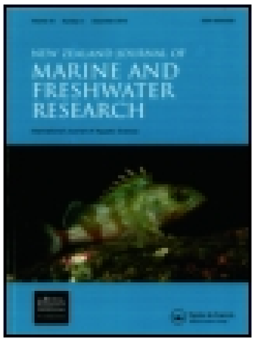

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Sea surface temperature variations at coastal sites around New Zealand

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Abstract Sea surface temperature (SST) observations from 16 coastal sites around New Zealand are analysed along with some corresponding air temperatures. Day-to-day variations in SST show weak periodicity over an 8–16 day range. Air temperatures are generally cooler and short-term fluctuations have 3–4 times the standard deviation of the SSTs. Seasonal SST variations are described and coastal SSTs are compared with offshore SST data. At Farewell Spit the coastal SSTs were always cooler than offshore SSTs which supports the view that upwelling is persistent in the Cape Farewell region. Inter-annual variations in SST are found to be correlated with Southern Oscillation atmospheric pressure anomalies. In particular we find that the El Niño phenomenon which is accompanied by warm SSTs in the central and eastern tropical Pacific is also accompanied by lowered SSTs throughout New Zealand's coastal waters.

Keywords sea surface temperature; Southern Oscillation; El Niño; upwelling

INTRODUCTION

In October 1977, a programme was instituted to obtain SST data at four coastal sites in the North Island, New Zealand (Auckland, Tauranga, Napier, New Plymouth) and in July/August 1978, this programme was extended to sites in the South Island (Nelson, Farewell Spit, Westport, Milford Sound, Bluff, Timaru, Lyttelton, and Kaikoura). Observations began at Greta Point in Wellington Harbour in May 1981 and at Lyall Bay, Wellington, in August 1982 (see Fig. 1).

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*Deceased

Voluntary observers were asked to measure the sea surface temperature, preferably at 0900 h each day. However, because of the constraints under which the observers operate, the time at which observations are made may differ at particular sites. Furthermore, an unbroken record of daily measurements is seldom achieved, with gaps in the data arising from such causes as thermometer breakages and delays in their replacement and the absence of observers during weekends, holidays, and illnesses.

Regular observations of daily sea surface temperatures have been made at Portobello Marine Station, University of Otago, since 1953, and at Leigh Marine Station, University of Auckland, since 1967 (Evans & Ballantine 1983). Otherwise there are no long-term SST data available for New Zealand coastal waters. Some shorter-term SST data are, however, available. Monthly mean SSTs for Auckland Harbour, Tamaki Estuary, Bay of Islands, and Kaipara Harbour have been published for the years 1928 to 1941 (New Zealand Marine Department 1929–41) and Skerman (1958) discussed SST observations made at Auckland, Wellington, Lyttelton, Timaru, Otago, and Bluff harbours from 1952 to 1955. Other SST data have been published for Auckland (Hounsell 1935; Hefford 1947; Slin 1968), Wellington (Ralph & Hurley 1952; Maxwell 1956; Ritchie 1970; Booth 1975), Otago Harbour (Hurley 1959; Hurley & Burling 1960; Slin 1968), Bay of Islands (Booth 1974), and Mangonui (Booth 1983). Since October 1982, weekly averaged satellite-derived SST charts covering the New Zealand region have been produced by the New Zealand Meteorological Service, Ministry of Transport.

OBSERVATIONS

At the commencement of the programme, measurements were made using mercury-in-glass stem thermometers mounted in cylindrical containers of clear plastic. Calibration checks were carried out on all thermometers issued to ensure that they were accurate to 0.05 °C. The reading accuracy was considered to be 0.1 °C. Beginning in late 1982 these thermometers were replaced with digital thermometers employing a thermolinear thermistor (YSI 400 series) as the sensing element; by

