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Decadal Climate Variability

Dynamics and Predictability

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Preface

Decadal climate variability is currently an area of considerable scientific interest whose importance is likely to grow over the next decade. Climate Change on decadal time scales can result, for example, from changes in the concentration of radiatively active gasses but also from natural variations. The causes of natural variability of the climate system on decadal time scales are presently not well known; understanding the mechanisms is however a prerequisite for any climate prediction of changes on these time scales. To this extent a major new experiment, called CLIVAR, has recently been launched by the World Climate Research Programme to determine climate predictability both globally and regionally, and to understand the physical processes giving rise to that predictability. The time scales of interest range from seasons to decades and centuries, and include phenomena such as El Niño Southern Oscillation and the North Atlantic Oscillation, but also long-term changes in the ocean thermohaline circulation.

The purpose of the NATO Advanced Study Institute, which was held in February 1995 in Les Houches, France was to introduce young scientists into the current state of the field. The focus was on modelling, analysing and understanding of ocean-atmospheric interactions, primarily on decadal time scales, although these can not be well separated from both shorter and longer time scale processes. Major topics addressed were observed characteristic patterns of natural variability on decadal time scales in the coupled atmosphere-ocean system, the generation mechanisms which are presently not well understood, the potential predictability of long-term variability, the possibility of rapid climate regime shifts on several timescales, the causes for the large changes taking place at the present time in the northern seas of the Atlantic ocean.

A number of mechanism which are most likely to cause decadal variability have been proposed. Nonlinear interactions within the atmospheric circulation can, in the presence of orography and topography, induce low frequency variability of definite spatial organisation. Interaction with slower components of the climate system (land, ocean, ice) can then produce apparent lower frequency variability. Variability can also arise due to the coupling of atmosphere and ocean. The variability due to El Niño-Southern Ocean (ENSO) is one example of a coupled mode which primarily associated with interannual time scales, but can also have decadal variability.

A coupled mode of decadal time scales, centered over the North Pacific in which the interactions of the atmosphere and the ocean are essential to the mode has been suggested, with the time scale set by ocean planetary wave propagation. Recent model results have shown the possibility that the thermohaline circulation can undergo substantial oscillations on decadal to millenial time scales. Apparently the atmosphere plays no active role but would have to adjust to changes in oceanic heat transport and consequently sea surface temperature. Only those mechanisms involving the ocean are likely to lead to some predictability, but this has yet to be demonstrated.

To provide a coherent structure to the course, principal lecturers developed their topics in depth over a series of lectures. Specific applications were further developed by supporting lecturers. We would like to thank all the lecturers who gave a stimulating series of lectures which are recorded in this volume.

Primary support for the Institute was provided by NATO, through the Special Programme on The Science of Global Environmental Change. Additional support was provided by the European Union and by CNRS, France. This support is gratefully acknowledged. We also thank Shona Anderson, Arne Biastoch and Nils Rix who converted the manuscripts into Latex, and a number of reviewers for helpful comments.

David Anderson
Jürgen Willebrand

April 1996

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OBSERVED CLIMATIC VARIABILITY: TIME DEPENDENCE

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1 Introduction

Preconceived notions concerning the nature and causes of climate variability determine the datasets that scientists examine, the analysis tools they employ, and the questions they address in their research. Their choices, in turn, define and limit the range of possible outcomes. If these notions are wrong, the research is likely to get off on the wrong track. If they are lacking altogether, the course of the research may be determined by default, through ad-hoc choices, as in the maxim: "If all you have is a hammer, all you'll see is nails".

This chapter is designed to complement the abundant literature on statistical analysis techniques used in climate research (e.g., Barnett 1981, Joliffe 1986; Richman 1986; Preisendorfer 1988; Vautard and Ghil 1989; Bretherton et al. 1992; von Storch et al.1995). Rather than illustrating

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how various techniques might be used, we will attempt to identify some of the opportunities and unresolved issues in climate research that invite further analysis of observed and model generated datasets. Rather than focusing on the solutions we will explore the problems. The choice of topics to be included was largely dictated by the author's preconceived notions concerning the nature of climate variability, which include the following:

1. The statistically robust, richly textured response to the annual cycle in sun-earth geometry is still capable of yielding new insights into the inner workings of the climate system (§2.1)

2. Quasi-periodic phenomena, even if they exist, are of only academic interest from the standpoint of short term climate variability, because they cannot possibly account more than a minute fraction of the total variance of the climatic variables of the greatest interest from the point of view of prediction. By far the most prominent quasi-periodic climate 'signal' is the equatorial stratospheric quasi-biennial oscillation (§2.2, 3), but this phenomenon exhibits only a tenuous connection with tropospheric climate variability. It will be argued that the dominant interannual signal in the climate system: the El Niño Southern Oscillation (ENSO) phenomenon (§2.2) occupies too broad a band of frequencies to be regarded as quasi-periodic.

3. As demonstrated clearly by recent numerical modeling results of Manabe and Stouffer (1996), not all interdecadal variability in climatic time series is caused by processes operative on the interdecadal time scale. Much of it is merely a reflection of inherently unpredictable sampling fluctuations due to the presence of variability on the intraseasonal and interannual time scales (§2.3-4, and 8).

4. Well defined interdecadal to century scale variability is clearly evident in certain climatic time series such as hemispheric- or global-mean surface air temperature, even in their raw, unfiltered form (§2.4).

5. Because of the inherent lack of stationarity of many climatic time series, in the absence of a priori predictions it is extremely difficult to demonstrate the statistical significance of 'regime shifts' or unprecedented events (§2.5).

6. With a few notable exceptions involving quasi-periodic phenomena, lead/lag relationships observed in association with interannual to in-

terdecadal climate variability are not particularly strong. Much of the observed variability can be described as separable functions of space and time (§3).

One-dimensional time series will be considered in the next section and multi-dimensional time series in the following one.

2 Climate time series

The evolution of the climate system can assume a wide variety of forms, but for the purpose of this chapter, it will be convenient to group them into the following categories: periodic and quasi-periodic phenomena, aperiodic and random variability, low-frequency trends, and distinctive temporal signatures such as discrete jumps.

2.1 Periodic phenomena

For the range of time scales emphasized in this volume, by far the most important periodic climate signal is the response to the annual march in the intensity and latitudinal distribution of incoming solar radiation. Even the more subtle features associated with the annual march are comparable to or larger in amplitude than the strongest interdecadal to century scale climatic signals and, because of their regularity, they are much easier to isolate and diagnose in observations and model output. The most dramatic and easily explained features of the annual march are the large summer-winter swings in temperature throughout extratropical latitudes and the related summer monsoon rainfall maxima over the subtropical continents. Let us pass over these and consider a few of the more subtle, less easily explained features of the annual march, which lend insight into the inner workings of the climate system.

The annual march of zonally averaged temperature at the mesopause level, near 80 km is exactly the opposite of what one would expect on the basis of radiative considerations: the summer hemisphere is cold and the winter hemisphere is warm. This anomalous behaviour is a consequence of a seasonally reversing pole-to-pole mean meridional circulation cell, characterized by ascent and adiabatic expansion over the summer pole and subsidence and adiabatic compression over the winter pole which drives the temperatures away from local radiative equilibrium. Throughout most of the layer that it occupies, this circulation cell is thermally direct, with warm air rising and cold air sinking, but at levels above 65 km it is thermally indirect (Leovy 1964).

In a similar manner, the tropical (20N-20S) tropopause is remarkably cold year round because of the upwelling associated with the Hadley Circulation, and the annual march of temperature at this level bears little direct relation to the variations in radiative heating associated with the earth's orbital geometry. Throughout this belt temperatures are higher in July, when the earth is farthest from the sun, than they are in January. Over the equator, where one would expect them to be zero, the differences range as high as 10 K (Reed 1963, Reed and Vlcek 1968). Furthermore, there is little indication of a semiannual cycle in response to the seasonal variations in solar declination angle.

