang 1992; Webster 1995). Thus the nature of the Indo-Asian monsoon can influence ENSO and vice versa at various times of the year. In fact, it has been suggested that the “predictability barrier” may be a consequence of the nature of ENSO links with the Indo-Asian monsoon system (Webster and Yang 1992; Webster 1995; Torrence and Compo 1998; Torrence and Webster 1998, 1999).

Other features of the global climate system may also be coupled to ENSO at various space and time frames. Much remains to be unraveled concerning possible relationships between the phenomenon and climatic features such as the North Atlantic Oscillation (NAO) (Hurrell 1995, 1996; Hurrell and van Loon 1997; Huang et al. 1998), the Arctic Oscillation (AO) (Thompson and Wallace 1998), the North Pacific Oscillation (NPO) (Glantz et al. 1991), and the Antarctic Circumpolar Wave (ACW) (White and Peterson 1996; White et al. 1998). A better understanding of ENSO links to the above features may shed light on questions about the extension of the phenomenon into Europe (Friedrich and Muller 1992; Friedrich et al. 1992; Wilby 1993; Friedrich 1994), the nature of the Pacific North American (PNA) teleconnection (Glantz et al. 1991), and the apparent propagational structure of ocean–atmosphere variables as ENSO phases evolve (Yasunari 1985, 1987a,b; Tourre and White 1995; Allan et al. 1996).

Further complicating this current understanding of ENSO, however, is growing evidence that the phenomenon is not spatially or temporally stable in the longer term and responds on a number of timescales (Gu and Philander 1995; Wang and Ropelewski 1995; Allan et al. 1996; Brassington 1997; Zhang et al. 1997; Torrence and Compo 1998; Torrence and Webster 1998, 1999; Xu et al. 1998). This response appears to result from the influence of a range of patterns of natural decadal- to secular-scale variability that modulate ENSO and, as a consequence, global climate. The current state of knowledge about the spatial and temporal nature and structure of ENSO and its modulation by natural decadal-scale features of the climate system, including possible anthropogenic influences, is examined in this chapter.
Contemporary research has suggested that the ENSO phenomenon has undergone a change in mode and nature since the mid-1970s, with a predominance of El Niño over La Niña phases (Graham 1994; Kerr 1994; Latif and Barnett 1994a,b; Miller et al. 1994a,b; Trenberth and Hurrell 1994; Wang 1995). Changes in ENSO and rainfall relationships (Kripalani and Kulkarni 1997; Nicholls et al. 1996, 1997; Suppiah 1996; Suppiah and Hennessey 1996), and a protracted El Niño or sequence of El Niños in the first half of the 1990s (Bigg 1995; McPhaden 1993; Jiang et al. 1995; Latif et al. 1995, 1997; Liu et al. 1995; Kleeman et al. 1996; Latif et al. 1996; Goddard and Graham 1997; Gu and Philander 1997; Webster and Palter 1997). Many of these aspects of the phenomenon can be seen in a basic examination of the raw Southern Oscillation Index (SOI) since 1876 (Fig. 1.1). Debate continues as to whether these recent fluctuations in ENSO are unique in the instrumental, historical, and proxy records of the phenomenon and as to whether they may be a sign of the influence of the enhanced greenhouse effect (Gage et al. 1996; Trenberth and Hoar 1996, 1997; Harrison and Larkin 1997; Rajagopalan et al. 1997; Allan and D’Arrigo 1999; Dai et al. 1998).

Evidence for a distinct “climatic shift” across the Pacific Ocean sector of the globe since the mid-1970s has been reported by a number of authors (Ebbesmeyer et al. 1991; Graham 1994; Latif and Barnett 1994a,b; Miller et al. 1994a,b; Nitta and Kachi 1994; Trenberth and Hurrell 1994; Jiang et al. 1995). The theory that a climatic shift may be taking place has gained support from the findings of similar changes in climatic patterns across the middle to higher latitudes of the Southern Hemisphere (van Loon et al. 1993; Hurrell and van Loon 1994; Karoly et al. 1996; Garreaud and Battisti 1999; Jones and Allan 1998), over the middle to higher latitudes of the North Pacific (Fig. 1.2) (Chen et al. 1992; Jacobs et al. 1994; Tanimoto et al. 1993; Deeinger and Cayan 1995; Lagerloef 1995; Mantua et al. 1997; Minobe 1997; Nakamura et al. 1997), in the North Atlantic and particularly with regard to the NAO (Fig. 1.3) (Deser and Blackmon 1993; Hurrell 1993, 1996; Hurrell and van Loon 1997), with respect to the Northern Hemisphere circulation in general (Nitta and Yamada 1989; Trenberth 1990; Barnett 1993; Nitta 1993; Graham et al. 1994; Lejenas 1995; Moron et al. 1998), and globally (Parker et al. 1994; White and Cayan 1998). In addition, interest in the post-1970s “climatic shifts” has been a catalyst for specific studies that have attempted to assess more about the nature, structure, and evolution of ENSO itself on decadal to secular timescales (Diaz and Pulwarty 1994; Gu and Philander 1995, 1997; Wang and Ropelowski 1995; Allan et al. 1996; Wang and Wang 1996; Brassington 1997; Kestin et al. 1998; Torrence and Webster 1998; Torrence and Compo 1998; Xu et al. 1998; Zhang et al. 1997).

It is also in the Pacific Ocean basin where the prime focus has been on the 1990–95 protracted El Niño or sequence of El Niño events, with ongoing discussions about the cause(s) of this long episode. Explanations have ranged from natural decadal–multidecadal climatic variability to evidence for the operation of the enhanced greenhouse effect on ENSO (Latif et al. 1995, 1997; Liu et al. 1995; Kleeman et al. 1996; Trenberth and Hoar 1996, 1997; Gu and Philander 1997; Harrison and Larkin 1997; Rajagopalan et al. 1997). More recently, Allan and D’Arrigo (1999) have shown that

![Graph of SOI vs Year from 1870 to 2000](image1)

![Graph of NP Index from Nov to Mar vs Year from 1930 to 1990](image2)
Ocean basin of decadal to multidecadal variability in the ocean-atmosphere system and links to low-frequency ENSO behavior both across the region and beyond. For higher latitudes in the Southern Hemisphere, studies by White and Peterson (1996) and White et al. (1998) detail the existence of the so-called ACW operating at a period of 4-5 years and taking some 8-10 years to circulate completely around Antarctica. These studies indicate that the ACW is potentially a major source of interannual to decadal variability, but because only little more than 10 years’ data on this oscillation are available, these researchers were thus unable to judge whether the ACW may also induce multidecadal fluctuations in the climate system.