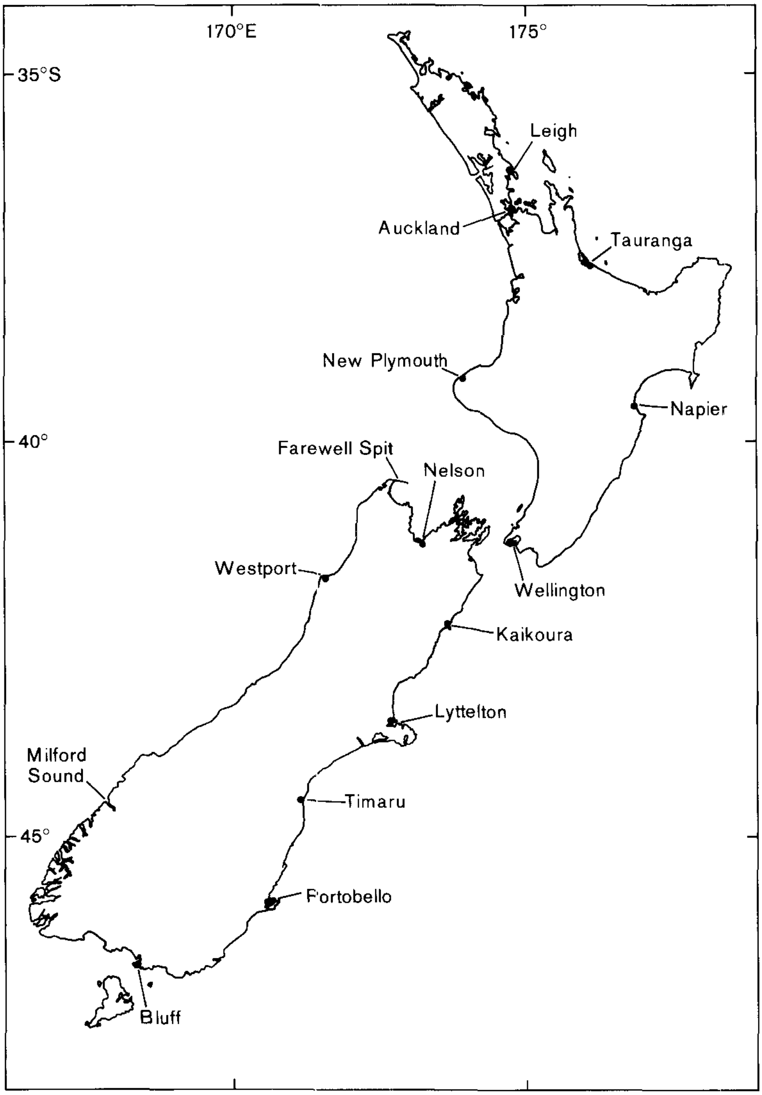

Fig. 1 Location of coastal sampling sites.

February 1983 these replacements were completed. The digital thermometers, calibrated in the laboratory about every 2 years, are accurate to 0.08 °C and reading errors are essentially nil. All data are held in computer files at the New Zealand Oceanographic Institute, Wellington.

RESULTS AND DISCUSSION

Short-period SST variations

Visual examination of the daily SST *versus* time plots show that short-period SST variations are superimposed upon an annual seasonal temperature signal (see Fig. 2). To determine the nature of the short-period variations we have examined in detail eight years' data from six of the measurement sites. Data sets which have near-complete records were chosen. However, occasional gaps of a day or two do exist and have been filled in with values calculated by linear interpolation. The most incomplete records examined are from Farewell Spit where 19 days or 5% of the data are missing.

To remove most of the variation associated with the annual seasonal cycle, a best-fit sine curve for each series was calculated (by least squares), and subtracted from the data. Then, for each data set, a high-pass series was created by subtracting the result of a low-pass first-order recursive filter of the form $y_i = a\,x_i + (1 - a)\,y_{i-1}$ with $a = 0.1$

