New Zealand Coastal Sea Surface Temperature

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Executive summary

This is an update to a 2015 report (Chiswell & Grant, 2015) on coastal sea surface temperature (CSST) prepared by NIWA for MfE.

CSST data from 11 sites around New Zealand have been collated and put into a common format (daily-mean temperatures).

CSST record lengths vary from 17 years at Ahipara Bay (southern end of Ninety Mile Beach) to about 66 years at Portobello (Otago Harbour), with some significant gaps in the records.

CSST reflects the large-scale oceanography, and shows a latitudinal gradient with sites in northern New Zealand having mean CSST of about 17 °C, whereas sites in southern New Zealand have mean CSST of about 12°C.

The annual range in CSST (warmest – coldest temperature) is typically 10 ° to 16.5 °C, depending on site.

Sea Surface Temperature (SST) for 10 oceanic sites 20-30 km offshore from the coastal sites was extracted from the NOAA Optimal Interpolation Climatology for comparison with CSST.

The low-frequency (1- and 5-year running mean) offshore temperature (SST) records match those in CSST well, suggesting that the offshore sea surface data can be used as a proxy for interannual changes in coastal temperature.

Long-term trends show warming CSST and SST at all sites, with the exception of Leigh where the trend between 1967 and 2017 is not statistically significant.

At the other sites, the long-term trends show warming ranging from 0.12 °C/decade since 1953 at Portobello Marine Station to 0.39 °C/decade since 1982 from offshore of Napier.

The warming trends do not show a latitude dependence but there is the suggestion they are stronger on the west coast than the east coast. This observation is result is consistent with Shears and Bowen (2017).

1 Introduction

Coastal Sea Surface Temperature (CSST) is both a response to and a control of the local climate. It has an impact on local flora and fauna and may well be important in controlling the local ecology (e.g., Barth *et al.*, 2007). It may be the limiting factor in range expansion of various introduced species, and impacts human activity.

CSST has been measured at a number of sites around New Zealand by a variety of different organisations over the last six decades.

This report presents CSST from 11 sites around New Zealand, ranging from Ahipara in the north of the North Island to Bluff at the south of the South Island (Table 2.1, Figure 2-1). For each site, we present a basic suite of statistics, including mean CSST over the length of the record, mean CSST for each month of the year, and, where there are sufficient data, present mean annual CSST for each year of the record.

This report is an update to a previous report made to MfE (Chiswell & Grant, 2015). We update the CSST records for the 5 sites where data are still being collected to the most current data. Data for the sites that have been discontinued are presented for consistency with the previous report.

For each coastal site, we also extract Sea Surface Temperature (SST) from a NOAA Ocean climatology for a site about 20-30 km offshore of the coastal site. This climatology runs from 1982 to 2017. A comparison of CSST and offshore SST shows that the long-term trend and interannual variability at the offshore site compares well with the long-term trend and interannual variability at each coastal site.

We have updated the report also by including a statistical analysis of the long-term trends in CSST and SST from each site.

2 Locations

There are 11 sites at which CSST data have been recorded over extended periods. The sites are Ahipara Bay, Leigh Marine Station, Tauranga – Moturiki Island, Napier, New Plymouth, Wellington (2 sites – Evans Bay and Lyall Bay), Lyttelton, Jacksons Bay, Portobello Marine Station, and Bluff (Table 2.1, Figure 2-1).

Data from these sites have been collected by a variety of organisations and archived at NIWA. There has been little co-ordinated effort to ensure that coastal sites measuring CSST have been maintained to a common standard. Nor have data been continuously collected at all sites. As a result, there is variation in the duration of the records, and some sites have long data gaps.

Eight of these sites are NIWA monitoring sites (as indicated in Table 2.1). Data are recorded just below low tide in 1–2m of water. Many of these sites have been automated in recent years, allowing for the frequency of data recording to increase from once per day to as often as hourly.

One site (Jackson Bay) is maintained by the Australian Bureau of Meteorology.

The remaining two sites are at the university marine stations and have the longest records of coastal SST in New Zealand. These are Portobello, in Otago Harbour where data have been collected since 1953, and Leigh, north of Auckland where data have been collected since 1967. Data for these sites are made available courtesy of Portobello Marine Laboratory, University of Otago and Leigh Marine Laboratory, University of Auckland.

The 10 oceanic sites for SST were about 20-30 km offshore from the coastal sites. This distance was chosen to maintain proximity to the coastal site yet take account of the underlaying ~25 km resolution of the global SST product and the need to avoid contamination by land effects.

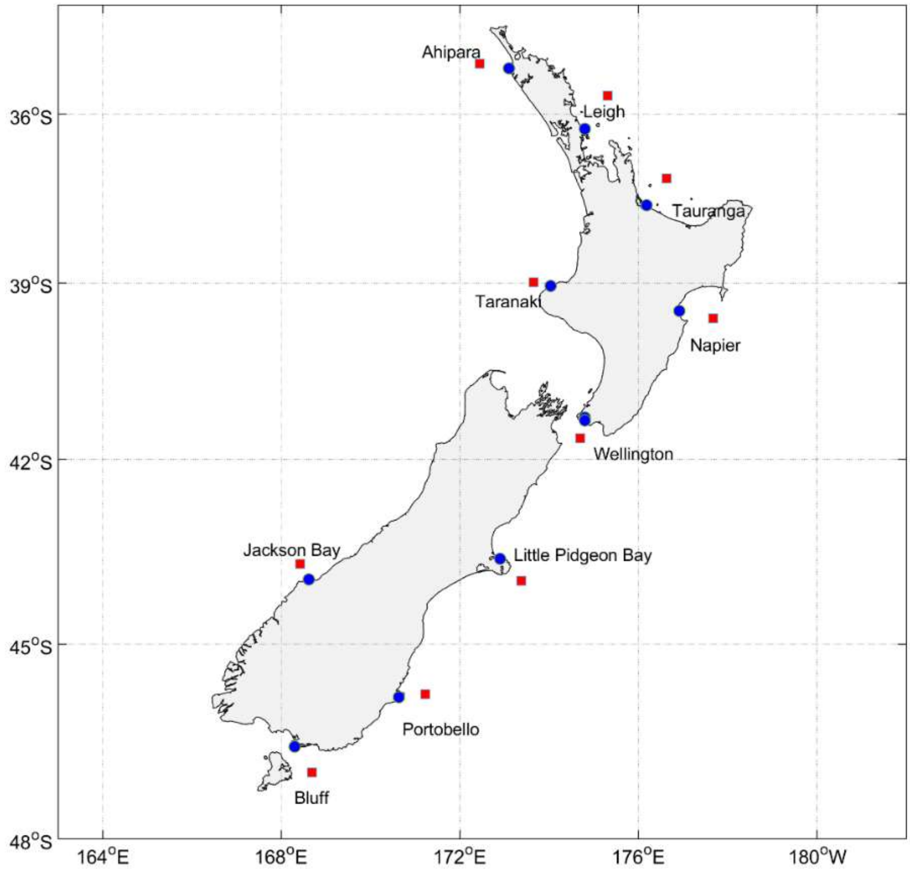

Figure 2-1: Locations of coastal CSST monitoring sites (blue circles) and offshore SST sites (red squares).

Table 2.1. Coastal SST monitoring sites, periods sampled, coastal logger location and location used for offshore satellite data. Locations shown in bold are the sites that have updated temperature since the 2015 Report.

Site	Data duration for coastal site	Coastal site Location	Offshore site Location
Ahipara Bay, Northland (NIWA)	1991 – 2008	35° 10' S 173° 6' E	35° 5' S 172° 26' E
Leigh Marine Station	**1967 – 2017**	**36° 16' S 174° 48' E**	**35° 40' S 175° 18' E**
Tauranga – Moturiki Island (NIWA)	**1997 - 1987; 1990 – 2009; 2016-2017**	**37° 38' S 176° 11' E**	**37° 9' S 176° 38' E**
Napier (NIWA)	1977 – 2005	39° 29' S 176° 55' E	39° 37' S 177° 41' E
New Plymouth (NIWA)	1977 – 2009	39° 3' S 174° 2' E	38° 59' S 173° 39' E
Wellington – Evans Bay (NIWA)	**1981 – 2017**	**41° 18' S 174° 48' E**	**41° 39' S 174° 42' E**
Wellington – Lyall Bay (NIWA)	1982 – 2005	41° 21' S 174° 48' E	41° 39' S 174° 42' E
Lyttelton – Little Pidgeon Bay (NIWA)	1978 – 2009	43° 38' S 172° 54' E	43° 59' S 173° 23' E
Jackson Bay	**1991 – 2018**	**43° 58' S 168° 37' S**	**43° 43' S 168° 25' E**
Portobello Marine Station	**1953 – 2018**	**45° 50' S 170° 38' E**	**45° 47' S 171° 14' E**
Bluff (NIWA)	1978 –1997	46° 36' S 168° 18' E	46° 60' S 168° 41' E

3 Methods

3.1 Coastal Sea Surface Temperature (CSST)

The earliest CSST measurements were made by voluntary observers using hand held mercury-in-glass thermometers. Readings were taken at about 9am on as many days as the observer was able - typically 3 to 5 days per week. Beginning in late 1982 the mercury thermometers were replaced with digital thermometers, and these in turn were replaced by internally recording data loggers with electronic sensors from 1990. As technology has improved, the loggers have been upgraded. These include Hugrun Seamon mini Temperature Recorders (accuracy 0.1°C), Star Oddi Starmon mini (accuracy 0.025°C), RBR TR1050/1060 (accuracy 0.002°C), and Seabird SBE56 (accuracy 0.002°C, highly stable).

CSST is influenced by tides, daily heating and cooling and other high frequency forcing such as weather events – often in a manner that is not predictable. This is illustrated in Figure 3-1, which shows CSST from Ahipara from January to March 2005. The figure shows both 8-hourly measurements (green) and the once-per-day data (blue). The daily-range in CSST was as much as 3° in mid-February, and as little as 0.2° in March.

Usually the sample depth was taken to be as shallow as possible where the data logger was covered with water at low tide. The measurement depth may have an influence on the amount of variation at each site, however, determining these influences and thus how representative individual records are of their local environment is well beyond the scope of this study.