Evidence for changes in the structure and general characteristics of ENSO, and possible links with the climate system operating at low frequencies, can be seen in the wavelet plots of the SOI and SST in the Niño-1+2.3, and 4 regions together with a comparison of fractional variance among these indices (Figs. 1.4 and 1.5). The widely accepted explanation is that the ENSO phenomenon in the 2- to 8-year band has fluctuated between more robust periods in the 1870s–80s, 1910s, 1950s, and 1970s–80s and less energetic or quiescent epochs in the late 1890s–1900s, 1920s–30s, and 1960s. The phenomenon also appears to display variations in its periodicity, with a dominant period of 3-4 years from 1870 to 1910, a 5- to 7-year periodicity from 1910 to 1930 and again from 1930 to 1960, and a period of 4-5 years from 1970 to 1990. Such fluctuations in ENSO may be reflected in recently reported variations in its impacts. In the Australian, Indian, and Southeast Asian regions, studies have suggested that correlation patterns and statistics indicative of rainfall and SOI relationships have changed significantly over the past several decades (Parthasarathy et al. 1991; Vijayakumar and Kulkarni 1993; Allan et al. 1996; Nicholls et al. 1996, 1997; Sippia 1996; Sippia and Hennsey 1996; Kripalani and Kalkarni 1997). Broad indications of changing relationships with Indian summer monsoon rainfall in the first half of the instrumental record linked to major fluctuations in atmospheric circulation are suggested by the schematics in Parthasarathy et al. 1991). This evidence is supported by the patterns in wavelet analyses of all-India summer monsoon rainfall, taken together with similar analyses of the SOI and SST in the Niño-1+2, 3, and 4 regions, and by a comparison of fractional variance in the 2- to 8-year band. These data indicate a pronounced reduction in signal strength in all of these variables during the period 1920–40s.

An examination of Figures 1.4 and 1.5 shows that there is more to ENSO than the “classical” phenomenon that tends to occur every 2 to 7 years. Using a wide range of analysis techniques and data sets indicative of the phenomenon, recent work has confirmed the existence of various ENSO-like patterns in the climate system on decadal and multidecadal timescales (Diaz and Pulwarty 1994; Allan et al. 1996, 1999; Mann and Park 1996, 1999; Wang and Wang 1996; Brassington 1997; Keenan et al. 1998; Torrence and Webster 1998, 1999; Folland et al. 1998; Torrence and Compo 1998; Jones and Allan 1998; Xu et al. 1998). Such interest reflects the convergence of ENSO research with a long history of concern about broader historical climatic fluctuations and changes (Allan et al. 1996). This convergence has gained further momentum because regions of the globe that are impacted by “classical” ENSO events are also often those showing the most prominent longer term decadal to multidecadal modulations of their climate. Some four protracted El Niño and six protracted La Niña sequences have occurred over the past 100–120 years, and many others occurred in pre-instrumental times and in times for which proxy data are available, back to the 1700s. Of those in the proxy record, several surpassed or rivaled the 1990–95 El Niño in duration. Although an anthropogenic cause has been suggested for this event in the UCAR (University Corporation for Atmospheric Research) Quarterly (1997), and by Trenberth (1998), and Dai et al. (1998), there is a growing realization of the important role played by natural low-frequency fluctuations in the global climate system in modulating a wide range of ENSO characteristics.

A growing number of studies have now begun to investigate decadal to multidecadal variability using new long-term historical to contemporary data sets, more sophisticated analysis techniques, and the power of numerical model simulations to attempt to reveal not just the nature and structure of such fluctuations but also the physical mechanisms underlying them. Strong evidence for the influence of a decadal mode of the ENSO-like pattern observed during the 1990–95 period of the protracted El Niño or sequence of El Niño events, with a major sea surface temperature (SST) focus in the western-central Pacific and important influences on the global climate, has been detailed by Latif and Barnett (1994a,b), Latif et al. (1995, 1997), Kleeman et al. (1996), and Allan et al. (1999). The dominance of decadal to interdecadal climatic variability and ENSO-like patterns over the tropical and southern Atlantic Ocean has been addressed in papers by Mann and Park (1994), Venegas et al. (1996), and Chang et al. (1997). Allan et al. (1995) and Reason et al. (1996a,b, 1998a,b) have shown the presence over the Indian
Fig. 1.4 (a) Wavelet power spectrum of SOI, 1876–1996, using the Morlet wavelet. The contour levels are in units of variance and are chosen so that 50%, 25%, and 5% of the wavelet power is above each level, respectively. The thick contour is the 10% significance level using the global wavelet spectrum as the background (significance determined from a Monte Carlo simulation of 100,000 white noise time series). Cross-hatched regions indicate the “cone of influence,” where the padding with zeros has reduced the variance. The global wavelet spectrum is given to the plot on the right. (b) Same as (a) but for the Niño-3 SST. (c) Same as (a) but for the Niño-4 SST. (From Torrence, pers. comm.)

Given the above, it is important to examine prominent climatic fluctuations observed and documented in the historical instrumental climate record and to assess their possible relationship with, and influence on, the “classical” nature and structure of the ENSO phenomenon.

Detailed Objective Analyses of Global Data

A wide range of papers by Mann and Park (1993, 1994, 1996, 1999), Mann et al. (1995), Folland et al. (1998), and Allan et al. (1999) have used high-quality near-global data sets of climatic variables such as precipitation, surface temperature (SST and land plus oceanic), and atmospheric pressure, together with more sophisticated objective analysis techniques such as singular spectrum analysis (SSA), empirical orthogonal function (EOF) analysis, and singular value decomposition (SVD), to investigate the nature and structure of climatic variability on decadal to multidecadal timescales. Mann and Park (1999) provide a comprehensive review of the various oscillatory spatiotemporal signal detection approaches that are being used to examine longer term fluctuations in various data sets that document aspects of the global climate system.

Recent papers examining oscillatory spatiotemporal signals in global climatic data by Mann and Park (1994, 1996, 1999) and Mann et al. (1995) have used multitaper method SVD (MTM-SVD) techniques to resolve distinct decadal to secular signals at...
various frequencies in the climate system. The local fractional variance SVD spectra of historical joint Northern Hemisphere surface air temperature and sea level pressure (SLP) data in Figure 1.6 is one example of the application of this technique. The potential for a more complete understanding of various features in the climate system can be seen in the specific resolution of significant signals at quasi-biennial (QB), “classical” ENSO (with various peaks in the low-frequency [LF] band), quasi-decadal (~10–12 years), interdecadal (~15–18 years), and multidecadal (~70–90 years) frequencies, and on the secular timescale (the global temperature increase) (Mann and Park 1999). Such analyses provide a powerful advanced signal detection procedure.

Another approach to the resolution of decadal to multidecadal climate signals has been to use EOFs of regional to global historical data (see Mann and Park 1999). Much of this work has tended to focus on post-1950s records of climatic variables, where the best quality and quantity of observations are generally available (e.g., Kawamura 1994; Zhang et al. 1997). However, as Zhang et al. (1997) also show, there is value in examining longer data sets back to the beginning of this century—at least when one looks at the new versions of historical reconstructions now becoming available (Parker et al. 1994; Allan et al. 1996; Basnett and Parker 1997). A recent analysis of SST data by Folland et al. (1998) has employed EOFs to low-pass-filtered global historical observations back to 1860, while Allan et al. (1999) have used both joint EOF and SVD analyses of global historical SST and mean SLP (MSLP) data available from 1871. In the EOF approach, the technique is applied to band-pass-filtered data that contain each of the significant signal bands resolved by the local fractional variance SVD spectra of joint SST and MSLP fields. The joint SVD analysis gives results very similar to those found by the joint EOF approach, and the reader is directed to Allan et al. (1999) for details of the former. The findings of the Folland et al. (1998) and the Allan et al. (1999) studies form the core of the following examination of ENSO relationships with decadal to secular features of the climate system.