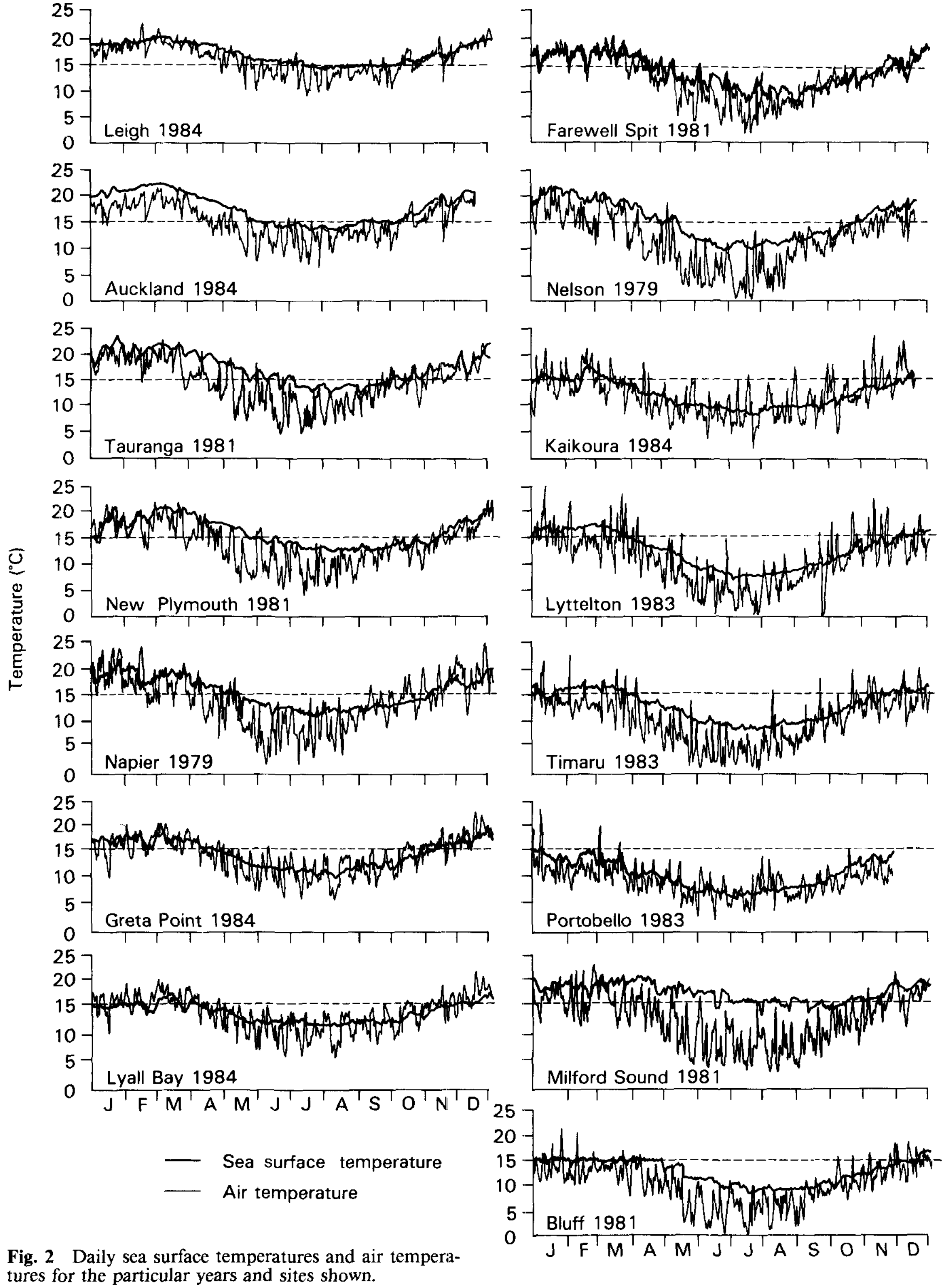

Fig. 2 Daily sea surface temperatures and air temperatures for the particular years and sites shown.

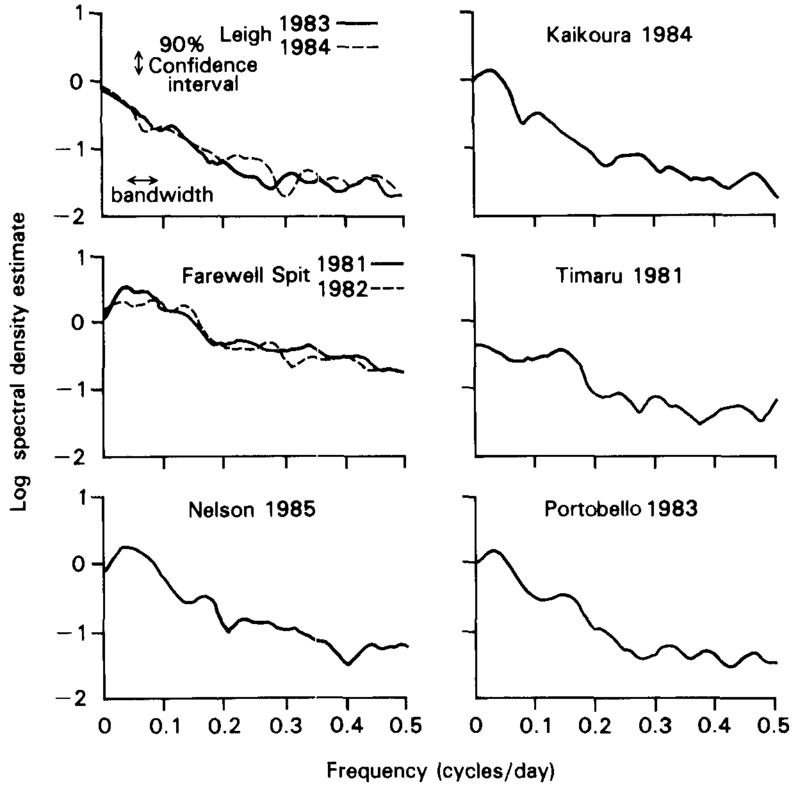

Fig. 3 Smoothed spectral density estimate for daily sea surface temperature data with the best fit sine curve removed and filtered as described in the text.

applied once from each end of the data. This resulted in a sharp drop off in power for frequencies below about 0.05 cycles/day.

Periodograms were then calculated and subsequently smoothed to give the spectral estimates shown in Fig. 3. The spectral estimates show no well-defined periodicity but indicate that the SST variations are broad-banded with a gradual drop in power as frequency increases. In the spectral estimates for Farewell Spit and Timaru in particular, there is a more rapid change in power between frequencies above and below about 0.17 cycles/day. The amplitude of the estimates is similar for all sites with the exception of Farewell Spit which has a higher spectral level. Farewell Spit SSTs are commented on below.

SST and air temperature correlation

Daily SSTs and 9 a.m. air temperatures for a particular year, chosen because it was the most complete year's SST data for each site, are plotted in Fig. 2. The air temperature records have no more than an occasional missing value. Air temperatures are, in general, cooler than the SSTs and air temperature fluctuations are much larger than SST fluctuations. Comparing the standard deviations (Table 1), short-term air temperature fluctuations (Columns b) are generally three to four times larger than the SST fluctuations, except for Farewell Spit (see below). At four sites we have used data from more than one year. The standard deviations calculated for the different years for each site are of similar magnitude.