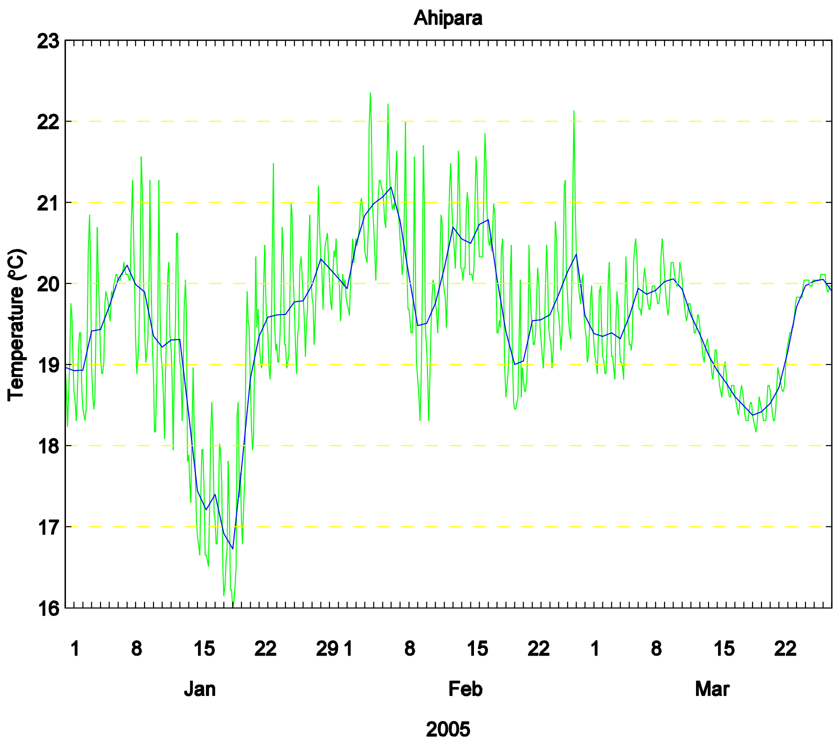

Figure 3-1: Coastal Sea Surface Temperature (CSST) from Ahipara Bay for January-March 2005. The 8-hourly record is shown in green, and the daily-mean record is shown in blue.

3.2 Oceanic Sea Surface Temperature (SST)

The NOAA Optimum Interpolation (OI) SST is an analysis of global sea surface temperature as measured from the AVHRR satellites (Reynolds *et al.*, 2002). Here we chose 10 oceanic sites that were approximately 20-30 km offshore from the coastal sites (one oceanic site covered both Wellington Lyall Bay and Evans Bay locations) and extracted the daily-mean SST values from the NOAA website.

https://www.esrl.noaa.gov/psd/data/gridded/data.noaa.oisst.v2.html

3.3 Southern Oscillation Index (SOI)

The Southern Oscillation Index (SOI) is defined as the difference between the atmospheric pressure at Tahiti and Darwin. Negative values of this index correspond to El Niño conditions, while positive SOI values coincide with La Niña episodes.

Here, the SOI was extracted from NIWA archives as monthly values.

3.4 Analyses

Raw CSST data were recorded at intervals ranging from hourly to daily. To put the data into a consistent format, for each site, the data were first averaged to produce daily-mean temperature series (i.e., one sample per day).

From the daily-mean records, we computed the mean temperature for each month (e.g., the mean January temperature was computed from all January data in the record), and the mean temperature for each year (e.g., the mean temperature in 2005). However, there are large gaps in many records, which can bias both the monthly-mean and annual-mean values, with potentially greater influence on the annual-mean records. For example, if January data are missing from one year, the annual-mean for that year will be biased low. For this reason, the annual-mean temperatures are reported only for years where there were more than 345 days with measurements in the year (i.e., ~95% of data had to be present in any given year for its mean value to be computed).

We also computed 1, 2 and 5-year running means (or moving averages) of each record. These were computed slightly differently. To be consistent with the 2015 report, the 2-year running mean was computed directly from the daily-mean records. The 1-year and 5-year running mean records were computed after first removing a 365.25 day annual cycle.

We also compute the annual cycle by fitting a sine wave to the data. This cycle is removed from the data before computing long-term trends so that the trends are not biased if, for example, more data were collected in summer than in winter at any site.

The daily-mean satellite SST data were treated in a similar manner to the daily-mean CSST data. However, since there is an onshore-offshore gradient that varies with location, the mean SST at each site will be different from the mean CSST at the respective coastal site. These offsets in SST were removed for comparison of the low-frequency signals.

3.5 Long-term trends

Records had the annual cycle of temperature removed and were smoothed with a 1-year filter before the trends were calculated. Because daily samples are not independent, these smoothed records were then subsampled at 6-monthly intervals (i.e., half the smoothing window length) to produce independent samples.

Trends were computed using linear least-squares regression which produces a linear estimate

$$\hat{T} = a + bt \ ,$$

where $\hat{T}$ is the trend in temperature (SST or CSST), *t* is time, and *a* and *b* are the intercept and slope of the trend.

The significance of the trend was calculated following Santer *et al.* (2000). First the standard error of the slope was calculated as

$$s_b = \frac{s_e}{[\Sigma(t-t)^2]^{1/2}} \ .$$

where s_e^2 is the variance of the residuals about the trend. We then compute the slope divided by its standard error

$$t_b = b / s_b \ .$$

Whether a trend is significantly different from zero or not at a defined significance level, α, can be determined by assuming t_b is distributed as Student's t distribution with n degrees of freedom. That is, the null hypothesis is that the data have no trend. If t_b exceeds the significance level, then one can assume the data have a trend.

We assumed the number of degrees of freedom was the subsampled record length minus 2. The significance was tested using the Matlab routine tcdf.m which returns the Student's t cumulative distribution function estimate given the number of degrees of freedom. A value greater than 0.975 is considered significant.

4 Results - CSST and SST by site

For each site we provide a figure showing CSST from the coastal site along with SST from the respective oceanic site.
The upper panel shows the daily-mean CSST in blue. The black line is CSST smoothed with a 2-year running filter. The black circles indicate the annual mean temperatures for years where there are more than 345 days of data (Figures 4-1 to 4-11). This panel shows the same data as the figure in the 2015 report, but has been replotted with a different scale.

The central panel shows the long-term SST record from the oceanic site from 1982 to 2017 in red along with the CSST record in blue, with the mean of the SST adjusted to match that of the CSST through the period of overlap. For some sites, e.g. Bluff, CSST dates back before 1982 and in these cases only CSST after 1982 are shown for comparison with SST.

The lower panel shows the long-term SST and CSST records after the annual cycle has been removed and the data smoothed with 1-year and 5-year running filters. The solid lines show the 1-year smoothed values, the dashed lines show the 5-year smoothed values.

We also provide a table for each site listing the site name, its latitude and longitude, mean CSST over the duration of the record, and the maximum and minimum daily-mean CSST over the entire record (Tables 4.1.1 to 4.11.1).

The monthly-mean CSST (Tables 4.1.2 to 4.11.2) and annual mean CSST are also provided for each site. Where less than 95% of the daily-mean records exist in any given year, the annual mean temperature is listed as ‘---‘.

4.1 Ahipara

The data were collected from a temperature logger placed on the seabed between rocky outcrops about 0.5m below low water level.

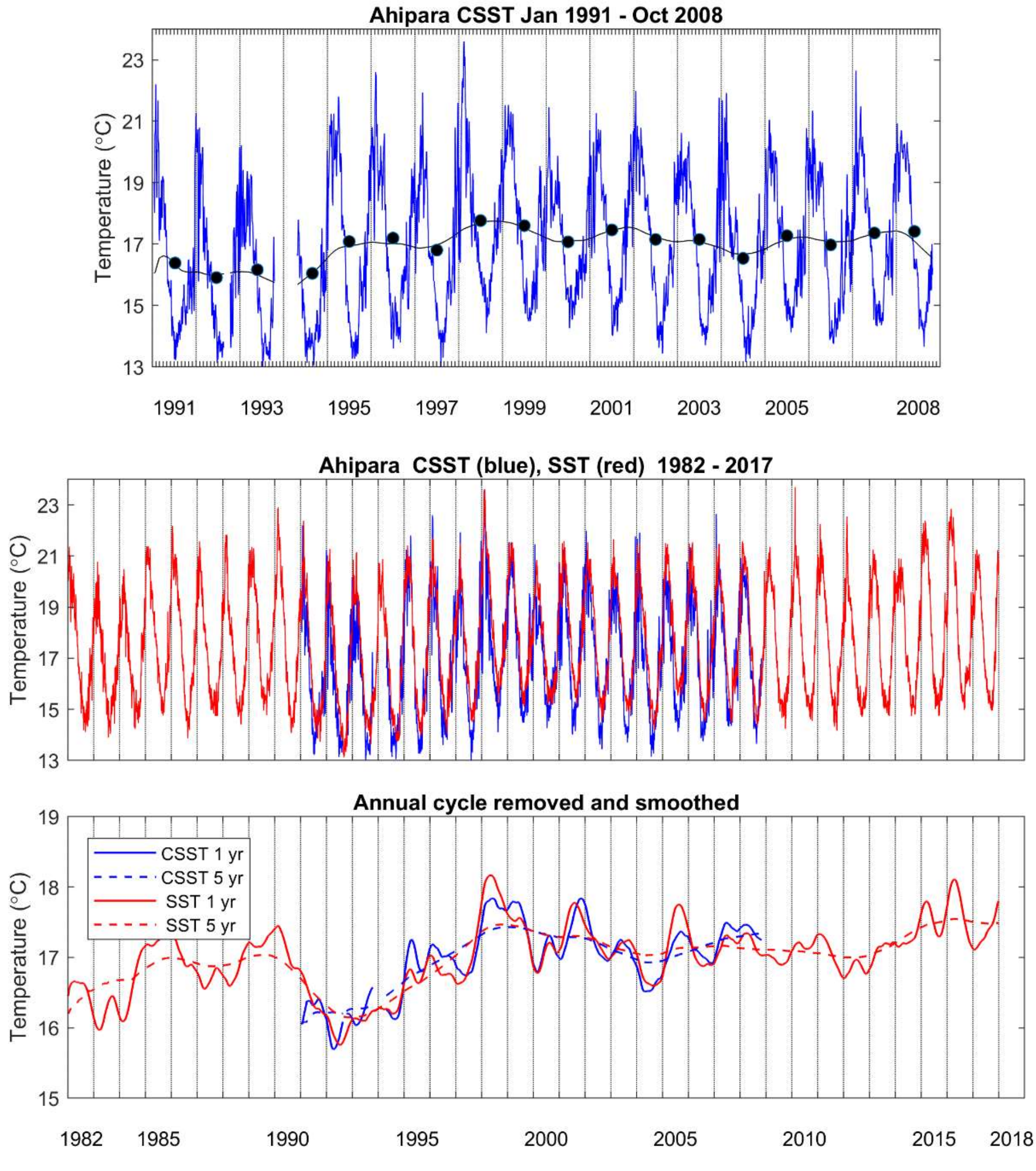

Figure 4-1: Daily coastal sea surface temperature (CSST) from Ahipara Bay, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.1.1 Ahipara Bay showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Ahipara	35° 10.3' S	173° 5.7' E	17.0	23.6	13.0