Yulaeva et al. (1994) have argued that this anomalous annual cycle is a consequence of the fact that the broad mountain ranges in the Northern Hemisphere (the Rockies, in particular) are much more effective in generating vertically propagating planetary-waves than their narrower counterpart, the Andes, in the Southern Hemisphere. The planetary waves in the winter hemisphere disturb the stratospheric polar vortex, transferring heat from low latitudes to higher latitudes. The same planetary-waves induce a time-mean poleward Lagrangian drift of air parcels in the winter hemisphere, which is fed by ascending motion throughout the tropics. The adiabatic cooling induced by this wave-driven ascent contributes to the remarkable coldness of the tropical tropopause. The more intense Northern Hemisphere wintertime planetary-waves, which attain their peak amplitude in January induce a stronger high latitude warming, accompanied by a stronger cooling of the tropical tropopause, than their Southern counterparts, which attain their peak amplitude in July. The almost perfect compensation between the tropical and extratropical annual cycles, as illustrated in Fig. 1 reflects the constraint that the wave-driven Lagrangian circulation cannot produce any net warming or cooling at any given level: it can only move heat poleward (e.g., see Andrews et al. 1987).

Figure 2 shows an extended time series of total column ozone at Arosa, Switzerland, as inferred from ground based measurements. During most years the column ozone exhibits a pronounced springtime maximum, believed to be a consequence of the same wave-induced poleward Lagrangian circulation mentioned in connection with Fig. 1, which carries ozone from its photochemical source region at the 25-km level over the tropics, pole-

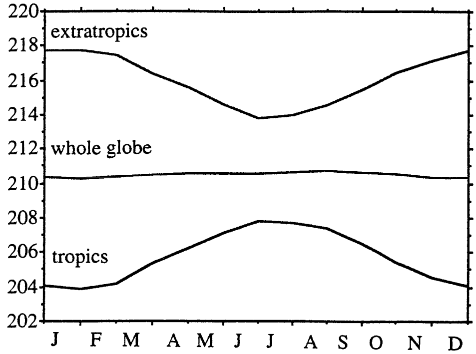

Figure 1: *The climatological mean annual march of lower stratospheric temperature over the tropics (30°N-30°S), the extratropics (poleward of 30°in both hemispheres) and the entire globe, based on data from channel 4 of the the microwave sounding unit for the period 1979 through 1991. The weighting function for this channel is centered near the 70-mb (18 km) level. From Yulaeva et al. (1994).*

ward and downward into a high-latitude reservoir centered near the 15-km level. The distinctive annual march of ozone concentrations at Arosa and other middle and high latitude stations reflects the cumulative effect of the wintertime transports.

Ozone is not the only climatic variable that exhibits a pronounced maximum in the March-April time frame. Sea surface temperatures (SST) over the equatorial Atlantic and tropical eastern Pacific, shown in Fig. 3 exhibit an annual cycle with March-April maxima. The year-to-year variability is larger in the Pacific than in the Atlantic because of the more pervasive influence of the El Niño/Southern Oscillation (ENSO) phenomenon. For example, the row of outlier points along the upper margin of the plot corresponds to the record breaking 1982-83 warm episode. The annual march in the Atlantic is not a pure sine wave: SST cools rather abruptly from May through July and warms more gradually throughout the remainder of the year. It is not at all obvious why SST along the equator should exhibit such a pronounced annual cycle. For discussions of this issue the reader is referred to the observational study of Mitchell and Wallace (1992), the coupled modelling study by Giese and Carton (1994), and the ocean modelling study of Köberle and Philander (1994). The annual march of SST in the equatorial eastern Pacific exerts a profound influence upon the rainfall in adjacent coastal regions of South America. Significant stream-flow in the Piura river in northern Peru (Fig. 4) is largely confined to the warm

