Chapter 9

El Niño and the Southern Oscillation

9.1 Interannual fluctuations of the Walker circulation: the "Southern Oscillation"

In some years, the actual tropical circulation, especially in the Pacific region, is quite different from the climatological picture. This phenomenon, which was detected about 60 years ago by Walker and given the name "Southern Oscillation", shows up very clearly in anti-phased fluctuations of surface pressure between the west and east Pacific. The extraordinary anticorrelation in monthly mean surface pressure at Darwin (on the north central coast of Australia) and Tahiti is shown in Fig. 9.1. The relationship actually extends over a wide area; Fig. 9.2 shows the spatial structure of the temporal correlation[1] of annual-mean SLP with that of Darwin. The correlation reveals a

[1] If the SLP at location $\mathbf{x}$ and time t is $p(\mathbf{x}, t)$, the *correlation coefficient*, $C(\mathbf{x}_0, \mathbf{x})$, between the time series of SLP at a reference location $\mathbf{x}_0$ and any other location $\mathbf{x}'$ is

$$C(\mathbf{x}_0, \mathbf{x}) = \frac{\overline{p'(\mathbf{x}_0, t)p'(\mathbf{x}, t)}}{\sqrt{\overline{p'^2(\mathbf{x}_0, t)}}\sqrt{\overline{p'^2(\mathbf{x}, t)}}},$$

where the overbar denotes the time average over the entire record and $p' = p - \overline{p}$ is the departure from that average. Note that, if $p'(\mathbf{x}, t) = \alpha p'(\mathbf{x}_0, t)$, where α is a constant, $C = sign(\alpha)$. If the two time series are perfectly correlated ($\alpha > 0$), $C = +1$; if perfectly anti-correlated ($\alpha < 0$), $C = -1$. If they are uncorrelated, $\overline{p'(\mathbf{x}_0, t)p'(\mathbf{x}, t)} = 0$ and so $C = 0$.

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trans-Pacific dipole, with structure roughly similar to that of the Walker cell. In fact, what we are seeing here are interannual fluctuations of the Walker circulation: along with these pressure variations are variations in rainfall and in the strength of the easterly Trade winds across the tropical Pacific basin and beyond. As a measure of these fluctuations, it has become conventional to define a "Southern Oscillation Index" (SOI) as

$$SOI = 10 \times \frac{SLP_{Tahiti} - SLP_{Darwin}}{\sigma} ,$$

where σ is the standard deviation of the pressure difference time series. The time series of the index is shown in Fig. 9.3; note the existence of dramatic and apparently isolated "events" (*e.g.*, 1940/41, 1982/83, 1997/98) but also periods of fluctuation (*e.g.*, 1968-77).

These fluctuations are strongest in the near-equatorial Pacific region, but in fact have a significant influence on the climate in other regions (*e.g.*, note the wave-like feature over N. America in Fug. 9.2). Fig. 9.4 shows annual rainfall at several tropical and subtropical locations. Note the tendency for certain anomalies—drought in eastern Australia, Indonesia/Melanesia, and as far as India and southeast Africa, and unusually strong rains in the central Pacific and equatorial Africa—to coincide with El Niño events.

9.2 SST variations: El Niño and La Niña

Manifestations are not, however, confined to the atmosphere. A phenomenon known as "El Niño" has been known for centuries to the inhabitants of the west coast of equatorial S America. Amongst other things, this comprises unusual warmth of the (usually cold) surface waters in the far eastern equatorial Pacific, poor fishing and unusual rains. Fig 9.5 shows a time series of SST in the far eastern equatorial Pacific. These show clear interannual fluctuations, on a typical time scale of a few years, with anomalously warm years occurring maybe twice per decade. Notice that the warm years (*e.g.*, 1983, 1998) tend to coincide with, or immediately follow, periods of strongly negative SOI (*cf.*, Fig. 9.3).