Coherence spectra have been calculated for data sets used for Table 1, Column b, and which have no more than 11% of the data missing. These are presented in Fig. 4. The coherences are generally higher at low frequencies and at Leigh, Farewell Spit, and Portobello there is a noticeable drop in coherence at about 0.25 cycles/day. These three sites exhibit the strongest coherence with values around 0.65 for frequencies 0.25 cycles/day and below, and 0.35 for higher frequencies. At Napier, Nelson, and Timaru, coherences are weaker, particularly over lower frequencies. At the remaining sites (Kaikoura, Milford Sound, and Bluff), coherence is generally less than 0.3 over the frequency range and, considering the 90% confidence intervals, are barely significant. The phase spectra indicate that short-term SST fluctuations are in phase with or lag air temperature fluctuations by up to one day.

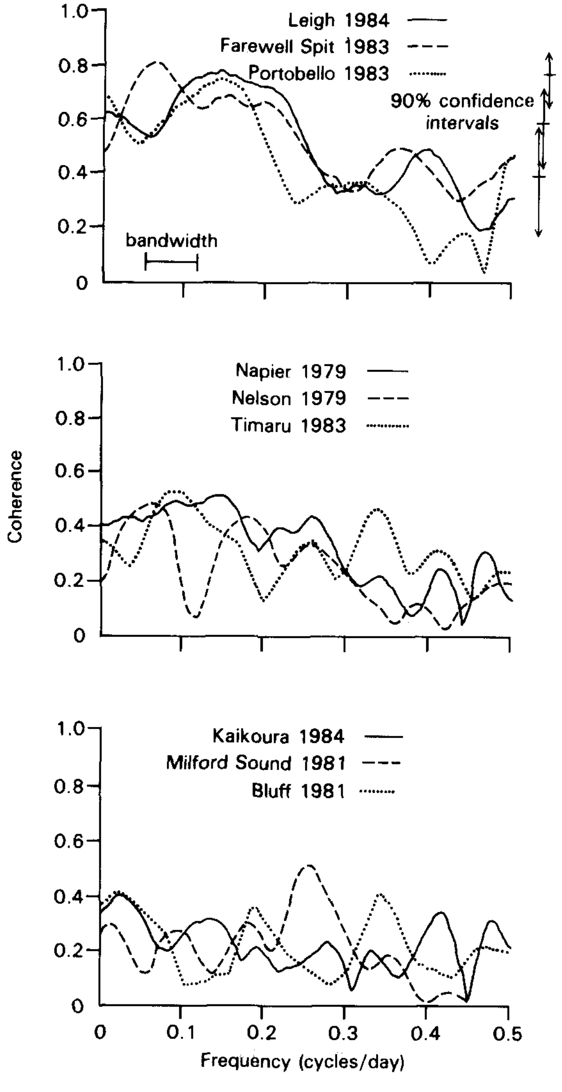

Fig. 4 Smoothed coherence estimates for sea surface temperature and air temperature series. All series have had the best fit sine curve removed and have then been filtered as described in the text.

Table 1 Standard deviations (°C) for SSTs and corresponding air temperatures. Columns a shows s.d. for the data as recorded. Columns b shows s.d. for data which has had the best fit sine curve removed and then filtered as described in the text and thus gives an indication of the day-to-day variability. Data % is the percentage of measured SST data for each data set used. For sets with less than 100%, the s.d. can be regarded as an indication only (the missing values have been filled using linear interpolation which will result in a reduction in calculated variance).

		Data	SST		Air	
Site	Year	%	a	b	a	b
Leigh	1983	100	1.96	0.43	2.84	1.38
	1984	100	2.12	0.42	2.81	1.37
Auckland	1984	71	2.90	0.45	3.34	1.69
Tauranga	1981	62	3.12	0.78	4.41	2.12
New Plymouth	1981	68	2.82	0.74	4.16	2.09
Napier	1979	89	3.15	0.79	5.15	2.73
Greta Point	1983	65	2.48	0.52	3.39	2.04
	1984	63	2.75	0.50	3.39	1.94
Lyall Bay	1983	58	1.58	0.49	3.39	2.04
	1984	61	1.84	0.53	3.39	2.04
Farewell Spit	1981	95	3.11	1.14	4.24	1.92
	1982	95	2.70	1.06	3.91	2.10
	1983	98	2.35	1.21	3.94	2.30
Nelson	1979	92	3.61	0.60	5.23	2.41
Kaikoura	1984	100	2.65	0.55	4.02	2.64
Lyttelton	1983	74	3.42	0.43	4.89	2.73
Timaru	1983	92	3.06	0.47	4.59	2.46
Milford Sound	1981	89	1.85	0.75	4.97	2.72
Portobello	1983	91	2.95	0.62	3.06	2.06
Bluff	1981	99	2.45	0.50	4.07	2.14

SST and wind correlation

For each of the nine SST data sets used in the above section, corresponding daily 9 a.m. wind components directed to the east and south were calculated from wind speed and direction data. Coherence spectra were then calculated for the SST and wind component series. Coherences were low and broad-banded, the highest being 0.3 to 0.35 between the following series: SST and westerlies at Leigh, SST and northerlies at Farewell Spit, and both westerlies and northerlies over the frequency range 0–0.25 cycles/day at Portobello and Milford Sound. Although the coherences are low, it is perhaps worth noting that, in general, at all sites the SSTs tended to decrease with westerly and southerly winds. However, coherences between air temperature and wind components show that air temperatures also tend to be lower with westerly and southerly winds, which suggests that the SST may respond to air temperature or factors influencing air temperature and not necessarily to advection or upwelling resulting from wind direction.