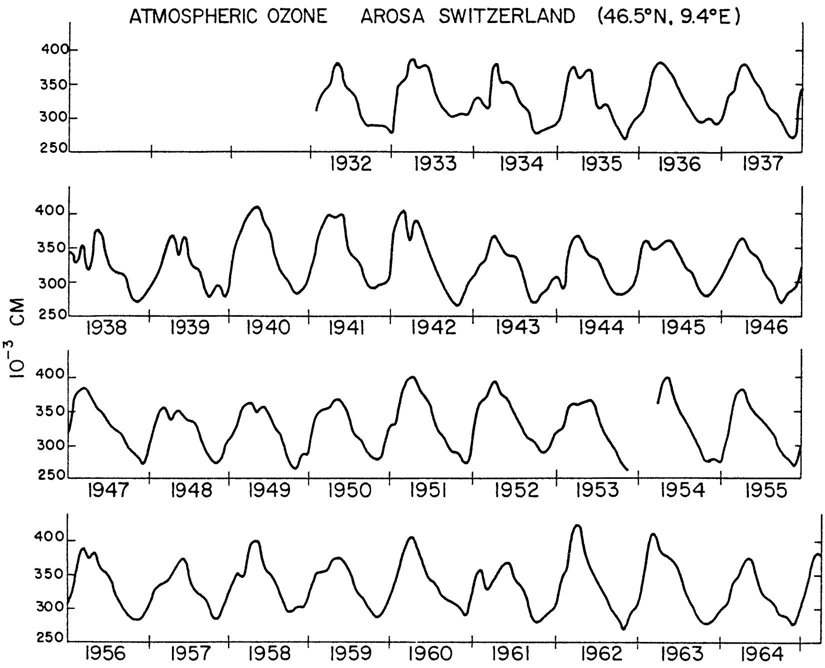

Figure 2: *Monthly mean column ozone amounts at Arosa, Switzerland, 1932-65, as inferred from ground based measurements. Units* 10^{-3} *cm at STP.*

season for offshore SST (January - May). Stream flow during the rainy season ranges from near zero during years with colder than normal SST to flood conditions during El Niño years.

The phenomena documented in Figs. 1-4 serve to illustrate the complexity of the response of the climate system to a simple periodic thermal forcing. Dynamical and physical linkages between the various components of the system give rise to a wide variety of phases, and amplitudes can be quite substantial, even in regions not subject to strong direct solar forcing.

For perfectly periodic phenomena such as the annual cycle, harmonic analysis is the best suited analysis tool. When performed on a suitably chosen period of record, it yields a "line spectrum" in which the lines are integral multiples of the fundamental frequency. In contrast, quasi-periodic phenomena correspond to peaks in a continuous spectrum, as defined by the methods of power spectrum analysis. Brier and Bradley's (1964) convincing demonstration that the lunar synodic cycle is evident in precipitation frequencies over the United States (Fig. 5) is a tribute to the

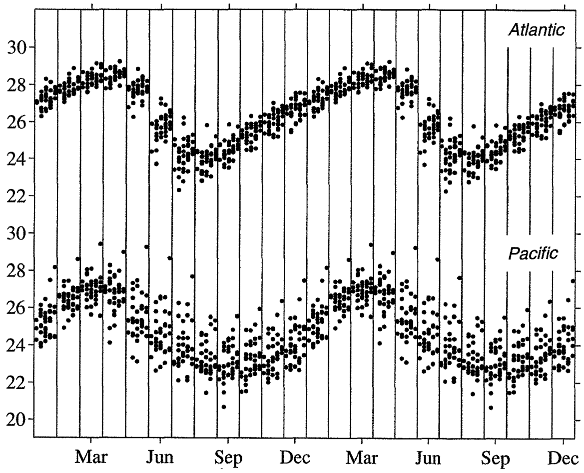

Figure 3: *Scatter plot of monthly mean sea surface temperature (°C) in the equatorial cold tongue regions of the Atlantic and Pacific for individual year/months, grouped by calendar month. The dots for each calendar month have been scattered along the x axis to make them more visible and the calendar year is repeated. Based on data from the Comprehensive Ocean Atmosphere Data Set (COADS) for 1946-85. From Mitchell and Wallace (1992).*

power of harmonic analysis for detecting weak periodic signals.

2.2 Quasi-periodic phenomena

Because climate research tends to be driven, in large part, by the quest for prediction, quasi-periodic phenomena have attracted a disproportionate amount of attention per unit explained variance in the climate record. The literature of the first half of this century abounds with claims of periodicities and quasi-periodicities in the climate record; many of them related to the 11-year cycle in solar activity and its harmonics and subharmonics. Few, if any of these claims have withstood the test of time. Decidedly fewer quasi-periodicities have been reported since the advent of power spectrum analysis, which imposes more rigorous standards for assessing statistical significance.