**ENSO**

Spectral analyses of atmospheric and oceanic variables indicative of the ENSO phenomenon show significant signals at about 2 years (QB) and in a band from 3–7 years (LF component) (Lau and Shyu 1988; Rasmussen et al. 1990; Ropelewski et al. 1992; Allan et al. 1996). The nature and structure of signals in the above bands can be seen in the 18- to 35-month QB and 32- to 88-month LF band-pass-filtered SOI, Niño-3, and Niño-4 series in Figure 1.7. The broad coherency of each of these components of ENSO across the three series is clearly evident. However, the superposition of QB and LF bands leads to instances of both strong positive and negative phasing (QB and LF being in phase and out of phase) of the signals. This very nature alone provides a degree of modulation of the overall ENSO signal. Not surprisingly, the LF band carries something of a propensity for longer sequences of both El Niño and La Niña. However, there is some evidence for the range of protracted historical instrumental ENSO phases detailed in Allan and D’Arrigo (1999) in Figure 1.7.

Enveloping the interplay between QB and LF signals in Figure 1.7 is a longer term multidecadal fluctuation in variance, which is highlighted for the Niño-3 region SSTs on the following World Wide Web (WWW) page: http://paos.colorado.edu/research/ novelets/novelet1.html. This feature displays some of the characteristics of broader ENSO nature discussed previously in this chapter, in that earlier and later portions of the time series show robust signals while the middle section experiences a period of quiescence. Such patterning provides a degree of lower frequency modulation of the 2- to 7-year band and appears to reflect the two teleconnection states discussed in Ward et al. (1994), Navarra et al. (1999), and Miyakoda et al. (1999). These fluctuations in variance need further physical explanation and understanding.

Expanded spatiotemporal resolution of the QB and LF components of the ENSO signal can be achieved through a joint EOF analysis of global historical SST and MSLP data band-pass filtered in the QB and LF year bands resolved by the MTM-SVD spectra in Figure 1.8. An analysis of these bands in Allan et al. (1999) reveals annual MSLP and SST anomaly patterns and joint time series indicative of QB and LF (or what might be termed “classical” ENSO) signals respectively (Figs. 1.9 and 1.10). Across the Pacific basin, both bands provide equally strong ENSO signals, while in the Indian and Atlantic Oceans more definitive MSLP and SST anomaly patterns are found in the LF year band. The superposition of the two joint annual EOF time
series produces signal modulations that lead to ENSO phases (El Niños and La Niñas) displaying a wide range of types encompassing variations in frequency, magnitude, and duration. When the above is extended to include modulations of the spatial EOFs of MSLP and SST, this finding has considerable ramifications for climatic impacts. Although not shown, the joint seasonal EOFs reveal that these interactions between dominant signal bands also lead to modulations of the evolutionary characteristics of ENSO phases.

The influence of interactions between the QB and LF year bands on the seasonal nature of ENSO can be seen in Table 1.1. This simultaneous correlation table provides a broad picture of the representativeness of each of the joint QB and LF ENSO seasonal time series with regard to the QB and LF components of the SOI and the Niño-3 and Niño-4 SST indices (Allan et al. 1996). Although the majority of seasons show correlations that are statistically significant at the 99% level, an examination of the amount of variance that they explain indicates that the most robust ENSO signal throughout the year is to be found on the LF year band. However, the well-documented boreal spring (austral autumn) “breakdown” or “predictability barrier” in ENSO relationships (Webster and Yang 1992; Webster 1995; Allan et al. 1996; Torrence and Webster 1998) is most strongly manifest on the QB band. This result suggests that it is important to look more closely at fluctuations around 2–2.5 years in efforts to understand and improve ENSO forecasts.
Fig. 1.9  Joint GMSLP2.1f and GISSST3.0 EOF 1 spatial correlation fields for MSLP (top panel) and SST (middle panel) (relative to the base period 1901–90), and joint EOF 1 time series (bottom panel) in the 2- to 2.5-year (QB) band. The joint spatial EOFs explain 16.4% of the variance in the 2- to 2.5-year band. Regions where <40% of the observations occur are masked. (From Allan et al. 1999.)
A further examination of Figures 1.9 and 1.10 reveals that, as for Niño-3 SST, both the QB and LF ENSO bands are also enveloped by lower frequency modulations in variance. This nature is most clearly manifest on the higher frequency QB band. Such variance structure has often been seen in previous studies that have examined raw or mildly smoothed ENSO indices, and it has generally been attributed to lower frequency decadal–multidecadal fluctuations (Torrence and Compo 1998; Torrence and Webster 1998; Xu et al. 1998). Assessment of the implications of this for ENSO research is only just beginning, with suggestions that at least two “types” of ENSO teleconnection states are associated with more and less robust periods of variance in the ENSO phenomenon (Ward et al. 1994; Navarra et al. 1999; Miyakoda et al. 1999). Such teleconnection states have important implications for ENSO-monsoon modulations (Webster and Yang 1992; Webster 1995; Torrence and Compo 1999; Torrence and Webster 1998, 1999; Xu et al. 1998) and climatic impact patterns during El Niños and La Niñas (Allan et al. 1996).

A broader perspective of the above ENSO characteristics over time is provided by the evolutive MTM-SVD spectra shown in Figure 1.11. The MTM-SVD spectra support the general thrust of numerous wavelet analyses of ENSO indices (Diaz and Pulwarty 1994; Wang and Wang 1996; Brassington 1997; Kestin et al. 1998; Torrence and Webster 1998, 1999; Torrence and Compo 1998; and Fig. 1.4), in showing more robust signals in the QB and LF ENSO bands during the first and last 40–50 years of the record and a period of very weak signal strength in the intervening epoch. The data show a collapse of the ENSO signal from a period of particularly strong fluctuations near 0.29 year$^{-1}$ and 0.15 year$^{-1}$ (3.4- and 6.7-year period) on the LF ENSO band in the specific period 1871–1931, to a more quiescent epoch apart from a power peak at 0.19 year$^{-1}$ (5-year period) from 1906 to 1966, and then a renewal of power at 0.29 year$^{-1}$ (3.4-year period) for the more recent 1936–96 epoch.

### ENSO and Decadal–Multidecadal Signals

Recent work byuang et al. (1997) on decadal climatic signals over the Atlantic Ocean sector has shown that the strongest ENSO-like delayed oscillator signals in SST for that region occur on about the quasi-decadal timescale. Using such findings as a guide to low-pass filtering of global SST data (MOHISTGC) to isolate interdecadal–decadal signals from those associated with ENSO-like features, Folland et al. (1998) then applied EOF analysis to the data and resolved four major low-frequency patterns. Of these EOFs, the third and fourth describe fluctuations operating on multidecadal timescales. The third EOF is of a fluctuation on a 20- to 30-year time frame and has similarities to the patterns in Mantua et al. (1997) and Zhang et al. (1997), which display ENSO-like SST structures in the equatorial Pacific and Indian Oceans. Such SST anomaly patterning has potential ramifications for an enhancement of El Niño-like and La Niña-like conditions on long timescales. The fourth EOF is seen to be related
to the 18- to 20-year rainfall signal in parts of southern Africa (Tyson 1986; Mason 1990, 1995).