Oceanic processes and short-period SST variations

The squared coherence between SST and air temperature show that up to 35% of the variance in SST was associated with air temperature fluctuations. Coherence spectra for SST and radiation (actinograph) data for Leigh 1983 show that at most 10% of the variance in SST was associated directly with incoming radiation. These figures suggest that much of the short-term SST variance results from activity within the ocean such as turbulence, eddies, waves, advection by currents, and upwelling of subsurface water. This agrees with the suggestion made by Evans & Ballantine (1983).

Seasonal SST variations

The most prominent signal in the daily SST data is associated with the seasonal temperature cycle, as evidenced in the plots of long-term monthly mean SST (Fig. 5). The highest long-term monthly mean SSTs occur in either January (4 sites), February (8) or March (3). The lowest occurs in either July (9 sites) or August (6). The summer to winter range of long-term monthly mean temperature was less than 5 °C at Milford Sound (4.1 °C) and Lyall Bay (4.7 °C), and more than 9 °C at Nelson (9.8 °C), Auckland (9.2 °C), Lyttelton (9.6 °C), and Portobello (9.2 °C).

Offshore SSTs were derived from the SST charts of Reid (1972) in combination with the weekly Global Operational Sea Surface Temperature Computation (GOSSTCOMP) charts published by the Satellite Services Division of the National Environmental Satellite, Data, and Information Service's National Climatic Data Center (National Oceanic and Atmospheric Administration, Washington D.C.). The annual ranges of the coastal SSTs are larger than those of the corresponding off-shore SSTs, the coastal temperatures, with the notable exception of Farewell Spit (see below), being warmer in summer and cooler in winter (Fig. 6). The smallest differences between the coastal and offshore SSTs occur at Leigh and Milford Sound. The coastal measurements are made on the open coast at Leigh (Evans & Ballantine 1983), and at the entrance to Milford Sound which opens onto the Tasman Sea. The largest differences occur at Nelson and Portobello. Nelson is located at the head of Tasman Bay, and the effect of insolation upon the temperature of the bay waters has been previously noted (Ridgway 1977). The sampling site at Portobello is located in semi-enclosed waters c. 9 km from the entrance to Otago Harbour and well sheltered from the open sea.

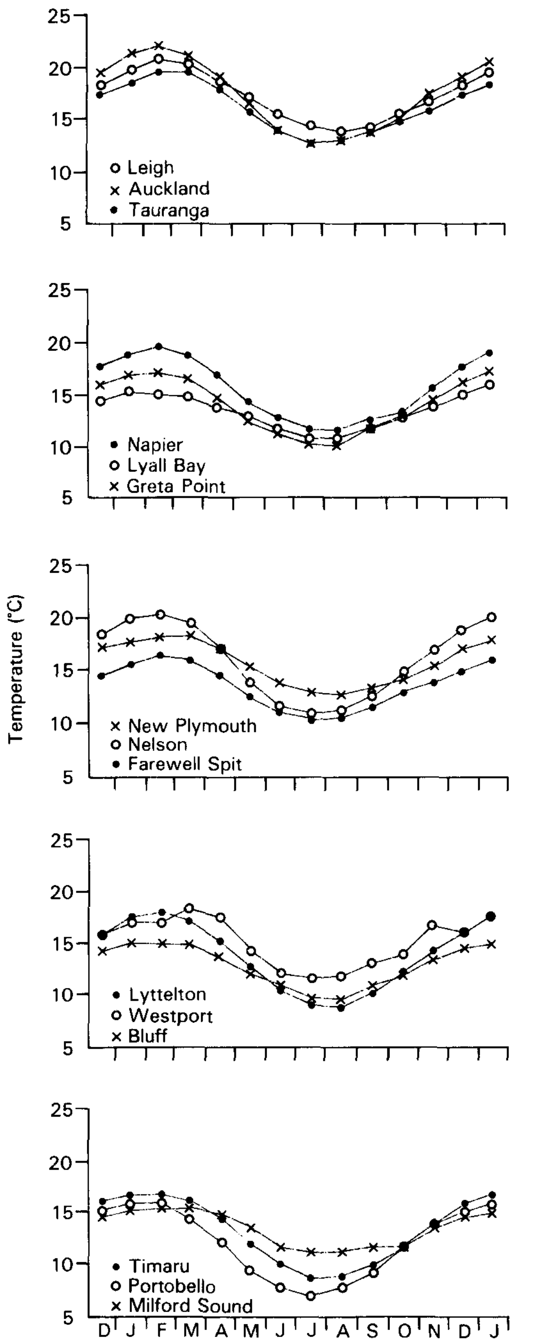

Fig. 5 Long-term monthly mean sea surface temperatures.