Some clues as to what is happening in the ocean are revealed by Fig. 9.6. Note the persistent W-to-E decrease of SST we noted before, the persistence of the warm waters in the west, and the annual development of very cold water in the east in the second half of the year, associated with

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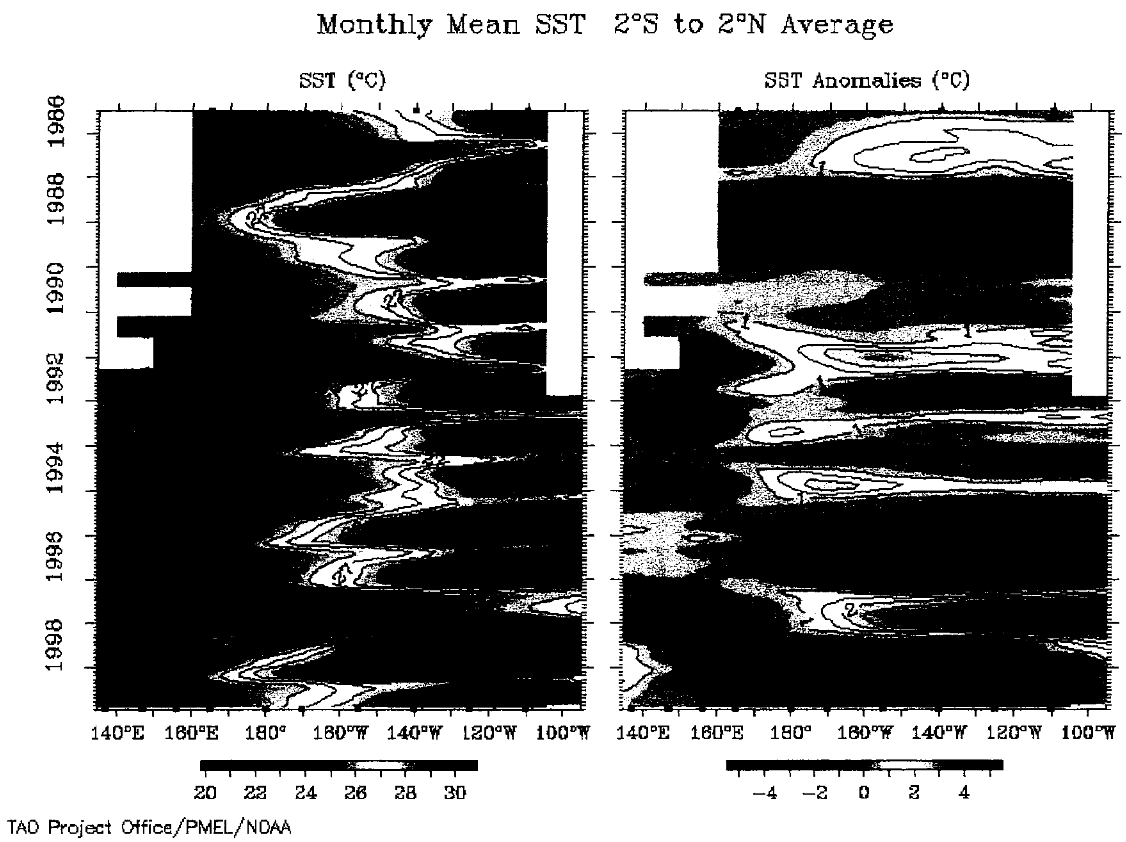

Figure 9.6: SST (left) and SST anomaly (departure from average for the time of year), as functions of time and longitude across the equatorial Pacific.

upwelling of cold water from depth. But, as Fig. 9.6 shows, the extent of this development varies from year to year. Occasionally, the development is unusually weak and in extreme cases (*e.g.*, 1997) hardly occurs at all. At such times, the eastern ocean, though still no warmer than the western equatorial Pacific waters, is very much warmer than normal for that time of year. It is these warm events that are referred to as "El Niño"[2]. In most of these cases the failure of the cold tongue in the eastern ocean is accompanied by an eastward encroachment of warm water from the west, so that the SSTs are anomalously high all the way from the eastern side almost to the date line.

9.3 The coupled phenomenon

The "El Niño" phenomenon, like the SO, is irregular but has typical periodicity of a few (2-5, usually) years. In fact, it is evident from Figs. 9.3 and 9.5 that periods of negative SOI correspond with warm periods in the east Pacific. This is shown more clearly in Fig. 9.7. Note the extemely strong anticorrelation.

9.4 Theory of ENSO

We have seen earlier that the ocean-atmosphere system is as depicted schematically in Fig. 9.8. The Walker circulation in the atmosphere is sustained by the east-to-west gradient in SST. The ocean is driven by the wind stress associated with the easterly Trade winds. But, of course, the strength of the Trades is determined in part by the strength of the Walker circulation: the system is circular (Fig. 9.9), with the potential for positive feedback: change one component, and the whole system responds in such away as to reinforce the change.