Table 4.1.2 Monthly mean temperature for Ahipara Bay over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19.3	19.8	19.3	18.6	17.1	15.6	14.4	14.3	15.0	15.9	16.9	18.3

Table 4.1.3 Annual mean temperature for Ahipara Bay for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1990	---	16.3	---	---	---	17.1	17.2	16.8	17.8	17.6
2000	17.1	17.5	17.2	17.2	16.6	17.3	17.0	17.4	---	---

4.2 Leigh Marine Station (Updated since 2015)

Data were collected from the edge of a rocky platform on the wave-exposed shoreline daily, prior to 2011 at which point the protocol was changed to using a temperature logger. Site operated by the University of Auckland.

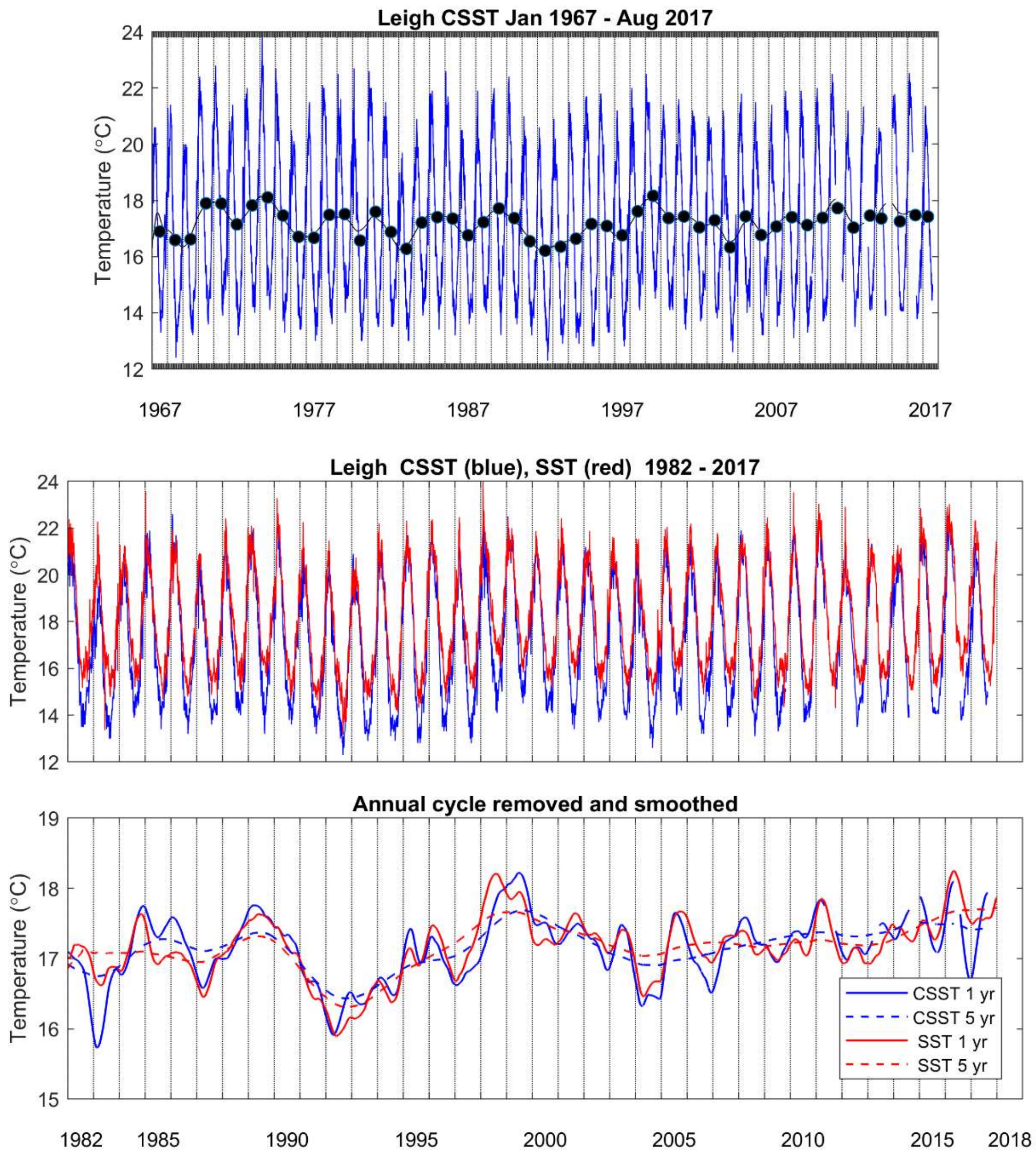

Figure 4-2: Daily coastal sea surface temperature (CSST) from Leigh Marine Station, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.2.1 Leigh Marine Station showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Leigh	36° 16.1'S	174° 48.0' E	17.2	23.8	12.3

Table 4.2.2 Monthly mean temperature for Leigh Marine Station over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19.8	20.6	20.4	19.3	17.5	15.7	14.4	14.0	14.4	15.3	16.6	18.2

Table 4.2.3 Annual mean temperature for Leigh Marine Station.for the 1990s and 2000s

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1960	---	---	---	---	---	---	---	---	16.6	16.6
1970	17.9	17.9	17.2	17.8	18.1	17.5	16.7	16.7	17.5	17.5
1980	16.6	17.6	16.9	16.3	17.2	17.4	17.3	16.8	17.2	17.7
1990	17.4	16.5	16.2	16.4	16.6	17.2	17.1	---	17.6	---
2000	17.3	---	---	17.3	---	17.3	16.8	17.0	17.5	---
2010	17.4	17.7	17.0	17.5	17.4	17.3	17.5	17.4	---	---

4.3 Tauranga – Moturiki Island (Updated since 2015)

Data were collected from a temperature logger which was shifted from Tauranga to Moturiki Island in 1990.

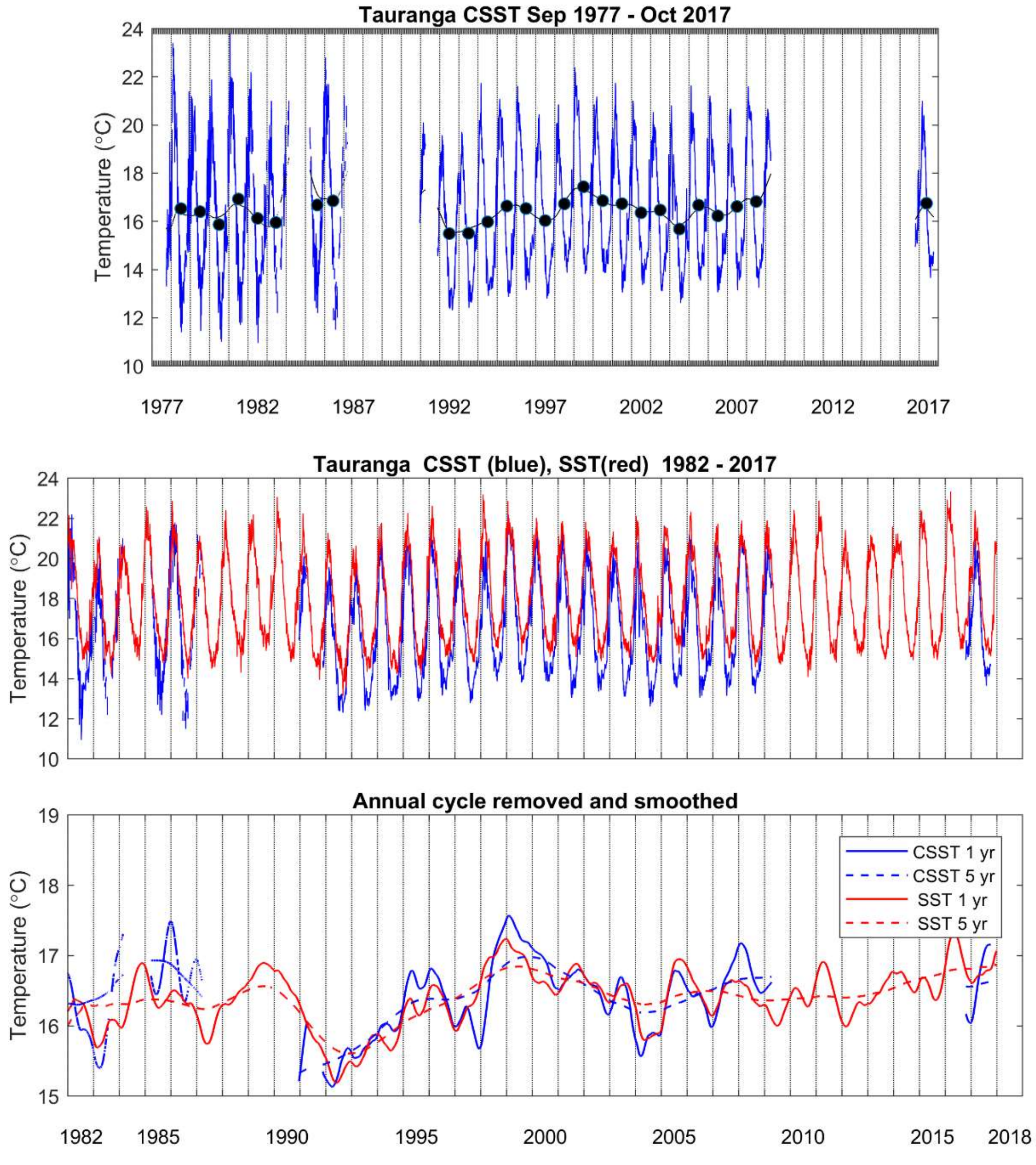

Figure 4-3: Daily coastal sea surface temperature (CSST) from Tauranga – Moturiki Island, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.3.1 Tauranga – Moturiki Island showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Tauranga	37° 38.4’ S	176° 10.8' E	16.5	23.8	10.9