By far the most notable, and perhaps the only universally recognized quasi-periodic phenomenon in the climate system on the interannual to interdecadal time scale is the regular downward progression of alternating, zonally symmetric easterly and westerly wind regimes in the equatorial

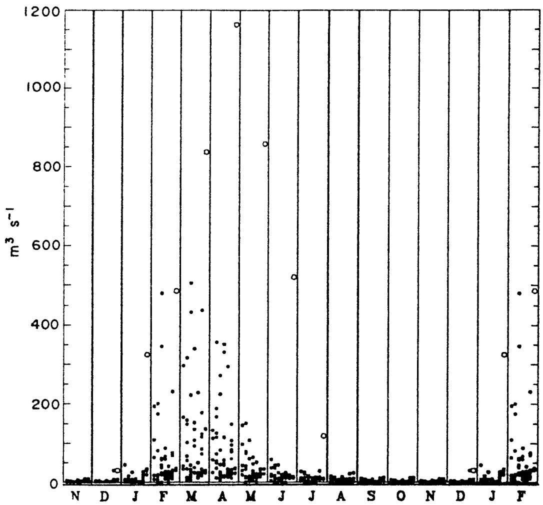

Figure 4: *Monthly-median discharge from the Piura River, which flows westward from the Andes to the Pacific in northern Peru. Each dot represents a particular year month. The dots for a particular calendar are scattered along the x axis to make them more visible and the calendar year is repeated. The circles represent months during the 1982-83 El Niño. From Deser and Wallace (1987).*

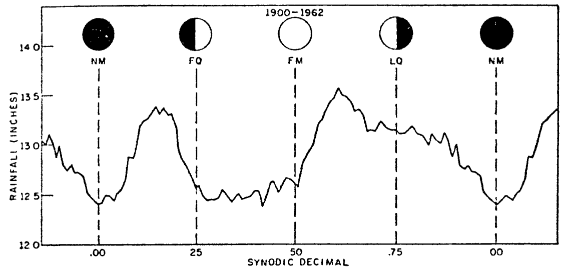

Figure 5: *The total rainfall for a network of more than 100 stations in the United States summarized according to the lunar synodic (29.53 day) month for the period of record 1900-62. From Brier and Bradley (1964).*

stratosphere, first pointed out by Reed (1960) and Ebdon (1961). The time required for the wind to execute a full easterly/westerly cycle ranges from slightly less than two years to about three years: hence the term quasi-biennial oscillation (QBO). This phenomenon dominates time series of zonal wind at levels between 10 and 100 hPa (17 and 30 km) at stations within 10 degrees of the equator, as illustrated in Figs. 6 and 7.

In comparison to the equatorial stratospheric QBO, time series related to ENSO such as the one shown in Fig. 8, exhibit a less regular behaviour, as evidenced by the greater breadth of its spectral peak in Fig. 9. The