9.4.1 What the observations suggest

The "big picture" of what happens during a warm ENSO event is illustrated in Fig. 9.10. In "normal" conditions, there is a strong E-W tilt of the thermocline and a corresponding E-W gradient of SST, with cold upwelled

[2]The opposite, cold, phase (*e.g.*, 1998-99) is known as "La Niña."

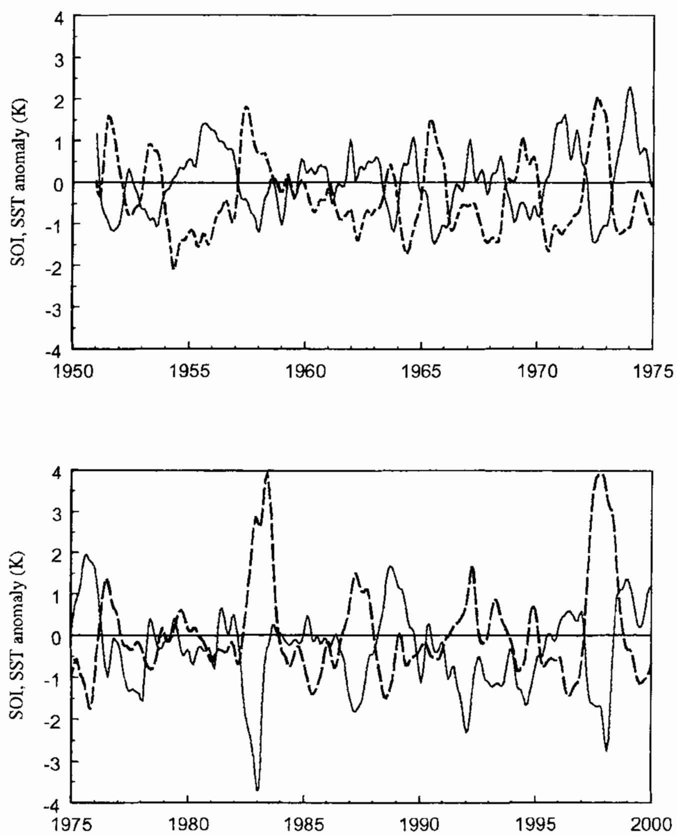

Figure 9.7: Monthly mean SOI index (red) and "Nino1+2" SST anomalies.