Table 4.3.2 Monthly mean temperature for Tauranga – Moturiki Island over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
18.8	19.9	19.6	18.4	16.6	14.7	13.6	13.5	14.0	14.8	15.8	17.2

Table 4.3.3 Annual mean temperature for Tauranga – Moturiki Island for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1970	---	---	---	---	---	---	---	---	16.4	16.4
1980	15.9	16.9	16.1	---	---	---	---	---	---	---
1990	---	---	15.5	15.5	16.0	16.6	16.5	16.0	16.7	17.4
2000	16.9	16.7	16.4	16.5	15.7	16.7	16.2	16.6	16.8	---
2010	---	---	---	---	---	---	---	16.8	---	---

4.4 Napier

Data were collected from a temperature logger mounted on a pile for Napier wharf.

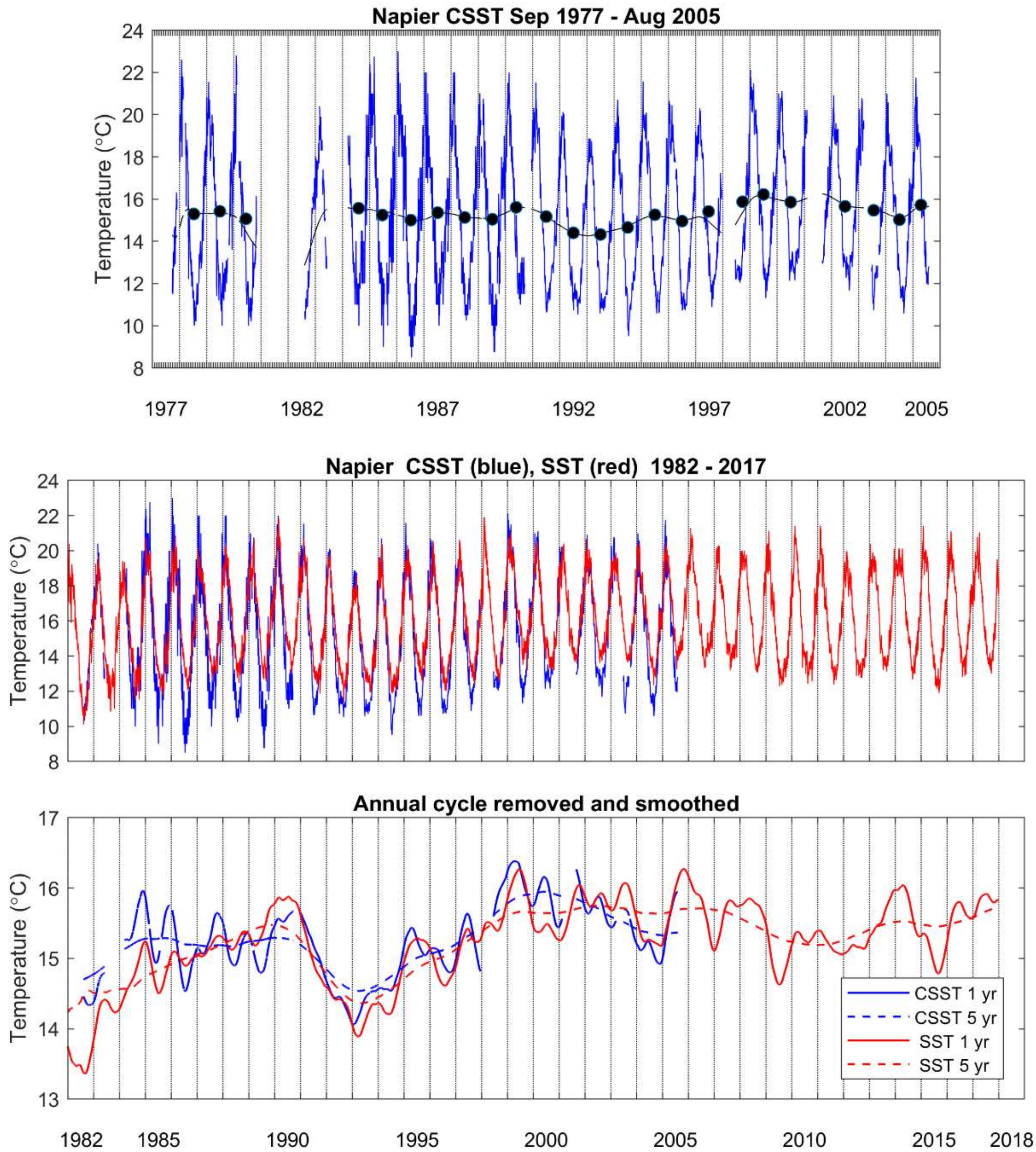

Figure 4-4: Daily coastal sea surface temperature (CSST) from Napier, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.4.1 Napier showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Napier	39° 28.5′ S	176° 55.2′ E	15.6	23.2	10.0

Table 4.4.2 Monthly mean temperature for Napier over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
19.1	19.6	18.6	16.8	14.6	12.5	11.5	11.5	12.4	13.7	15.5	17.3

Table 4.4.3 Annual mean temperature for Napier for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1970	---	---	---	---	---	---	---	---	---	---
1980	---	---	---	---	---	---	---	15.2	15.2	---
1990	---	15.2	14.4	14.5	14.7	15.3	15.0	---	---	16.2
2000	15.9	---	15.7	---	15.0	---	---	---	---	---

4.5 New Plymouth

New Plymouth (Port Taranaki).

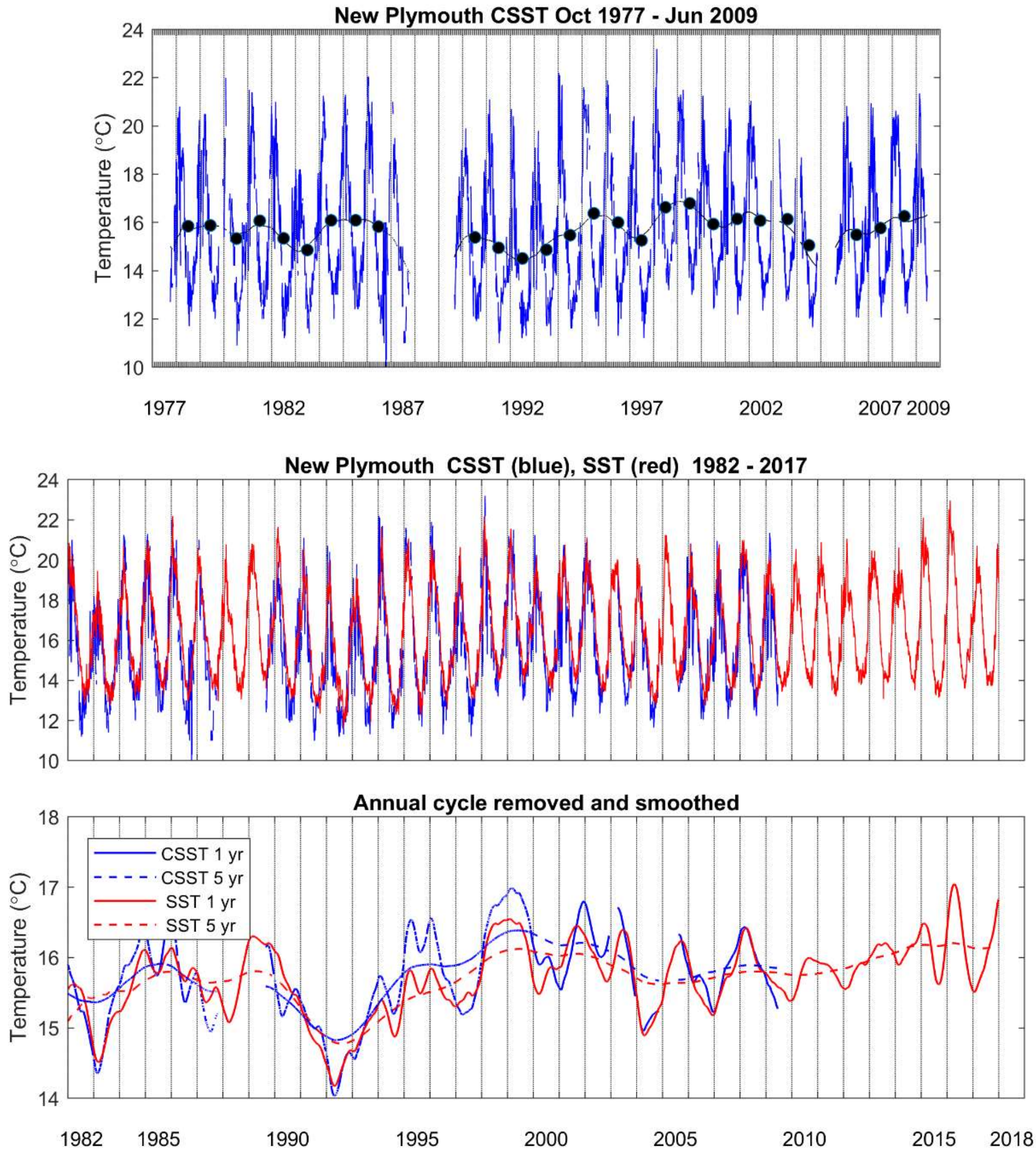

Figure 4-5: Daily coastal sea surface temperature (CSST) from New Plymouth, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.5.1 New Plymouth showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
New Plymouth	39° 03.34' S	174° 2.1' E	15.6	23.2	10.0

Table 4.5.2 Monthly mean temperature for New Plymouth over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
18.3	18.9	18.5	17.2	15.7	14.0	12.9	12.9	13.5	14.3	15.4	17.0

Table 4.5.3 Annual mean temperature for New Plymouth for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1970	---	---	---	---	---	---	---	---	---	---
1980	---	---	15.3	---	---	---	---	---	---	---
1990	---	---	---	---	---	---	---	---	---	---
2000	15.9	16.1	---	---	---	---	15.5	15.8	16.2	---

4.6 Wellington – Evans Bay (Updated since 2015)

Data were collected from a temperature logger, on the bay shoreline adjacent to NIWA at Greta Point.