In the Allan et al. (1999) analysis, joint EOFs of the 11- to 13-, 15- to 20-, and 20- to 30-year signal bands (Figs. 1.12, 1.13, and 1.14) resolved by the MTM-SVD spectra in Figure 1.8 have spatial patterns of SST and MSLP anomalies that all show ENSO-like characteristics. The spatial patterns and time series of these EOF bands, and their relationship to the SST EOFs in Folland et al. (1998), are discussed in the following subsections.

Quasi-Decadal and Interdecadal Bands

Fluctuations in the 11- to 13-year or quasi-decadal band (Fig. 1.12) display a pattern with the warmest SST anomalies displaced into the central-western equatorial Pacific in the current Niño-4 area. Mean SLP anomalies show a dipole structure across the central-eastern half of the Pacific basin, with distinct centers around 30°N and 40°S. This structure is very different from the QB and LF ENSO patterns in that region (Figs. 1.9 and 1.10), which show a single, distinct central-southeastern Pacific MSLP node of the Southern Oscillation. The 15- to 20-year or interdecadal signal (Fig. 1.13) has the warmest Pacific SSTs displaced slightly into the Southern Hemisphere and toward the South American coast in something like the contemporary Niño-1+2 and Niño-3-region configuration. As with the quasi-decadal band, MSLP anomalies in the Pacific region have nodes in both hemispheres in similar geographical locations.

Fluctuations in MSLP and SST anomaly patterns extend into the Indian and Atlantic Ocean basins on both quasi-decadal and interdecadal timescales. Over the former, MSLP and SST distributions vary between the bands and, in conjunction with the QB and LF signals, may go a long way toward explaining Indian Ocean SST dipole patterns (Nicholls 1989; Drosdowsky 1993a,b; Allan et al. 1996). In the Atlantic sector, both bands show a marked enhancement of spatial patterns indicative of signals described previously on decadal timescales by Chang et al. (1997).

Joint time series on these bands are suggestive of signals carrying an ENSO-like temporal structure responsible for protracted El Niño and La Niña phases. In a number of recent studies of the 1990-95 protracted El Niño sequence (Latif et al. 1997; Kleeman et al. 1996), the SST pattern across the Pacific during much of that period has a distribution matching that seen in the quasi-decadal spatial SST EOF (Fig. 1.12). In addition, the longer term fluctuations shown in Figures 1.12 and 1.13 are generally well aligned with protracted El Niño and La Niña events documented in the literature (Allan and D’Arrigo 1999). An even better matching is found when both the QB and LF joint time series are superimposed with those on the quasi-decadal and interdecadal bands, and the composite signal is constructed.

Multitaper method SVD evocative spectral power (Fig. 1.11) carries something of the quasi-decadal and interdecadal signals, but not as clearly as for the higher frequency ENSO bands discussed previously. As with wavelet studies (Brasnett 1997; Torrence and Compo 1998; Torrence and Webster 1998, 1999; Wang and Wang 1996), spectral power resolved at about the 0.09 year⁻¹ (11.1-year period) quasi-decadal and the
Fig. 1.3 Joint GMSLP2.1f and GISST3.0 EOF 1 spatial correlation fields for MSLP (top panel) and SST (middle panel) (relative to the base period 1901–90), and joint EOF 1 time series (bottom panel) in the 15- to 20-year band. The joint spatial EOF explains 28.4% of the variance in the 15- to 20-year band. Regions where <40% of the observations occur are masked. (From Allan et al. 1999.)

Fig. 1.4 Joint GMSLP2.1f and GISST3.0 EOF 1 spatial correlation fields for MSLP (top panel) and SST (middle panel) (relative to the base period 1901–90), and joint EOF 1 time series (bottom panel) in the 20- to 30-year band. The joint spatial EOF explains 27.7% of the variance in the 20- to 30-year band. Regions where <40% of the observations occur are masked. (From Allan et al. 1999.)
0.06 year^{-1} (16.7-year period) interdecadal timescales shows fluctuations over time. In general, enhanced and quiescent signal strength tends to be aligned with the epochs of robust and weak QB and LF ENSO spectral power examined in the earlier section. This again reinforces the notion that ENSO modulations must be viewed in conjunction with fluctuations in the climate system on decadal–multidecadal time frames.

20- to 30-Year Band

The 20- to 30-year fluctuation in the joint EOF analysis of Allan et al. (1999) has limited realizations over the 124 years of data, and it is weak in the MTM-SVD spectra of Figure 1.11, so its statistical stability could thus be questioned. However, it is resolved as significant in the MTM-SVD fractional variance spectra for joint MSLP and surface air temperatures over the Northern Hemisphere in Mann and Park (1996) (Fig. 1.6), and a similar spatiotemporal pattern is evident as the third low-frequency EOF in global SST data in Folland et al. (1998). As a consequence, we have examined this signal in this chapter.

In Folland et al. (1998), the third low-frequency EOF shows strong signals at about 20–40 years in its time series, with peaks at about the turn of the century, in the 1920s–30s epoch, and in the period since the mid-1970s. All of these time frames exhibit patterns of ENSO-like SST anomaly response in the Indo-Pacific domain, while the second low-frequency (60- to 80-year period) EOF of Folland et al. (1998) certainly provides additional modulation for at least climatic signals in the Sahelian region. Interestingly, such findings cast doubt about the Chang et al. (1997) decadal signal in the Atlantic Ocean being the obvious “cutoff” for ENSO-like signals in the climate system. There is thus a need to reexamine new global historical data sets with broader perspectives of ENSO and low-frequency climatic variability in mind.

Basically, the 20- to 30-year band signal (Fig. 1.14) shows an enhancement and meridional broadening of equatorial Pacific SST anomalies, and more of a coalescence of the MSLP feature over much of the Pacific Ocean. In the Atlantic sector, signal strength and coherency are less than for either of the quasi-decadal and interdecadal bands. Across the Indian Ocean basin, MSLP and SST anomaly patterns are slightly more coherent than in the above bands, with a stronger MSLP feature at the middle to higher latitudes of the Southern Hemisphere. In general, the overall spatial pattern is dominated by a strong, Pacific-centered ENSO-like phenomenon. As is noted in Folland et al. (1998), similar findings of ENSO-like patterns in decadal–multidecadal SST data alone, and the maintenance of SST–rainfall relationships from interannual ENSO through to multidecadal ENSO-like timescales, suggest that teleconnection structures have a degree of very broad spatiotemporal coherency.

The joint EOF time series in the 20- to 30-year band is indicative of about five epochs of El Niño–like and La Niña–like patterns in the climate system over the period of record. Of particular interest is the tendency for El Niño–like conditions to be enhanced since the mid- to late 1970s, which coincides with the timing of the change in the ENSO regime across the Pacific Ocean basin (Graham 1994; Latif and Barnett 1994a,b; Miller et al. 1994a,b; Trenberth and Hurrell 1994; Wang 1995). Once again, the importance of interactions between climatic modes is revealed if the 20- to 30-year joint EOF time series (Fig. 1.14) is superimposed on those at 2–2.5, 2.5–7, 11–13, and 15–20 years (Figs. 1.9, 1.10, 1.12, and 1.13).