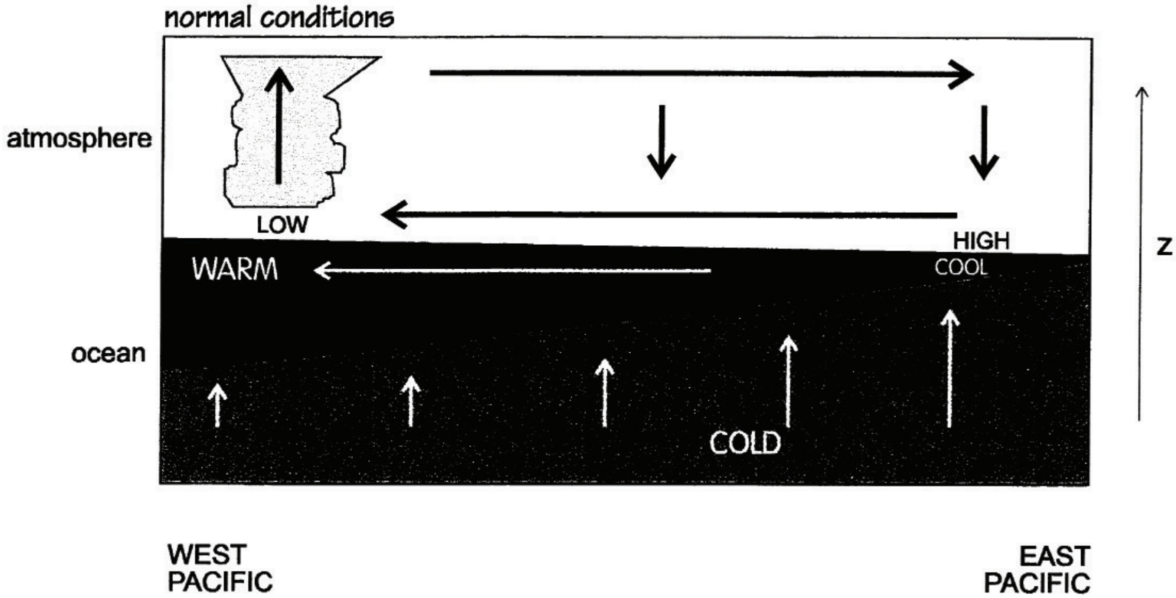

Figure 9.8: Schematic of the tropical Pacific Ocean-atmosphere system.

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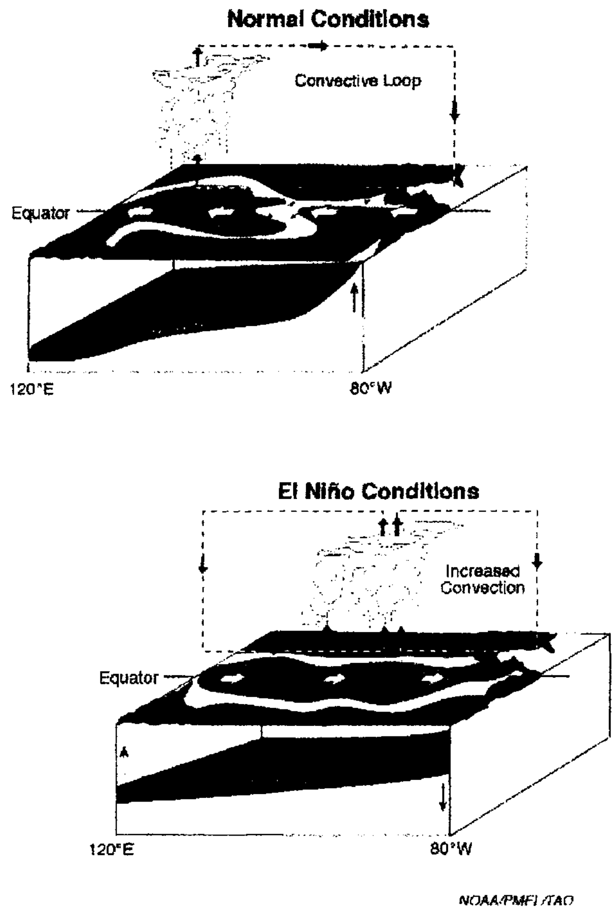

Figure 9.10: A schematic of the ocean-atmosphere behavior in the tropical Pacific basin under "normal" conditions and during a warm event.