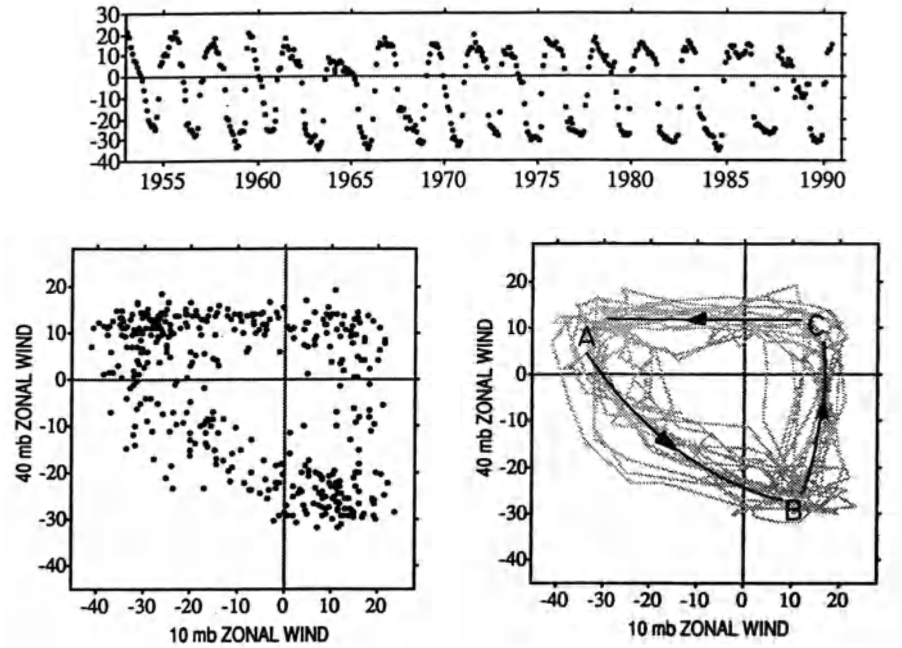

Figure 6: *Top panel: monthly mean zonal wind at the 30-mb (24 km) level over the equator in units of m/s. Lower left: scatterplot of 5-month running mean zonal wind anomalies over the equator at the 10 versus 40-mb (30 vs. 22 km) levels. Lower right: gray lines represent the trajectories in the same two dimensional "phase space", constructed by connecting the points in the bottom left panel in chronological order. Arrows indicate idealized orbits showing the sense of the motion along the trajectories. From Wallace et al. (1993). Data courtesy of Barbara Naujokat, Free University of Berlin.*

power spectrum of the QBO is dominated by a spectral peak centered near a period of 28 months, while the ENSO time series exhibits a much broader band of enhanced power extending all the way from 2 to almost 10 year periods. A measure of the breadth of the peaks is the ratio of the lower to the higher frequencies that bound them: it is of order 0.6 for the QBO compared to 0.2 for the ENSO time series. It is evident from a comparison of Figs. 6 and 8 that, whilst several cycles of the QBO are sufficient to illustrate how it behaves, many more realizations of the ENSO cycle are required in order to sample its full range of variability. One might even question whether even the 120 year record in Fig. 8 is long enough.

Most climatic time series from which the climatological mean annual march has been removed lack robust, well-defined peaks in their power spectra. Rather than focusing one's attention on marginally significant, narrow spectral bumps and dips, which account for only very small frac-

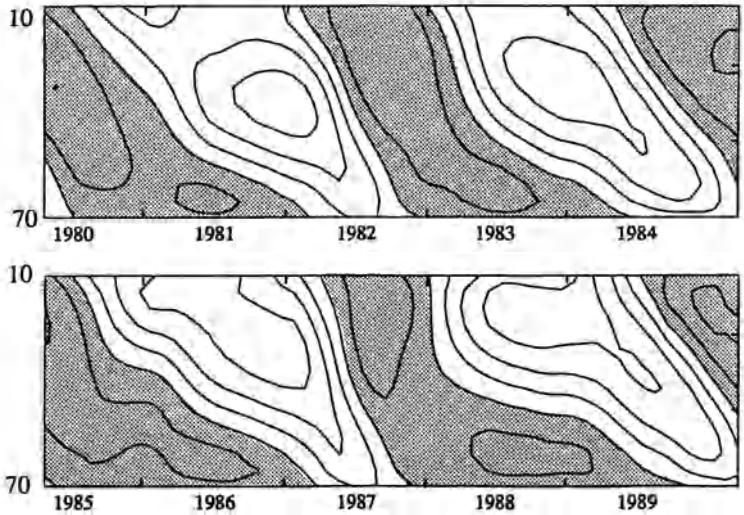

Figure 7: *Time-height section of 5-month zonal wind anomalies over the equator. Contour interval 10 m/s. Westerlies are shaded. The ordinate ranges from the 70-mb pressure level near the tropical tropopause at 17 km to the 10-mb level near 31 km and the scale is logarithmic in pressure and approximately linear in height. Labels on the abscissa denote the midpoint of the calendar year. From Wallace et al. (1993)*

tions of the total variance of the time series, is usually more informative to regard the time series as aperiodic (i.e., without periodicities or quasi-periodicities) and to focus on the gross features of the spectra and the relationships between variables that prevail across wide ranges of frequencies and account for substantial fractions of the total variance.