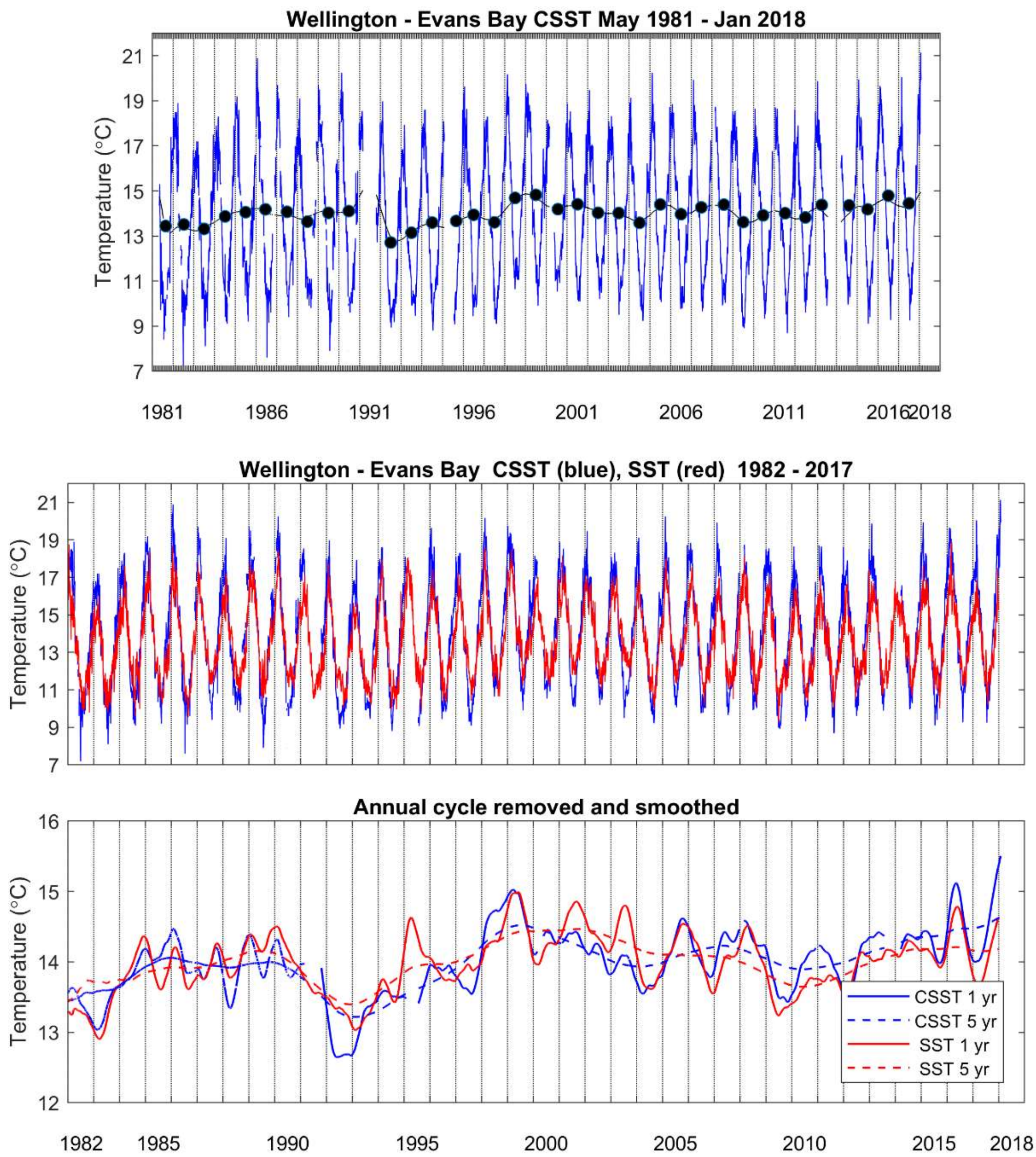

Figure 4-6: Daily coastal sea surface temperature (CSST) from Wellington – Evans Bay, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.6.1 Wellington – Evans Bay showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Wellington - Evans Bay	41° 18.2' S	174° 48.3' E	13.9	21.1	7.2

Table 4.6.2 Monthly mean temperature for Wellington – Evans Bay over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
17.5	17.7	16.7	14.9	13.1	11.3	10.3	10.5	11.6	13.0	14.6	16.1

Table 4.6.3 Annual mean temperature for Wellington – Evans Bay for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1980	---	13.4	13.5	13.2	13.9	14.1	14.2	14.1	13.6	14.0
1990	14.1	---	12.7	13.2	13.6	13.7	13.9	13.6	14.7	14.8
2000	14.2	14.2	14.0	14.1	13.6	14.4	14.0	14.1	---	13.6
2010	13.9	14.0	13.8	14.4	14.4	14.2	14.8	14.4	---	---

4.7 Wellington – Lyall Bay

Data come from Lyall Bay on the open coast, exposed to Cook Strait, several km to the South of the Evans Bay site described above.

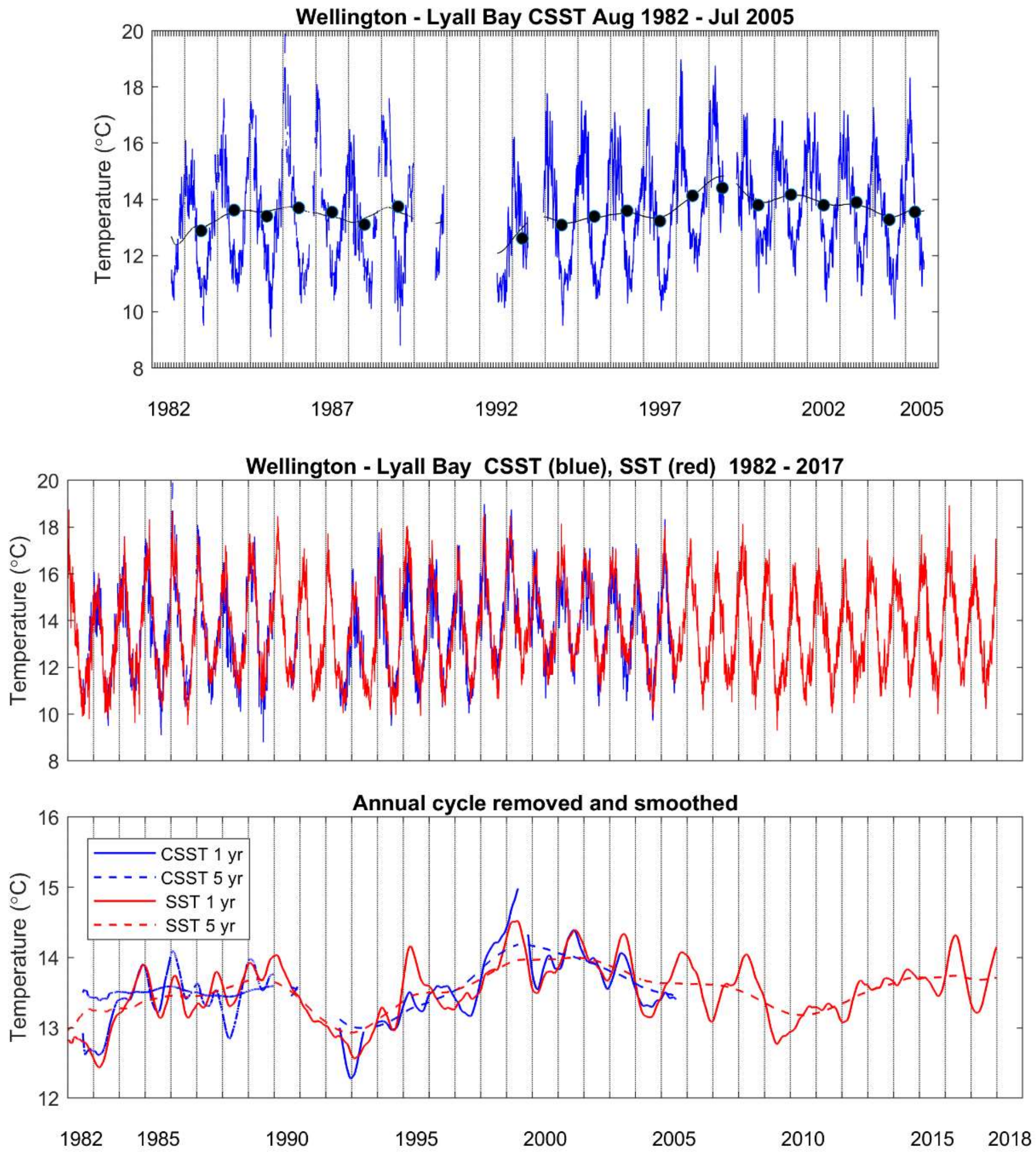

Figure 4-7: Daily coastal sea surface temperature (CSST) from Wellington – Lyall Bay, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.7.1 Wellington – Lyall Bay showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Wellington - Lyall Bay	41° 20.8' S	174° 47.5′ E	13.5	19.9	8.8

Table 4.7.2 Monthly mean temperature for Wellington – Lyall Bay over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15.8	15.6	15.3	14.5	13.4	12.2	11.4	11.3	11.8	12.7	13.8	14.7

Table 4.7.3 Annual mean temperature for Wellington – Lyall Bay for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1980	---	---	---	12.8	13.6	---	---	---	---	---
1990	---	---	---	---	13.1	13.4	13.6	13.3	14.2	---
2000	13.8	14.2	13.8	13.9	13.3	---	---	---	---	---

4.8 Lyttelton – Little Pidgeon Bay

Initially this record was from Lyttelton Port but was shifted to Little Pigeon Bay.