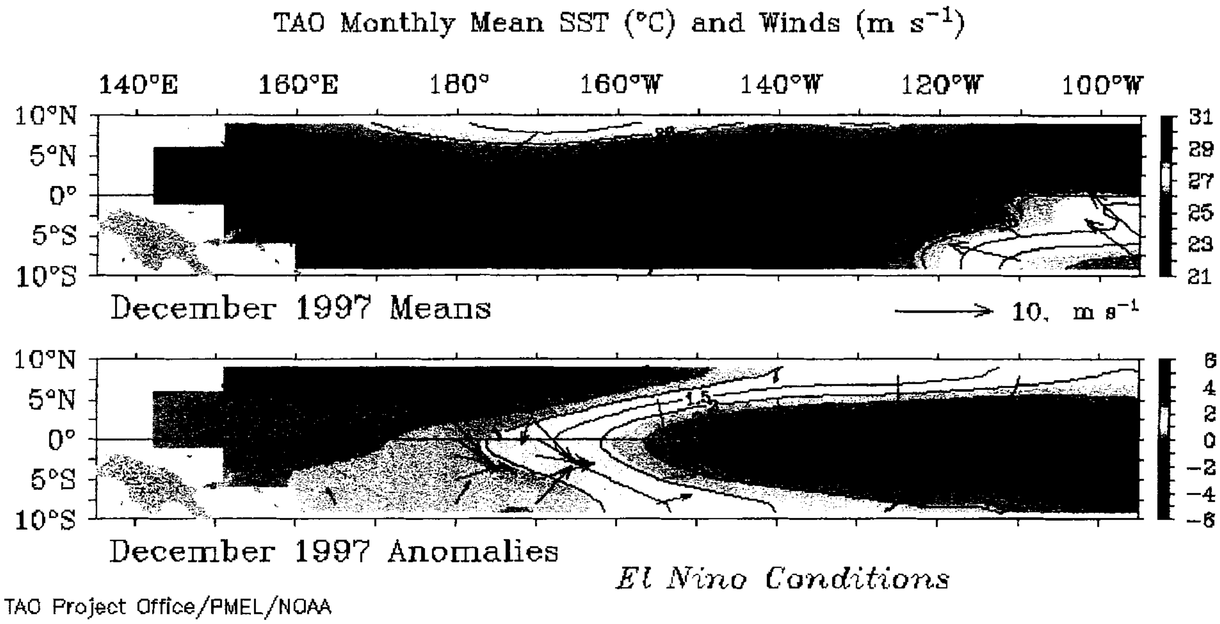

Figure 9.11: SST, winds (and anomalies) during the warm phase (El Niño) in Dec 1997.

water to the east and warm water to the west. Atmospheric convection over the warm water drives the Walker circulation, reinforcing the easterly trade winds over the equatorial ocean. During a warm El Niño event, the warm pool spreads eastward, associated with a relaxation of the tilt of the thermocline. Atmospheric convection also shifts east, moving the atmospheric circulation pattern with it. This leads to a weakening or, in a strong event, a collapse of the easterly trade winds, at least in the western part of the ocean. These features are illustrated by Figs. 9.11 and 9.12, during the two extreme phases of the phenomenon. Note especially how the Trades were weak during the warm event of 1997 and strong during the cold event of 1998.

9.4.2 The ocean forces the atmospheric behavior

Remark 1 *The atmospheric fluctuations manifested as the Southern Oscillation seem to be an atmospheric response to the changed lower boundary conditions associated with El Nino SST fluctuations*

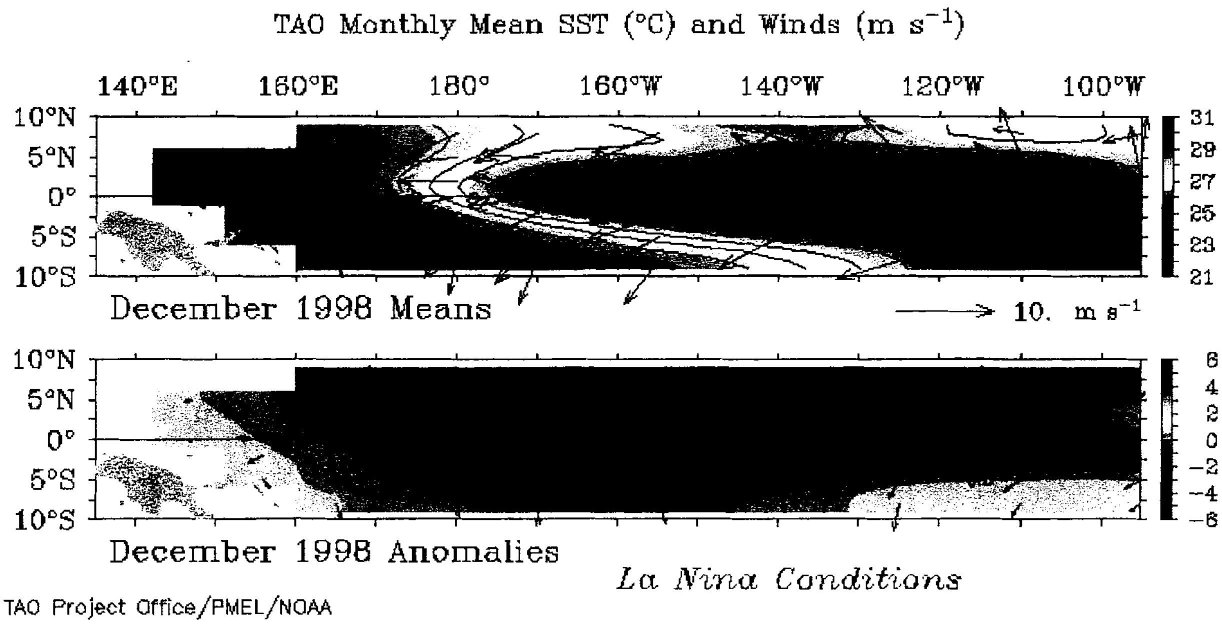

Figure 9.12: SST, winds (and anomalies) during the cold event (La Niña) of December 1998.