**ENSO and Multidecadal–Secular Patterns**

In Folland et al. (1998), the first EOF of low-pass-filtered global SST data is highly correlated with the global warming trend and shows a tendency for maximum warming in the middle to higher latitudes in both hemispheres, while displaying very little evidence for coherent equatorial Pacific warming indicative of any modulation of the core region of ENSO SST fluctuations (Cane et al. 1997). Patterns of SST anomalies in the second EOF of Folland et al. (1998) closely resemble those associated with the long-term Sahelian rainfall series and the interhemispheric temperature contrast (Folland et al. 1986; Parker and Folland 1991; Folland et al. 1991) and appear to be operating on a timescale of about 60–80 years.

To resolve secular climatic signals in Allan et al. (1999), a low-pass filter (>29 years) was applied to the data prior to the joint EOF analysis. This approach reveals two dominant modes: a global warming trend pattern in EOF 1 and the Sahelian rainfall/interhemispheric temperature contrast signal (Folland et al. 1998) operating on a timescale of about 60–80 years in EOF 2. Together, the above signals account for some 72.4% of the variance on secular timescales.

The spatial pattern of SST anomalies in the joint EOF 1 diagram (Fig. 1.15) has low weights in the eastern equatorial Pacific and central Indian Ocean basins and in the North Atlantic south of Greenland. In general, the most coherent and strongest warming trend in SSTs occurs at middle to higher latitudes in both hemispheres. The spatial distribution of MSLP anomalies suggests an increase in values across most of the Indian Ocean basin, with mixed signals over the rest of the globe. The Pacific Ocean basin is the only region where coherent positive and negative MSLP anomaly features are found together. The joint EOF time series (Fig. 1.15) serves to illustrate that EOF 1 is capturing the observed global warming signal (Folland et al. 1998).

For EOF 2 (Fig. 1.16), the spatial patterns of MSLP and SST anomalies are indicative of the Sahelian rainfall/interhemispheric temperature contrast signal. These spatial patterns show a distinctive ENSO-like fluctuation and a marked shift toward enhanced El Niño–like conditions since the 1970s. Whether this aspect of the recent climate is carried by this band alone, or the 20- to 30-year signal discussed earlier, or a combination of both, is still unclear.

**Global Rainfall Correlations and Documentary Evidence**

Resolution of the dominant signals and patterns in global historical MSLP and SST data at various interannual to secular timescales do not in themselves provide a picture of the degree of climatic impact they cause. In the literature, these data have generally been presented through maps and diagrams showing relationships and correlations between climatic phenomena and variables such as rainfall, temperature, streamflow, etc. (see
Fig. 1.15 Joint GMSLP2.1f and GISST3.0 EOF 1 (global warming trend signal) spatial correlation fields for MSLP (top panel) and SST (middle panel) (relative to the base period 1901–90), and joint EOF 1 time series (bottom panel) in the >29-year band. The joint spatial EOFs explain 47.5% of the variance in EOF 1 for the >29-year band. Regions where <40% of the observations occur are masked. (From Allan et al. 1999.)

Fig. 1.16 Joint GMSLP2.1f and GISST3.0 EOF 2 (60– to 80-year Sahelian/interhemispheric temperature contrast signal) spatial correlation fields for MSLP (top panel) and SST (middle panel) (relative to the base period 1901–90), and joint EOF 2 time series (bottom panel) in the >29-year band. The joint spatial EOFs explain 24.9% of the variance in EOF 2 for the >29-year band. Regions where <40% of the observations occur are masked. (From Allan et al. 1999.)
Lau and Sheu 1988, 1991; Diaz et al. 1989; Rasmusson and Arkin 1993 for detailed studies of global precipitation). Such an approach has been employed particularly with regard to ENSO influence on regional to global scales (Ropelewski and Halpert 1987, 1989; Halpert and Ropelewski 1992; Kiladis and Diaz 1989; Allan et al. 1996). This section of the chapter relates the various climatic features and bands found in the spatiotemporal analyses of global historical MSLP and SST observations to global rainfall patterns through correlations and various documentary evidence.

Raw seasonal rainfall data for global land areas obtained from Hulme (1992) (see comparison with other climatologies and discussions with regard to temporal and spatial sampling by Hulme and New 1997) since 1900 are simultaneously correlated with seasonal joint EOF time series filtered in the 2- to 2.5-, 2.5- to 7-, 11- to 13-, 15- to 20-, and 20- to 30-year bands, and with >29 years EOF 1 and 2 time series (seasons are January–March [JFM], April–June [AMJ], JAS, and OND). Apart from the QB and LF ENSO bands, for which considerable documentary evidence supporting impacts already exists, efforts are made to provide additional documentary and observational support for the other seasonal rainfall correlation patterns at lower frequencies.

**Interannual QB and LF ENSO**

Global patterns of correlations between QB and LF joint seasonal MSLP and SST EOF time series and raw seasonal Hulme rainfall are shown in Figures 1.17a,b. Statistically significant and coherent correlations on the QB and LF bands show a pattern that reflects the well-documented ENSO-sensitive regions noted above. However, several interesting aspects of these relationships are found when the QB and LF rainfall correlations are examined separately. Over southern Africa, the ENSO response in JFM is strongest on the QB band (Fig. 1.17a) and is reinforced by the relatively weaker LF pattern (Fig. 1.17b). Such a structure is consistent with the findings of efforts to understand the role of the stratospheric Quasi-Biennial Oscillation (QBO) in modulating ENSO influences over that part of the African continent (Mason and Tyson 1992; Mason and Lindesay 1993; Jury et al. 1994; Mason 1995). A similar response to the QBO is reported during the October–November (“short rainy” season) over Kenya (Ogando et al. 1994) and is supported by moderate QB band correlations in Figure 1.17a.

Distinct tropospheric QB relationships with rainfall have been reported from China (Shen and Lau 1995), Europe (Brasil and Zolotokrylin 1995), and India (Torrence and Webster 1999). In Figures 1.17a,b, the northeastern Brazilian, East African, Argentinian, and Sri Lankan regions show that peak ENSO signals are generally evenly divided between the QB and LF bands. Across the prime ENSO-sensitive areas of eastern Australia, southern United States, India, and China, the balance between QB and LF bands is variable and either signal can play an important role in regional ENSO impacts. Over Sahelian Africa, an ENSO signal is evident during JAS in the LF component. Regions with rainfall regimes not generally associated with ENSO, or having ephemeral ENSO sensitivity, across Europe (Fraedrich and Muller 1992; Fraedrich et al. 1992; Wilby 1994) and over western Canada (Shabbir et al. 1997) show a general dominance of the LF signal component. Interestingly, the AMJ season of “spring
Quasi-Decadal and Interdecadal Bands

Correlation patterns over the global land regions and islands on these bands are detailed in Figures 1.18a,b. As on the QB and LF bands (Figs. 1.17a,b), there is a strong tendency for the most coherent and significant correlations to be found in “classical” ENSO-sensitive areas. On the quasi-decadal band (Fig. 1.18a), parts of eastern Australia in all but the AMJ season, southern Africa in JFM, northern Argentina and Uruguay in AMJ and OND, East Africa in OND–JFM, and northeastern Brazil in AMJ display an ENSO-like rainfall response. Other strong correlations are found over the eastern United States in JFM. On the interdecadal timescale (Fig. 1.18b), strong and coherent ENSO-like responses are found over East Africa in OND, China and Mongolia in AMJ, and parts of eastern Australia in all seasons but JAS. Other well-organized responses are found over the eastern United States and western Canada in JFM.