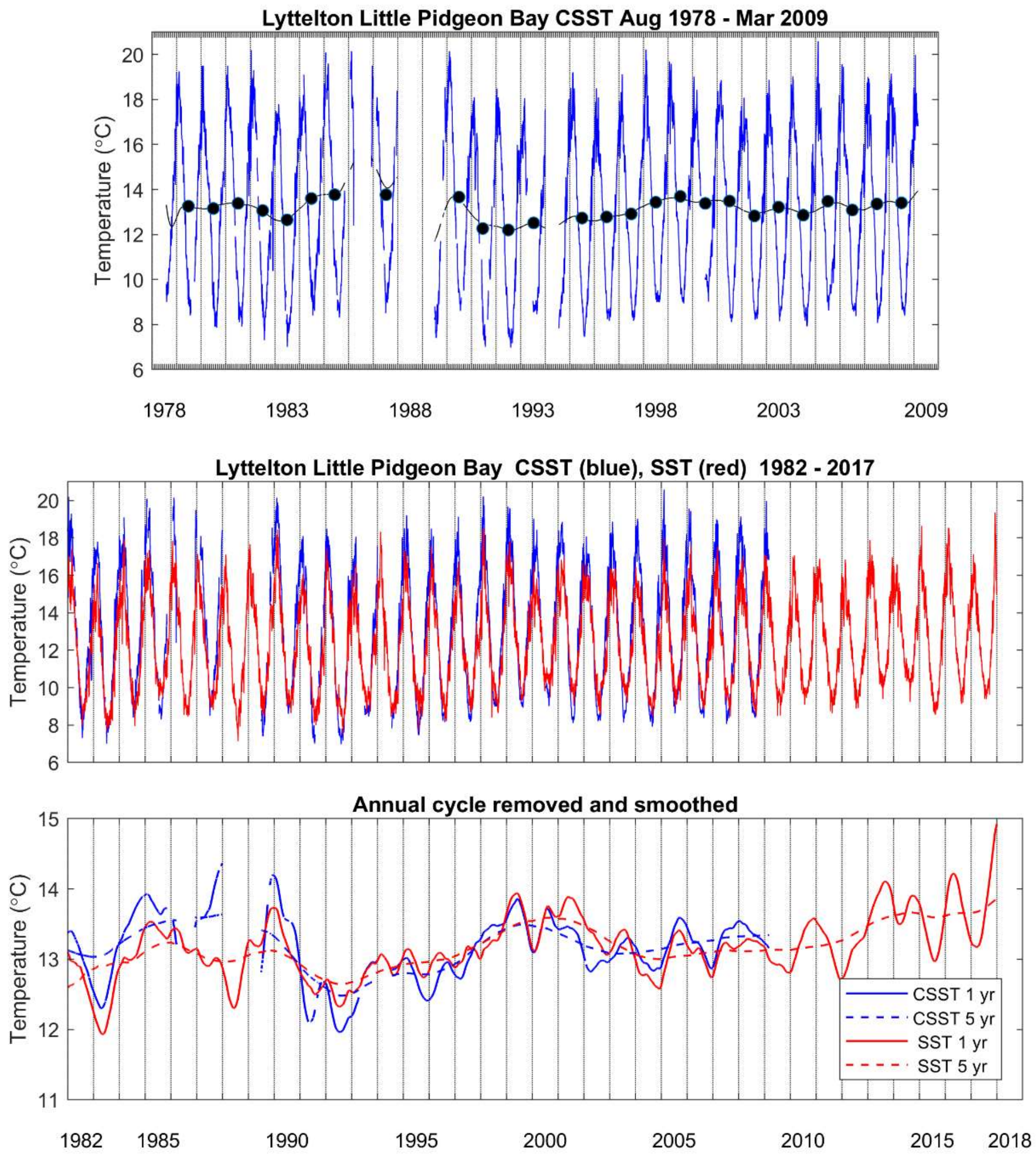

Figure 4-8: Daily coastal sea surface temperature (CSST) from Lyttelton - Little Pidgeon Bay, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.8.1 Little Pidgeon Bay showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Lyttelton Little Pidgeon Bay	43° 37.9' S	172° 54.18' E	13.2	20.6	7.0

Table 4.8.2 Monthly mean temperature for Little Lyttelton - Pidgeon Bay over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
17.4	17.7	16.7	14.7	12.5	10.1	8.7	8.8	10.0	11.9	14.0	15.9

Table 4.8.3 Annual mean temperature for Little Lyttelton - Pidgeon Bay for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1970	---	---	---	---	---	---	---	---	---	---
1980	13.1	13.5	13.0	12.7	---	---	---	---	---	---
1990	---	---	12.2	---	---	12.7	12.8	12.9	13.4	13.7
2000	---	13.5	12.6	13.3	12.9	13.5	13.1	13.4	13.4	---

4.9 Jackson Bay (Updated since 2015)

Jackson Bay is on the west coast of the South Island.

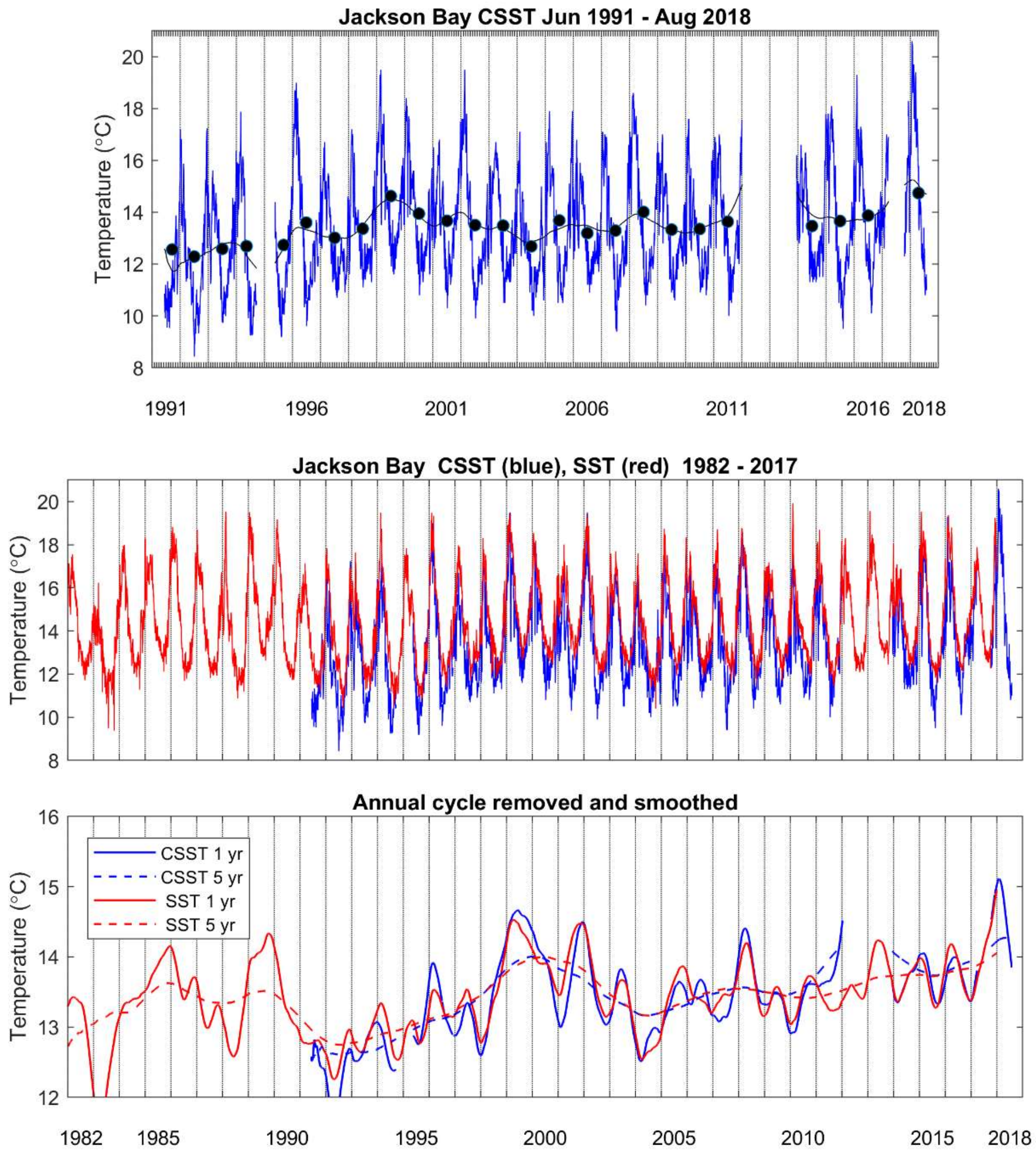

Figure 4-9: Daily coastal sea surface temperature (CSST) from Jackson Bay, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.9.1 Jackson Bay showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Jackson Bay	43° 58.4' S	168° 36.9' S	13.4	20.6	8.4

Table 4.9.2 Monthly mean temperature for Jackson Bay over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15.1	15.9	15.2	14.4	13.4	12.0	11.1	11.2	11.7	12.4	13.1	14.2

Table 4.9.3 Annual mean temperature for Jackson Bay for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1990	---	---	12.3	12.6	---	---	13.6	13.0	13.3	14.6
2000	13.9	13.6	13.5	13.5	12.7	13.7	13.2	13.3	---	13.3
2010	13.4	13.6	---	---	13.5	13.7	13.9	---	---	---

4.10 Portobello Marine Station (Updated since 2015)

Portobello data are provided by University of Otago. To date we have data until 31 August 2018.