This has been demonstrated in a whole range of models, from the very simplest to full, three-dimensional general circulation models (GCMs). In simple terms we should expect (on the basis of our simple model) that the Walker circulation would be reduced (and the Pacific Trades tend to collapse) if the E-W contrast in SST is reduced as it is during El Nino. Specifically, one would expect to see equatorial wind anomalies in response to a shift of the heating region to be much as observed. There have been many studies using sophisticated atmospheric general circulation models (GCMs). These experiments quite successfully reproduced the Southern Oscillation, given the SST evolution as input.

9.4.3 The atmosphere forces the oceanic behavior

Remark 2 *The oceanic fluctuations manifested as El Nino seem to be an oceanic response to the changed wind stress distribution associated with the Southern Oscillation.*

This was first argued by Bjerknes, who suggested that the collapse of the trades in the west Pacific in the early stages of an El Nino would drive (see Fig. 9.13) an oceanic Kelvin wave (of thermocline depression) eastward; this

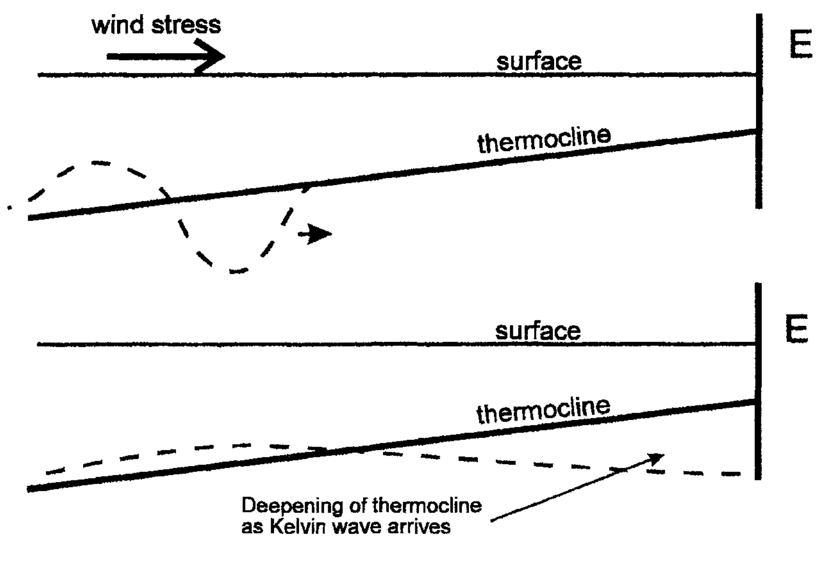

Figure 9.13:

would deepen the thermocline in the east Pacific some two months later (the speed of the relevant Kelvin waves in the equatorial ocean is about $2ms^{-1}$). This would raise the SST in the east (the upwelling continues but warmer water is being upwelled to the surface). The basic postulate—that the ocean responds to the atmosphere—has been confirmed in ocean models forced by "observed" wind stresses.

9.4.4 ENSO is a coupled atmosphere-ocean phenomenon

Remark 3 *The El Nino - Southern Oscillation phenomenon arises spontaneously as an oscillation of the coupled ocean-atmosphere system*

Bjerknes first suggested that what we now call ENSO is a single phenomenon and a manifestation of ocean-atmosphere coupling. The results noted above appear to confirm that the phenomenon depends crucially on feedback between ocean and atmosphere. This is demonstrated in coupled models, in which ENSO-like fluctuations may arise spontaneously. Studies have been done with coupled models of varying complexity; such models, given the right parameters, spontaneously produce ENSO-like oscillations.

9.5 Further reading

A good, basic discussion of all the issues presented here (and several of the figures), as well as discussion of the impact of El Nino, can be found in:

Philander: *El Nino, La Nina and the Southern Oscillation.* Academic Press, 1990. (The later chapters are at an advanced level.)

An interesting series of articles on the large 1982-83 El Nino was published in *Science* on 16 Dec 1983. For discussion of the ocean and atmosphere, see the articles by Cane and by Rasmusson and Wallace.

Information about past and current behavior can be found on many web sites, such as **http://www.elnino.noaa.gov**