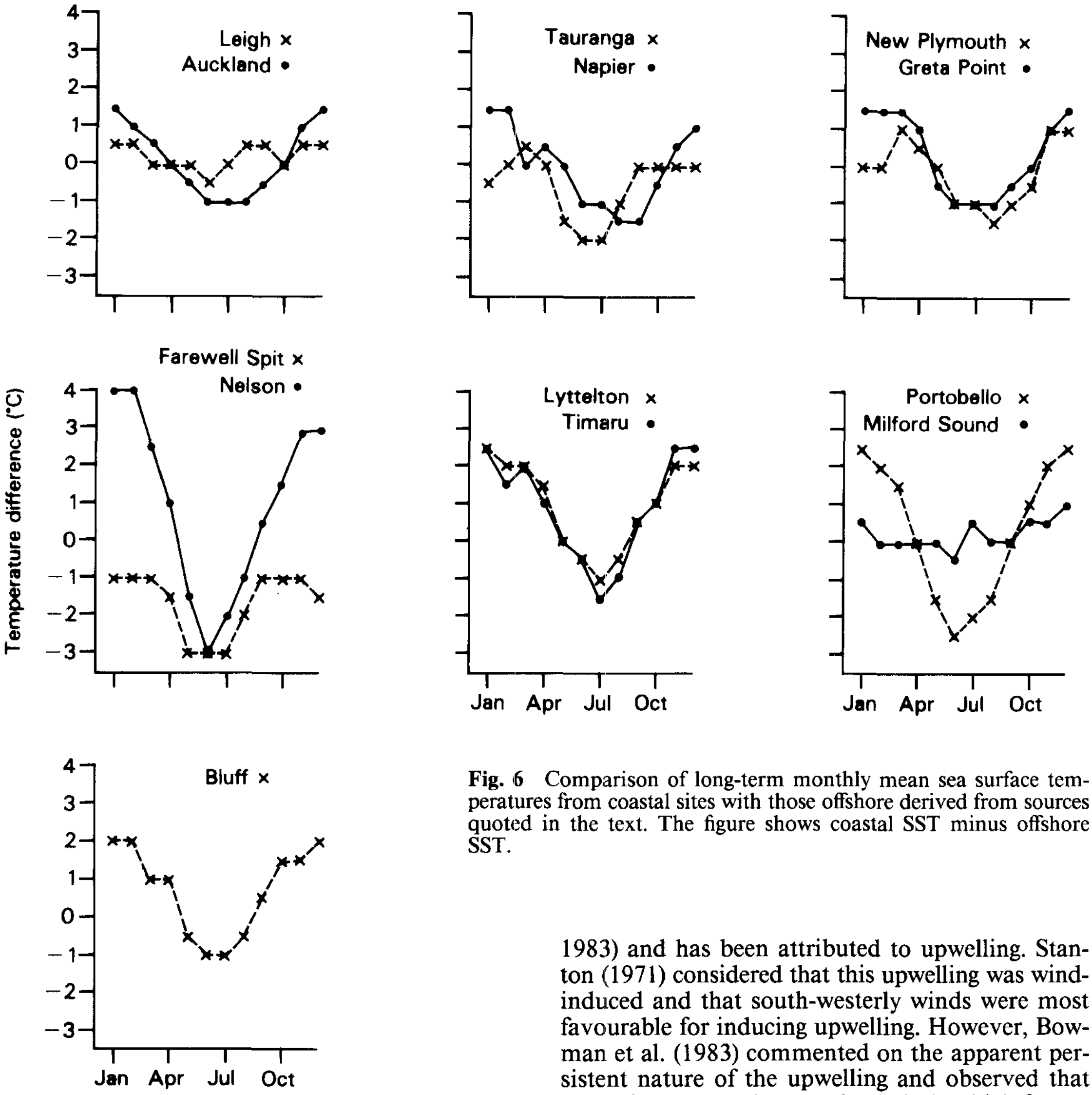

Fig. 6 Comparison of long-term monthly mean sea surface temperatures from coastal sites with those offshore derived from sources quoted in the text. The figure shows coastal SST minus offshore SST.