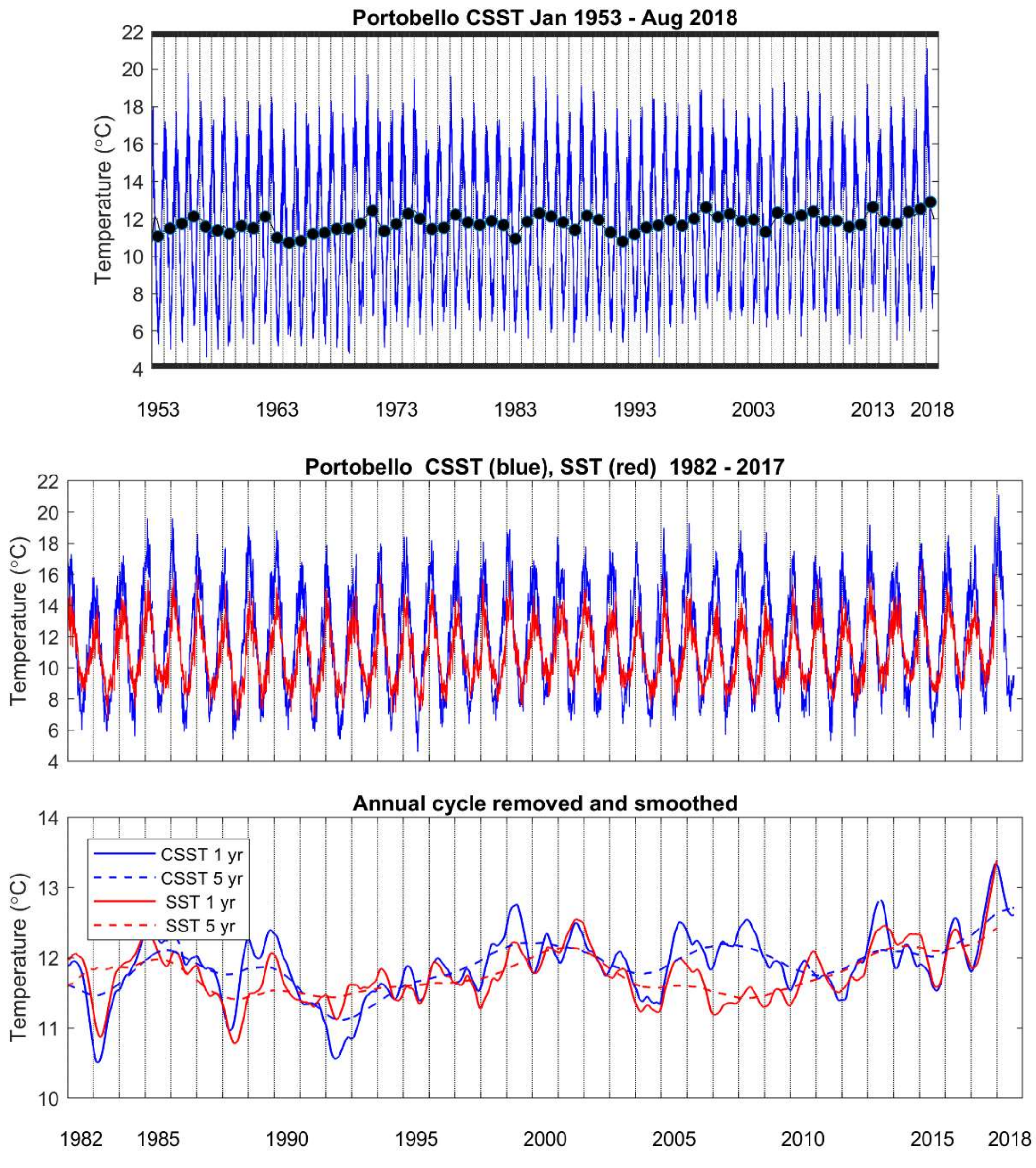

Figure 4-10: Daily coastal sea surface temperature (CSST) from Portobello Marine Station, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.10.1 Portobello Marine Station showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Portobello	45° 49.7' S	170° 38.4' S	11.7	21.1	4.6

Table 4.10.2 Monthly mean temperature for Portobello Marine Station over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
16.1	15.9	14.5	12.3	9.8	7.8	7.0	7.8	9.5	11.5	13.4	15.0

Table 4.10.3 Annual mean temperature for Portobello Marine Station for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1950	---	---	---	11.1	11.5	11.7	12.1	11.6	11.4	11.2
1960	11.6	11.5	12.1	11.0	10.7	10.8	11.2	11.3	11.5	11.5
1970	11.8	12.4	11.3	11.7	12.3	12.0	11.4	11.5	---	---
1980	11.8	11.9	11.7	10.9	11.7	12.2	---	11.8	11.3	12.1
1990	12.0	11.3	10.8	11.2	11.5	11.7	11.9	11.6	12.0	---
2000	12.1	12.2	11.9	11.9	11.3	12.3	12.0	12.2	12.4	11.9
2010	11.9	11.6	11.7	12.6	11.9	11.8	12.4	12.5		

4.11 Bluff, South Island

The data logger was mounted outside the harbour, opposite Ocean Beach.

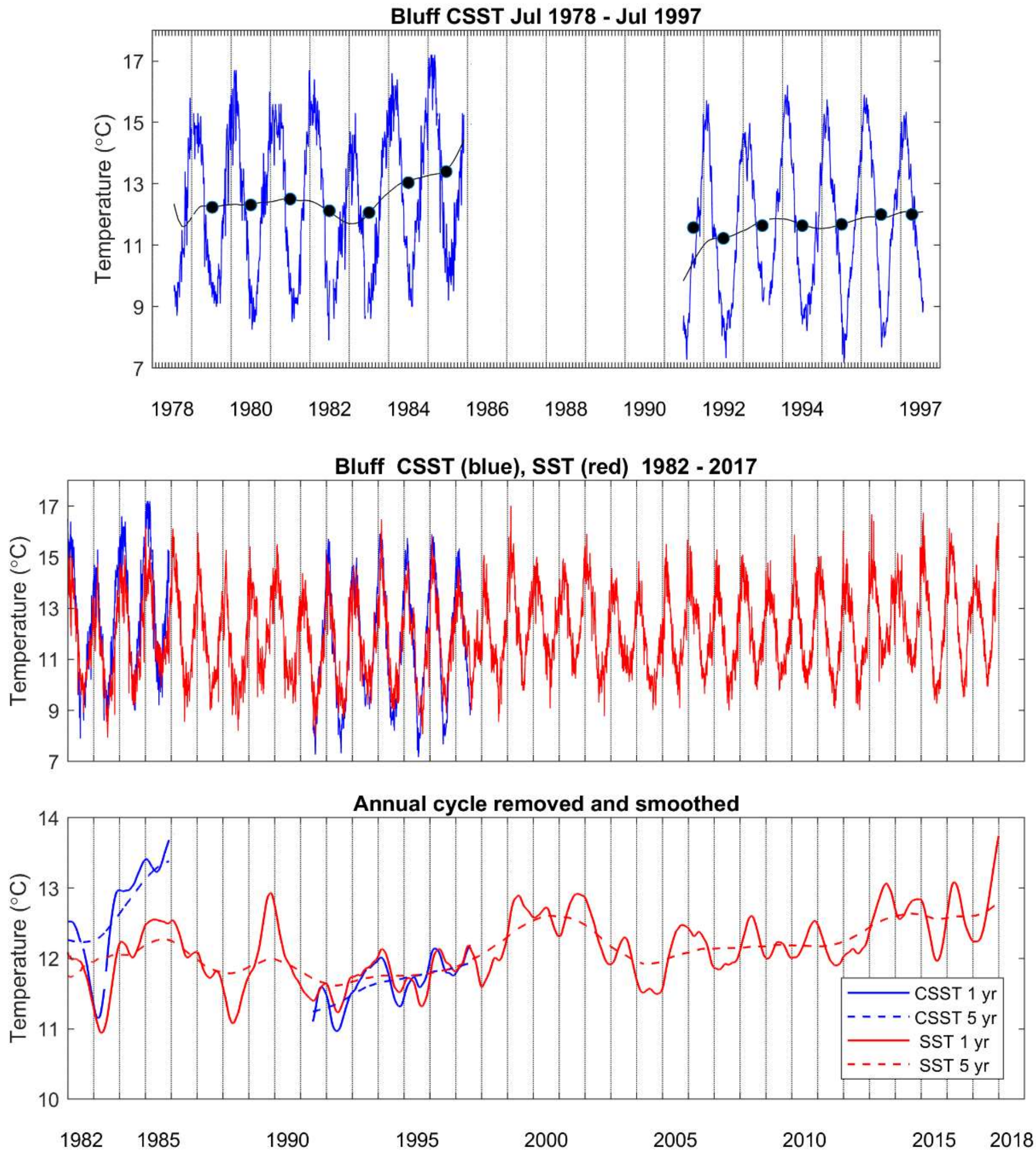

Figure 4-11: Daily coastal sea surface temperature (CSST) from Bluff, along with offshore oceanic sea surface temperature (SST). Upper panel shows the full CSST record, middle panel shows CSST and SST from 1982 to 2017, lower panel shows low frequency components of SST and CSST. SST has been adjusted to have the same mean as CSST.

Table 4.11.1 Bluff showing location, mean, maximum (max) and minimum (min) CSST.

Name	Latitude	Longitude	Mean CSST	Max CSST	Min CSST
Bluff	46° 35.6’ S	168° 17.9' E	12.1	17.2	7.2

Table 4.11.2 Monthly mean temperature for Bluff over all available records.

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
15.0	15.2	14.4	13.1	11.5	10.0	9.0	9.2	10.2	11.5	12.7	14.0

Table 4.11.3 Annual mean temperature for Bluff for the 1990s and 2000s.

	Year of decade									
Decade	0	1	2	3	4	5	6	7	8	9
1970	---	---	---	---	---	---	---	---	---	---
1980	12.3	12.5	---	---	13.0	---	---	---	---	---
1990	---	---	11.2	---	11.7	11.7	12.0	---	---	---

5 Sea Surface Temperature Statistics

5.1 Yearly and monthly statistics

Overall mean and monthly-mean CSST for each site are presented in Table 5.1, and Figure 5-1 shows the mean, minimum and maximum daily-mean CSST using all available data for each site.

It should be noted that these mean, minimum and maximum temperatures are those seen over the whole record at each site, and are impacted by the length of record and any data gaps. The values will not reflect any warming that has occurred since the records were discontinued.