The wider ramifications of the rainfall responses in Figures 1.18a,b can be seen when they are examined in conjunction with the ENSO patterns in Figures 1.17a,b. In regions such as East Africa in OND, southern Africa in JFM, and parts of Australia throughout much of the year, there are strong modulations and reinforcements of ENSO-induced rainfall patterns by rainfall correlations on either or both bands. Regions that are not known as ENSO sensitive, but show strong and coherent QB and LF patterns that are reinforced by quasi-decadal and interdecadal correlations, are western parts of Canada and the eastern United States in OND–JFM. Thus the phasing of QB, LF, quasi-decadal, and interdecadal band signals is a major source of rainfall modulations and variations in overall climatic impacts from event to epoch timescales.

Multidecadal 20- to 30-Year Band

Global rainfall responses on the 20- to 30-year band (Fig. 1.19a) continue the tendency seen with the quasi-decadal and interdecadal bands in Figures 1.18a,b for ENSO-like rainfall responses to dominate the correlation patterns. This is evident over southern Africa and eastern Australia in JFM and over central regions of Australia, East Africa, and Argentina in OND. Apart from the above relationships, the only other consistent pattern on the 20- to 30-year band is a response over western Canada and the eastern United States in JFM.

Sahelian 60- to 80-Year Band and Global Warming Signals

The EOF 2–rainfall correlation pattern in Figure 1.19b is the first in any band examined to show a shift away from ENSO-like climatic impacts. The most coherent feature of this band is the strong rainfall correlation signal in JAS that extends in a band across Sahelian to East Africa. The African response continues to be concentrated over
Fig. 1.18a Global maps of seasonal correlations between the joint EOF 1 time series (bandpass filtered in the 11- to 13-year band) and raw land-plus-island precipitation data from Hulme (1992) for the period 1900-94, in the 11-13 year band. Those correlations above $r = +0.2$ (marked with "+" ) or below $r = -0.2$ (marked with "−") are significant at the 95% level. Plots top to bottom are JFM, AMJ, JAS, OND.

Fig. 1.18b Global maps of seasonal correlations between the joint EOF 1 time series (bandpass filtered in the 15- to 20-year band) and raw land-plus-island precipitation data from Hulme (1992) for the period 1900-94, in the 15-20 year band. Those correlations above $r = +0.2$ (marked with "+" ) or below $r = -0.2$ (marked with "−") are significant at the 95% level. Plots top to bottom are JFM, AMJ, JAS, OND.
Fig. 1.19a  Global maps of seasonal correlations between the joint EOF 1 time series (band-pass filtered in the 20- to 30-year band) and raw land-plus-island precipitation data from Hulme (1992) for the period 1900-94, in the 20-30 year band. Those correlations above $r = +0.2$ (marked with "+") or below $r = -0.2$ (marked with "−") are significant at the 95% level. Plots top to bottom are JFM, AMJ, JAS, OND.

Fig. 1.19b  Global maps of seasonal correlations between the joint EOF 2 time series (60- to 80-year signal in data low-pass-filtered for >29 years) and raw land-plus-island precipitation data from Hulme (1992) for the period 1900-94, in the 60-80 year band. Those correlations above $r = +0.2$ (marked with "+"), or below $r = -0.2$ (marked with "−") are significant at the 95% level. Plots top to bottom are JFM, AMJ, JAS, OND.
parts of the Sahelian region in OND and confirms the dominance of low-frequency fluctuations over ENSO impacts in West Africa. Weaker correlation structures are found over Canada and the northwestern United States in JFM and JAS and over far eastern Russia in OND–JFM. Overall, the rainfall modulation provided by the 60- to 80-year signal appears to be a significant source for long-term variability in the West African monsoon system.

The distribution of rainfall correlations with the EOF 1 global warming trend time series is shown in Figure 1.20. Significant and coherent rainfall correlations are found over a number of global regions in various seasons. Well-documented droughts in Sahelian Africa (particularly far western West Africa) and the Ethiopian region appear to have been modulated by a combination of the 60- to 80-year and global warming signals (Figs. 1.19b and 1.20). Strong positive rainfall correlation patterns are suggested over northeastern Canada in AMJ–OND, the Argentinian region in OND–JFM, and parts of central to far eastern Europe and Asia for much of the year.

Important supportive evidence for the longer term climatic fluctuations seen in the rainfall correlation patterns over this century can be found in documentary sources and studies. Such material is detailed in the following subsection.

**Documentary Evidence for Climatic Variability and Links to Rainfall Correlations**

Unlike studies of the higher frequency ENSO phenomenon, which have included considerable objective analysis of regional to global impact patterns, longer term decadal to multidecadal fluctuations in the climate system have far fewer realizations. Although considerable instrumental data are available back to the early parts of this century, the most consistent type of evidence used to investigate long-term climatic patterns has tended to be documentary. Prior to concerns about changes in the nature of ENSO since the 1970s, three climatic fluctuations during this century caught the attention of researchers. These fluctuations are detailed here, and relationships with the various seasonal rainfall correlation bands are discussed.

**The Turn of the Century**

Perhaps the first concerted scientific effort to synthesize information on an apparent low-frequency fluctuation in the global climate system was the work by Sir John Eliot, the second British director of the Indian Meteorological Department (Eliot 1904, 1905). Having been involved in both meteorological observations and research in India since the 1870s and having presided over the department from 1889 to 1903, Eliot was well placed to see and influence the evolution of efforts to find reliable precursors of the Indian monsoon system (Allan et al. 1996). It was during Eliot's term that the Indian Meteorological Department expanded the range of parameters and regions examined in the formulation of predictors of the Indian monsoon to include conditions over the Indian Ocean, northeastern Africa, and southern Australia. However, by the turn of the century, the forecast structure had been found wanting with the failure of the forecasts from 1899 to 1901 and the 1902–05 efforts that were being provided confidentially.
to the Indian government. It was with such experiences, and about the time of his retirement from service in India in 1904, that Eliot put together papers indicating the "uniqueness" of the climate from about 1894 to 1902 throughout much of the then British Empire (Eliot 1904, 1905). By 1908, Sir Gilbert Walker, Eliot's successor in the Indian Meteorological Department, had been asked by the Indian government to explore the nature of possible changes in Indian climate and the likely role of human activities in such changes (Walker 1910). This work indicated the presence of some type of natural fluctuation in climatic patterns across the Indian subcontinent but concluded that no human-induced component was responsible.