Farewell Spit SSTs

In marked contrast to the other sites, at Farewell Spit the monthly means of the observed SSTs were always lower than the corresponding offshore SSTs (Fig. 6). This is considered to be the result of persistent upwelling. The Farewell Spit observations were made near the lighthouse situated near the outer end of the spit and on its northern (Tasman Sea) side. The presence of unusually cold surface water in the vicinity of Cape Farewell has been described by several workers (Garner 1959, 1961; Stanton 1971, 1976; Bowman et al. 1983; Bradford 1983) and has been attributed to upwelling. Stanton (1971) considered that this upwelling was wind-induced and that south-westerly winds were most favourable for inducing upwelling. However, Bowman et al. (1983) commented on the apparent persistent nature of the upwelling and observed that upwelling occurred even when winds which favour downwelling were blowing. They suggested that the upwelling may be driven by bottom friction and vertical mixing as well as by wind. They also noted that there appeared to be significant differences in upwelling between spring and neap tides. Re-calculating the spectral estimates for Farewell Spit with less smoothing, we found that the frequency band < 0.17 cycles/day separates into bands with peaks at periods 7.5, 13.6, and 28 days. While these bands are only barely resolved at the 90% confidence level they are close to peaks at 7.4, 14.7, and 27.8 days in spectral estimates for the maximum daily tide range at Westport. This suggests a link between the SSTs and the tidal range and hence between upwelling and the tidal range.

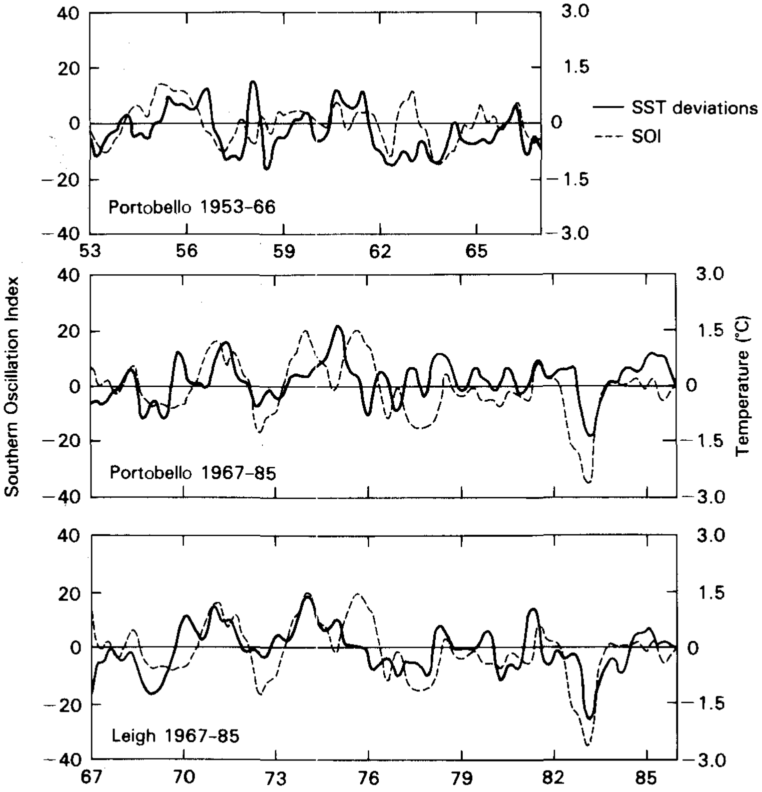

Fig. 7 Departures from long-term monthly mean sea surface temperatures for Leigh and Portobello, and the monthly mean pressure difference between Tahiti and Darwin (SOI). (The data used for this plot have been smoothed for clarity of presentation.)

Inter-annual SST variations

A prominent inter-annual signal in the coastal SSTs is associated with the Southern Oscillation atmospheric pressure anomalies occurring in the tropical Pacific region. The pressure at sea level fluctuates in a see-saw fashion between the south-east Pacific subtropical high-pressure region (the Easter Island High) and the low-pressure region situated over the Indian Ocean (the Indonesian Low).

The Southern Oscillation phenomenon is related to changes in tropical and subtropical wind systems, rainfall patterns, sea level elevations, and SST anomalies in the South Pacific Ocean, the most notable of which is the positive SST anomaly off the Peru coast associated with El Niño. These relationships have been recognised and discussed by many workers (e.g., Weare 1982, 1983; Wyrtki 1982; Gill 1983; Hsiung & Newell 1983). It has been suggested (Wyrtki 1982) that a decrease in the strength of the south-east trade wind field causes an eastward propagating equatorial Kelvin wave, the energy for which is provided by accumulated warm water in the west Pacific. Gill (1983) developed a model to deduce the surface current field during Southern Oscillation/El Niño events, and applied the model results to examine SST anomalies in the equatorial Pacific. He concluded that the warm surface waters which are present in the central and eastern Pacific during El Niño years result from an anomalous advection of surface water from west to east.

The pressure changes associated with the Southern Oscillation are well illustrated by using as a Southern Ocillation Index (SOI), atmospheric pressure differences between Tahiti and Darwin. These data are representative of the Easter Island High and the Indonesian Low, respectively.