2.3 Aperiodic and random variability

Whether the variability associated with a particular aperiodic phenomenon should be viewed as deterministic or random depends upon the range of frequencies under consideration. For example, baroclinic waves and their attendant cyclones and fronts are deterministic and quite predictable out to several days, yet they have to be treated stochastically in seasonal-to-interannual climate prediction. The "stormtracks" (the envelopes in which the most vigorous baroclinic wave activity resides) might evolve in a deterministic manner on the seasonal to interannual time scale, but not the individual cyclones within them. In a similar manner, ENSO is deterministic and to some extent predictable on the seasonal to interannual time scale, but it would have to be treated stochastically in dealing with decade-to-century scale variations.

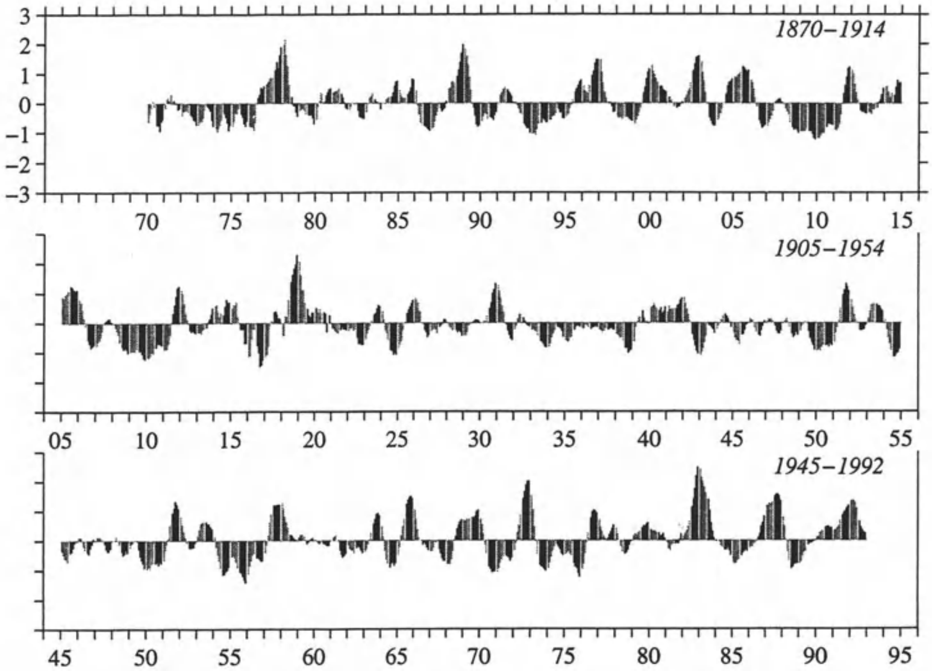

Figure 8: *Sea surface temperature (SST) averaged over the region 6°N-6°S, 90°- 180°W depicted by the shading in Fig. 18 of chapter 2. Gray bars denote warm season (January through May) values and black bars denote cold season (July through November) values. Based on data from the Comprehensive Ocean-Atmosphere Data Set (COADS). The time series has been smoothed with a 5-month running mean filter. To compensate for changes in instrumentation discussed in section 2.3 of chapter 2 a constant value 0.3 K has been added to monthly values prior to December 1941.*

The distinguishing characteristic of random variability, in the sense that the term will be used in this chapter, is the lack of autocorrelation at all lags other than zero. Successive values in the time series are independent of one another: the next data point cannot be predicted with any degree of skill whatsoever on the basis of a knowledge of the previous time history. The Fourier transform of such a lag correlation function, which defines the power spectrum of the associated time series exhibits equal power at all frequencies. It is commonly referred to as "white noise" in analogy with the electromagnetic signature of white light, whose electromagnetic spectrum