The impacts and consequences of this turn-of-the-century fluctuation in the climate system can be seen in the extent of crop and animal losses in countries surrounding the Indian Ocean basin (southern, eastern, and central Africa; Australia; Mauritius; and India) (Eliot 1905). Its wider extension led to rainfall deficiencies and major displacements of farming populations across the Great Plains region of the United States in the mid- to late 1890s (Warrick 1980; Stockton and Meko 1983) and droughts in northern China in the 1890s (Whetten and Rutherfurd 1994), in Indonesia in the mid-1890s to 1903, as shown by tree-ring studies (Jacoby and D'Arrigo 1990; D'Arrigo et al. 1994), in northeastern Brazil for the first 5 years of the twentieth century (Diaz et al. 1989), in southeastern England during the 7 years prior to 1901 (Noble 1903), and across central to eastern Russia in 1901–03, resulting in famine in that region (Noble 1903).

In Australia, it became known as the "Federation Drought" and was most strongly manifest from coastal to inland regions of the states of Queensland, New South Wales, and South Australia (Foley 1957). The drought during 1895–1903 was responsible for an Australian wheat shortfall estimated at 13 million bushels and losses of some 50 million sheep in New South Wales alone (Eliot 1905). According to Foley (1957), in Australia as a whole, sheep numbers were halved and cattle losses were of the order of 30%. This period was also one of increased dust storms in Australia that led to reports of dust fallout over New Zealand from Australian continental sources (Noble 1904). Haze, smoke, and dust observed over northern Australian ports and by steamer operating to and from Hong Kong and the Philippines were discussed in terms of possible volcanic eruptions in Indonesia but could well have been products of large wildfires in the jungles of Borneo and Sumatra (Noble 1904). Although it was written in the late 1950s, the following comment from Foley (1957; p. 208) is still relevant today: "It is difficult for present-day Australians to realise the magnitude of the effects of this drought on the economy of the country."

Over southern Africa, the period was generally punctuated by years of extreme drought and cold in which cattle and sheep losses were in the millions and maize and wheat crops failed (Eliot 1905; Lindesay and Vogel 1990). The severest drought conditions over southern Africa occurred during 1902–03 (Lindesay and Vogel 1990). In central Africa, drought conditions tended to persist from 1898 to 1903, while in eastern Africa the Nile discharge was very low for the year 1898 and for the whole period from 1900 to 1902 (Noble 1903; Eliot 1905).

During 1896–97, food crops in British India were some 33% below normal (about 18–19 million tons) and the country needed to import about 6 million tons of rice from Burma (Eliot 1905). Some 62 million people were affected, with relief efforts focusing on the 34 million people most severely hit by famine conditions. Cattle losses were massive, with estimates in the Province of Hissar alone that 92% of the cattle used to plow fields and to provide the power to lift water from wells had been lost between April 1895 and October 1897 (Eliot 1905). For the period 1899 to 1900, the effects were less severe and more scattered, but still nearly 4 million cattle were lost in the Central Provinces and in and around Bombay.

The influence of this climatic anomaly extended to high latitudes of Asia, leading to heavy cattle losses and some 15 million starving peasants in central-eastern and southeastern Russia (Noble 1903). The cost of cereal produce (rye and wheat) used by the Russian government to alleviate the famine was estimated at about 1.7 million pounds sterling alone.

In the Great Plains region of the United States, the 1890s drought peaked in the years 1894–95, with estimates that some 300,000 farmers were displaced and that wheat yields fell to as low as 9 bushels/acre (Warrick 1980). Population decline due to drought and malnutrition during the 1890s was particularly severe over a large portion of the Great Plains region. These impacts were compounded by a lack of government or public assistance, and a general vulnerability to natural disasters. According to the summary of Warrick (1980; p. 107): "Many areas experienced a dramatic loss of 50 to 75 percent of their population."

Research on this climatic fluctuation at the time is best summed up by Eliot (1905; p. 216): "Hence it is evident that during the dry period, from 1895 to 1901, there were disturbing actions of great magnitude which gave rise to large general variations of pressure probably over at least half the Eastern Hemisphere. The data at present available give no indication of the region in which the opposite and compensatory variations of air mass and pressure occurred."

Since that time, the most thorough investigations of the nature and extent of this climatic fluctuation have been undertaken mainly by Indian scientists (Pant et al. 1988; Parthasarathy et al. 1991, 1992; Thapliyal and Kulshrestha 1991; Vijayakumar and Kulkarni 1995; see also Fu and Fletcher 1988). The overall findings of this work are indicative of a change in the broad characteristics of the Indian monsoon system from meridional in the pre-1890s period to the development of more zonal atmospheric flow regimes in the 1890s–1900s epoch. This conclusion is supported by spatiotemporal fluctuations in the areas of statistically significant ENSO and rainfall correlations over India, Sri Lanka, and Southeast Asia (Parthasarathy et al. 1991; Vijayakumar and Kulkarni 1995; Suppiah 1996; Kripalani and Kulkarni 1997).

From the various decadal to multidecadal rainfall correlation patterns detailed in Figures 1.18a, b and 1.19a, b, and discussed earlier, the most likely candidates to explain the turn of the century climatic fluctuation are the 60- to 80-year Sahelian/interhemispheric thermal contrast mode (Fig. 1.19b) in combination with the 20- to 30-year band signal (Fig. 1.19a). In addition, these modes were reinforced by ENSO-like patterns on the quasi-decadal and interdecadal timescales (Fig. 1.18a, b).

As was documented earlier in this chapter, large-scale drought conditions with crop and animal losses extended into the first three to five years of the twentieth century.
in Africa, India, China, Russia, northeastern Brazil, and eastern Australia. Correlation patterns for southern Africa suggest that the combined influence of low rainfall regimes from the quasi-decadal, interdecadal, and 20- to 30-year bands during JFM provided the strongest influence in that region. For Sahelian Africa the 60- to 80-year band carries the dominant rainfall suppression signal, while the global warming trend signal was generally the most coherent mode working against this pattern in far western West Africa. Across East Africa, enhanced precipitation on the interdecadal and 20- to 30-year bands in OND was countered by reduced rainfall as a result of the global warming signal in that season (see Fig. 1.20). Farther north in Ethiopia and the Horn of Africa, mixed signal responses appear to be operating, although the 20- to 30- and 60- to 80-year bands in JAS would favor dry conditions.

In northern India, the strongest signal reflecting a fluctuation in the Indian summer and reduced rainfall is evident on the 60- to 80-year band in JAS. Some evidence for premonsoon suppression of precipitation is found on the interdecadal band in AMJ. Farther east in China, the major reduction in rainfall would appear to be a result of the combined influence of the quasi-decadal and 20- to 30-year bands in JAS and the interdecadal band in AMJ. The situation in central to eastern Russia appears to be the result of rainfall suppression brought about by the influence of the global warming trend time series (inverse of Fig. 1.20) in OND.

In northeastern Brazil, the influence on rainfall deficits appears to be mostly derived from ENSO-like patterns on the quasi-decadal band in AMJ. Some reinforcement of this tendency may come from the EOF 1, greater than 29 years low-pass-filtered global warming trend signal. However, the rainfall modulation in this region has far less discernible low-frequency influences than for others discussed above.