The literature shows that the minima which appear in the SOI (Fig. 7) in 1953, 1957–58, 1963, 1965–66, 1969, 1972, 1976–77, and 1982–83 were all accompanied by positive SST anomalies in the central and eastern tropical Pacific, and the occurrence of the El Niño phenomenon. Visual correlation between the SOI and the SSTs for Portobello and Leigh (Fig. 7) suggests that these episodes were also accompanied by negative SST anomalies at these sites. To examine this further, the coherence and phase spectra between the SOI and the departure in monthly mean SST from the long-term monthly means from Portobello and Leigh were calculated (Fig. 8 and 9). These show maximum coherences of 0.55 to 0.7 for frequencies below 0.03

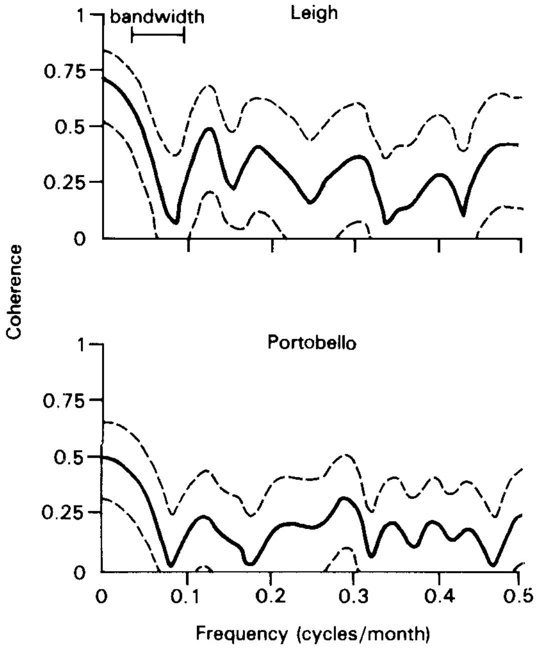

Fig. 8 The coherence spectra and 90% confidence intervals for the data plotted in Fig. 7.

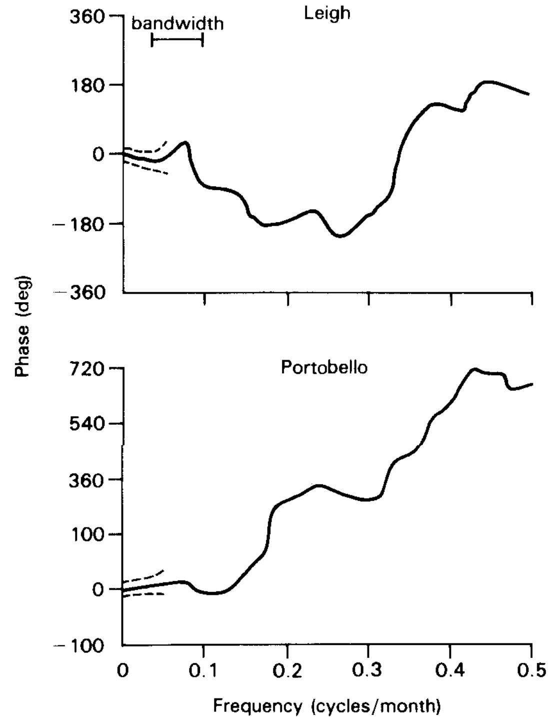

Fig. 9 The phase spectra and 90% confidence intervals for the data plotted in Fig. 7. Note that the confidence intervals are shown only where the coherence is considered significant.

cycles/month between Leigh SST departures and the monthly SOI. For Portobello the same low-frequency band showed the strongest coherence with values 0.45 to 0.5. At these frequencies the respective series are virtually in phase, the phase spectra indicating a lead of Leigh SSTs over the SOI of about 1 month and a lag of Portobello SSTs over the SOI of about 1 month.

The SST data sets available for the other coastal sites in New Zealand do not extend further back than October 1977 (Auckland, Tauranga, Napier, and New Plymouth); however, the monthly SST departures from the long-term monthly means at these four sites show negative anomalies were present in October–December 1977. Furthermore, cool anomalies were present at all sites during the strong southern oscillation event of 1982–83.

SST analyses which cover the Pacific Ocean to 30° S are published by the National Weather Service (National Oceanic and Atmospheric Administration, Washington D.C.) in the Oceanographic Monthly Summary series. These charts of monthly SST anomalies in the western Pacific Ocean suggest that in February 1981 a positive SST anomaly was present in New Zealand waters and a negative SST anomaly was present off the coast of Peru, whereas in February 1983 the reverse situation was found. This is consistent with the New Zealand coastal SST data. It therefore appears that the Southern Oscillation/El Niño phenomenon which is accompanied by increased SSTs in the central and eastern tropical Pacific, is also accompanied by lowered SSTs throughout New Zealand's coastal waters. This supports the work of Trenberth (1976) who showed that the effect of the Southern Oscillation is not confined to tropical and subtropical latitudes but is clearly linked to mid-latitude systems.

ACKNOWLEDGMENTS

The coastal sea surface temperature programme at the New Zealand Oceanographic Institute was instigated by Norm Ridgway who passed away while this paper was in preparation. He is remembered with respect and affection.

Sincere thanks are expressed to the many voluntary observers who carry out the measurements; to the marine laboratories at Leigh, (operated by the University of Auckland), and at Portobello (University of Otago), for making available their SST data; to Mike Moore for his assistance with the time series analysis, and to Karl Majorhazi for drafting the figures.

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