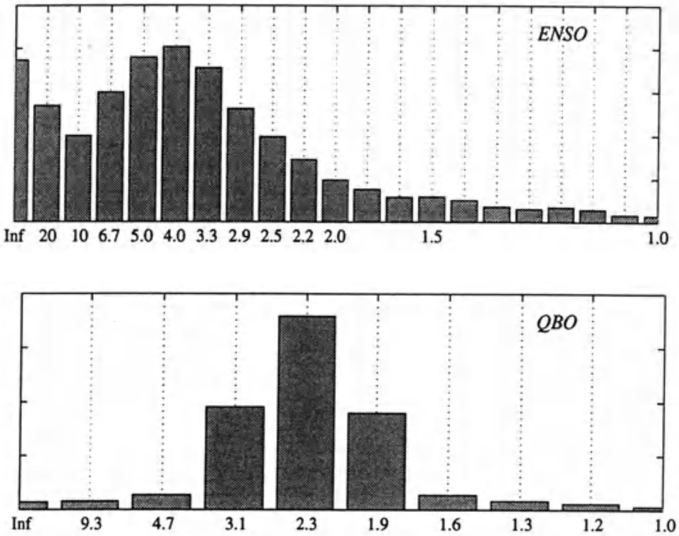

Figure 9: *Power spectra of (top panel) equatorial Pacific SST (the time series in Fig. 8) based on twice-yearly data for 1882-1992 and (bottom panel) zonal wind at the 30-mb level over the equator (the time series in the top panel of Fig. 6). The abscissas of both panels are linear in frequency, but are labeled in terms of period, in years.*

is independent of frequency. It follows from elementary sampling theory that the expected value of the variance of such a time series is independent of the length of the time series and the expected value of the variance of time means of consecutive segments of the series, each consisting of N successive (independent) data points, decreases in inverse proportion to N.

In contrast, the spectra of aperiodic time series generated by deterministic processes tend to be "red": i.e., their spectra tend to drop off with increasing frequency. Such time series are sometimes modeled stochastically in terms of a first order autoregressive process, defined by the relation

$$x_{n+1} = ax_n + (1-a)\varepsilon_n$$

where the subscripts n and $n+1$ refer to successive values of the series x, ε is a "white noise" time series of unit variance, and a is the linear correlation between successive data points in the time series, commonly referred to as the "lag 1 autocorrelation", a measure of the "redness" of the time series. When a random time series is being generated to be used as a proxy for an observed time series, a is chosen to match the observed time series. The autocorrelation at lag N is a^N and the characteristic "decorrelation time" τ (the time required for the autocorrelation between lagged data points in the time series to drop off by a factor of e) is given by $\delta t/(-\ln a)$, where δt is the time increment between successive data points. For purposes of significance testing, the effectively time between independent data samples in the time series is 2τ (Leith 1973). The expected value of the variance of a such a "red noise" time series increases with sampling interval, but the rate of increase slows as the sampling interval becomes much longer than the decorrelation time. In the limiting case $a = 1$, the time series can be modelled as a 'random walk' process whose expected variance increases linearly with sampling interval.

The expected variance of means of N successive data points in a "red" time series decreases with increasing N at a rate more gradual than $1/N$, but approaches $1/N$ as the averaging interval becomes much longer than the decorrelation time. In other words, for averaging intervals much longer than τ, non-overlapping means of a "red" time series are linearly independent: their variability must be regarded as random and inherently unpredictable sampling fluctuations associated with whatever physical processes happen to be operative at higher frequencies. In a similar manner, the power in the spectrum of a "red" time series increases with decreasing frequency, but the rate of increase slows as frequency becomes smaller than the inverse of the decorrelation time and it eventually levels off. Hence, at sufficiently low frequencies, even 'red' time series exhibit 'white' spectra.

Madden (1976) expressed concern that the month-to-month and winter-to-winter variability inherent in the climate record might be nothing more than sampling variability associated with the presence of higher frequency phenomena such as baroclinic waves with characteristic time scales of days and sporadic blocking episodes that might last as long as a week or two. To illustrate the validity of his concern, we will make use of a synthetic "climate", whose low frequency behaviour is known with much greater precision than that of the real atmosphere. The results presented in this subsection are based on a 100,000 day, 'perpetual January' simulation with a low resolution (rhomboidal 15 truncation) GFDL general circulation model (GCM) run with fixed climatological mean SST. If a single winter is regarded as being 100 days in length, this run provides a sample size equivalent to 1000 winters: roughly 20 times as many as in the observational record.

The statistics presented in Fig. 10 are based on the simulated 500-hPa height field poleward of 20°N. The calculations described below are roughly equivalent to what would be obtained if they were performed on the time