Across eastern Australia, there is strong modulation of rainfall patterns toward dry conditions on the quasi-decadal band in JAS-JFM, on the interdecadal band in OND-AMJ, on the 20- to 30-year band in OND-JFM, and on the 60- to 80-year band in JFM. Thus a conjunction of such signals, as in the turn-of-the-century epoch, would work to reinforce drought conditions in eastern margins of the continent.

The 1920s–30s Period

The next major climatic fluctuation with wide-ranging effects over many areas of the globe occurred during the 1920s–30s period. This epoch is most well known for the "Great Plains Drought" or "Dust Bowl" in the grain belt of the central United States (Worster 1979; Heathcote 1980). Nevertheless, wider drought impacts were sustained in southern Africa, Australia, parts of Amazonia, and eastern China.

Although we speak of the 1930s period of United States drought conditions (Warrick 1980), the Great Plains Drought was most intense in the years 1934, 1936, and 1939 (Stockton and Meko 1983). Impacts of the "Dust Bowl" are well documented in the literature, and the subject has been the source for numerous geographical, socioeconomic, and historical studies, mainly because of the inextricable influences of the Great Depression and bad farming practices (Skaggs 1975, 1988; Warrick 1980). Climatic manifestations at this time included not only drought and high temperatures but also the
1920s and 1960s (Ye and Yan 1993; Nitta and Yoshimura 1993; Qiang and Demaree 1993). The former time indicates the beginning of the 1920s–30s climatic fluctuation, which appears to have been synchronous with atmospheric warming in the Northern Hemisphere and a period of low global ocean cloudiness prior to a long-term increasing trend (Mingli and Fletcher 1993). The early 1920s were also part of a period of increasing Indian monsoon activity from about 1900 to 1940 (although there was a tendency for marginally drier conditions during the Indian summer monsoon) (Fu and Fletcher 1988; Fu and Qiang 1991; Parthasarathy et al. 1991, 1992; Vijayanakumar and Kulkarni 1995; Suppiah 1996). It also marks a period of low rainfall at Tornoto that lasted into the 1930s (Sarker and Thapliyal 1988), the start of a wetter period in Sahelian Africa (Nicholson 1989); a period of pronounced dry conditions in north-central Amazonia from the 1920s to the mid-1940s (Marengo 1995); and a tendency for drier conditions in eastern China (Mingli 1993). Whetton et al. (1990) indicate particularly low (high) river flow in the 1920s–30s period for the Krishna River in India (the Sêne River in West Africa). For South America, Marengo (1995) showed that the most prominent river flow changes were increased streamflow for the Paraná River in Argentina and the Rio Negro in northeast Brazil from 1920 to 1925 and decreased flow in the Orinoco River in north Amazonia from 1925 to 1939 and in the Rio Negro in northeast Brazil from 1928 to 1932.

Evidence from the rainfall correlation maps in Figures 1.18a,b and 1.19a,b for a climatic fluctuation during the 1920s–30s epoch leading to drought in the Great Plains of the United States, and in southern Africa, Australia, India, parts of South America, and China, is varied. As with the turn-of-the-century fluctuation in climate, it appears that the combined effects of decadal to interdecadal signals are responsible. Over the central United States, the most discernable rainfall correlations indicative of suppressed precipitation are on the 60- to 80-year band in AMJ-OND (inverse of Fig. 1.19b given the time series in Fig. 1.16 at this time) and on the 20- to 30-year band in AMJ. This overlapping amalgam of influences is probably the likely source of variations in the intensity of this drought (Stockton and Meko 1983).

In southern Africa, the drought signal appears to be centered on the 20- to 30-year band in JFM, with some influence from the quasi-decadal and interdecadal bands in that season. The role played in rainfall patterns by other fluctuations such as the 18- to 20-year oscillation (Tyson 1986a; Mason 1990, 1995), resolved as EOF 4 in the low-frequency part of the analysis in Folland et al. (1998), is not addressed. However, over far western and Sahelian Africa, this epoch shows a tendency toward wetter conditions as seen in the rainfall correlations on the 60- to 80-year band in JAS–OND (inverse of Fig. 1.19b given the time series in Fig. 1.16 at this time). Interestingly, in central to eastern Africa, the combined influence of the rainfall correlations from the global warming trend to the 20- to 30-year and interdecadal bands in OND is suggestive of a period of wetter conditions in the late 1920s.

Over eastern Australia, most of the drought response in the second half of the 1920s seems to have been a result of the operation of the 20- to 30-year band in OND–JFM. The propensity for long periods of dry conditions during much of the 1930s was apparently ameliorated considerably by the inverse of the rainfall correlations on

the quasi-decadal and interdecadal timescales (Figs. 1.18a,b with the time series in Figs. 1.12 and 1.13). The influence of the quasi-decadal and interdecadal bands during much of the year, in conjunction with the 20- to 30-year band in OND–JFM, appears to have been the major low-frequency source of the prolonged 1939–45 drought.

In India during the 1920s–30s epoch experienced mixed rainfall conditions, with generally drier conditions in the 1920s perhaps being linked to the rainfall correlations on the interdecadal band in AMJ over the second half of the decade and on the 60- to 80-year band in JAS during the first half of the 1920s. For the 1930s, the opposite pattern on the above bands would appear to have contributed to slightly wetter conditions.

The situation in South America can best be deduced for Argentina and northeastern Brazil. Over northern Argentina during the first half of the 1920s, increased rainfall and river flow appear to be linked to the inverse of significant correlations on the quasi-decadal band in JAS. The reverse appears to be occurring over central Argentina at this time. In northeastern Brazil, the same epoch is one of positive rainfall correlations on the quasi-decadal band in AMJ. During the late 1920s to early 1930s, lower rainfall over southeastern Brazil is consistent with negative rainfall correlations on the quasi-decadal band in AMJ.

Over northern China, lower rainfall in the 1920s is reflected in the inverse rainfall correlations on the interdecadal band in AMJ. Across central to eastern China, a reduction in rainfall is related more to inverse correlation patterns on the above band in JFM–AMJ.

The Late 1960s to 1970s

Unlike the situation with previous climatic fluctuations this century, the intense scientific interest in the climate system and ENSO in recent decades has been able to draw on an increasingly vast amount of high-quality data from ground-based and satellite platforms that provide detailed information on the global environment. The two climate variations during this time that have received particular attention in climatological and environmental research are the so-called Sahelian drought and the "climatic shift" in ENSO characteristics in the Pacific Ocean sector. The latter focus has also been paralleled by expanding interest in wider regional to global fluctuations in climate on decadal to interdecadal timescales, which have already been discussed extensively elsewhere in this chapter.

From the mid-1970s to 1980s, considerable scientific research was focused, and concern generated, by the prolonged drought conditions that developed over Sahelian Africa from about 1968 (Nicholson 1985, 1989; Lamb and Peiperl 1991). Continuing into the early 1990s, this climatic event has been the major catalyst for debate about biogeophysical versus large-scale climatic fluctuations as the principal cause of extended drought conditions and climatic change (Nicholson 1993; Nicholson et al. 1996). Recent overviews, such as Druyan (1989), indicate that large-scale climate controls appear to play the dominant role in Sahelian drought, with more localized feedbacks having very much less of a major role in exacerbating the situation. The scope of