The mean temperature at each site is largely set by the large-scale oceanographic circulation, modified by local influences. Consequently, as one would expect, there is an approximate latitudinal gradient in overall mean CSST (Figure 5-1), with Ahipara and Leigh Marine Stations having the warmest mean CSST (~17°C) and Bluff and Portobello having the lowest mean CSST (~12°C).

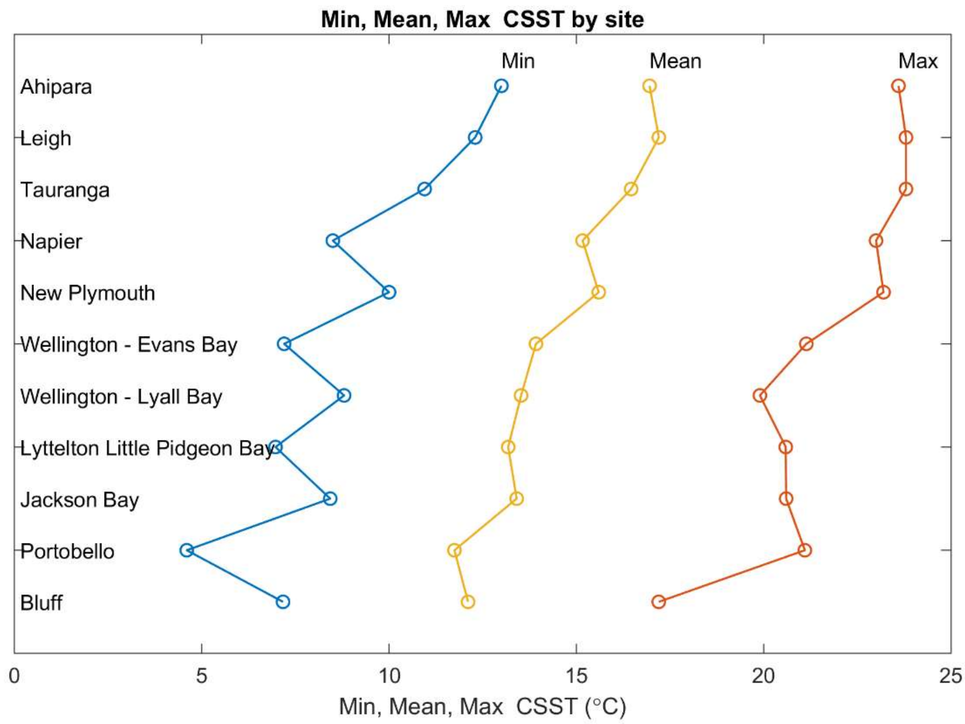

Figure 5-1: Minimum, mean and maximum CSST plotted by site.

Table 5.1 Overall mean and monthly mean CSST for each site

Site	Mean Temp	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Ahipara	17.0	19.2	19.8	19.3	18.5	17.1	15.6	14.4	14.3	15.0	15.9	16.8	18.2
Leigh	17.2	19.8	20.6	20.4	19.3	17.5	15.7	14.4	14.0	14.4	15.3	16.6	18.2
Tauranga	16.4	18.7	19.9	19.6	18.4	16.6	14.8	13.6	13.5	14.0	14.8	15.7	17.1
Napier	15.2	19.1	19.6	18.6	16.8	14.6	12.5	11.5	11.6	12.4	13.7	15.5	17.3
New Plymouth	15.6	18.3	19.0	18.5	17.2	15.7	14.0	12.9	12.8	13.5	14.3	15.4	17.0
Wellington - Evans Bay	13.9	17.5	17.7	16.7	15.0	13.3	11.4	10.3	10.5	11.6	13.0	14.6	16.2
Wellington - Lyall Bay	13.5	15.7	15.6	15.2	14.4	13.4	12.2	11.4	11.3	11.8	12.7	13.7	14.7
Lyttelton Little Pidgeon Bay	13.2	17.4	17.7	16.7	14.7	12.5	10.1	8.7	8.7	10.0	11.9	14.0	15.9
Jackson Bay	13.2	15.2	16.0	15.5	14.7	13.5	12.0	11.2	11.2	11.8	12.5	13.2	14.3
Portobello	11.7	16.1	15.9	14.5	12.4	9.8	7.9	7.1	7.9	9.6	11.6	13.4	15.0
Bluff	12.1	14.9	15.2	14.4	13.1	11.4	10.0	9.0	9.2	10.2	11.4	12.8	14.0

Figure 5-2 shows the amplitude of the annual cycle of CSST and SST for each site. This is the amplitude of a sine wave fit to the data. The amplitude is thus half the range in the annual cycle. Because fitting a sine wave to the records smooths out the daily signal, the annual amplitude will be less than half the range seen in temperature. For example, for Ahipara, the range between maximum and minimum observed temperature was about 10.6 °C, whereas the range in the annual cycle (i.e., twice the amplitude) is about 5.4 °C.

The offshore annual cycle tends to decrease from about 3 °C in the north to about 2 °C in southern New Zealand. The coastal annual cycles are typically higher than offshore and show little evidence of any change with latitude.

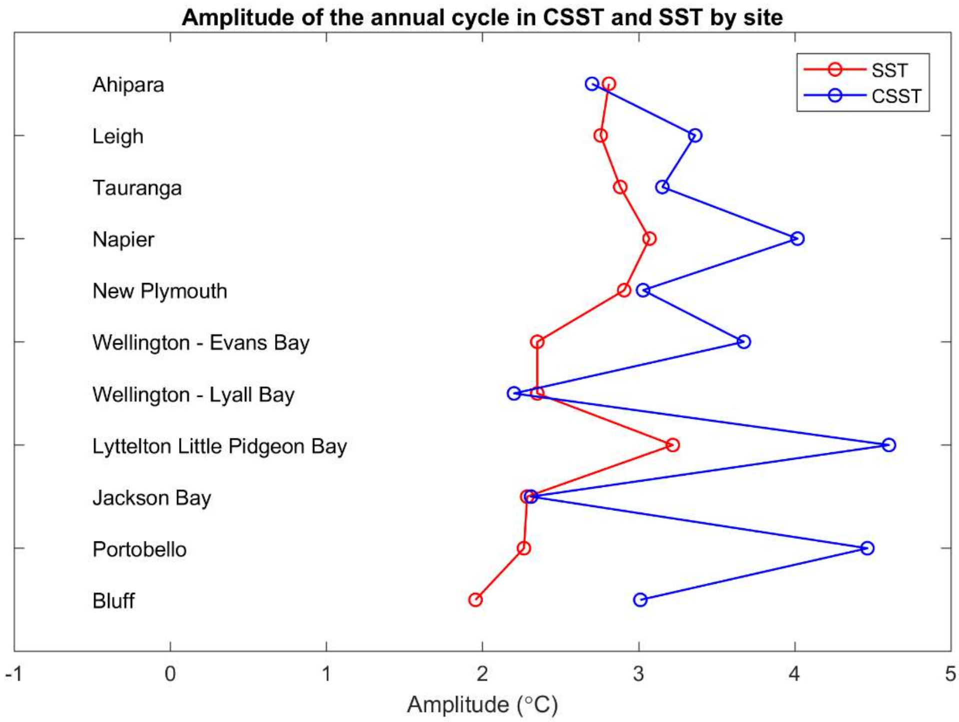

Figure 5-2: Amplitude of the annual cycle in sea surface temperature (after fitting with a sine wave) at coastal (CSST) and offshore (SST) sites.

5.2 Comparison of CSST and SST

In the next section, we provide a discussion of the long-term trends computed for CSST and SST at each site. But before doing so, it is instructive to compare CSST and SST for the various sites to provide an indication of how low the low-frequency signals vary across the sites.

A visual examination of CSST and SST for the sites (Figure 4-1 to Figure 4-11) shows that in general there is a clear correspondence between coastal and offshore sea surface temperature after the annual cycle has been removed, and the data filtered to remove high frequency oscillations. For example, Leigh (Figure 4-2) shows a near one-to-one correspondence between oscillations in the 1-year smoothed CSST and SST. Similarly, the 5-year smoothed CSST and SST are nearly identical.

Good agreement is also true for sites on the west coast (see Jackson Bay, Figure 4-9), and Evans Bay (Figure 4-6). However, Portobello (Figure 4-10) shows larger differences between CSST and SST, particularly between 2005 and 2010.

The agreement (or lack of agreement) between the 1-year smoothed CSST and SST records can be quantified by computing the cross-correlations between these records. Many of the CSST records are short and or intermittent over the 1982 to 2017 time period (e.g., Bluff, Tauranga). Unfortunately, cross-correlations between sites can only be compared if they are computed from the same time periods. For example, it is clear that a cross-correlation computed using the Bluff record (Figure 4-11) would not be comparable with a cross-correlation computed from Portobello (Figure 4-10).

Thus, we only computed cross correlations for the 3 sites that have continuous CSST over the satellite time period (Leigh, Evans Bay and Portobello).

The cross-correlations between the one-year smoothed CSST and SST records for these sites are shown in Figure 5-3. The standard error in the cross-correlation was computed using the formulae specified in Sciremammano (1979), and cross-correlations can be considered significant if they exceed this value.

Highest correlation occurs with near zero lag for Leigh and Portobello. CSST at Evans Bay shows a 14 day lead over SST at the oceanic site.

Peak cross-correlations are 0.83 for Leigh, 0.75 for Evans Bay and 0.67 for Portobello. The order of these peak values reflects the visual examinations which, for example, show a much better agreement between the interannual fluctuations of CSST and SST at Leigh than Portobello.

We cannot tell if the decrease in correlation going south from Leigh to Portobello is a result of a latitude dependence on the relationship between CSST and SST, or is because Evans Bay and Portobello coastal sites are more disconnected from the open ocean than the Leigh station.

Figure 5-4 shows the 5-year smoothed CST and SST from all sites. These data have had the mean temperature at the respective sites removed to account for the latitudinal range in sea surface temperature. The upper panel shows 5-year smoothed CST from the coastal sites and has a number of large gaps reflecting the intermittent nature of the records. Since the 5-year smoothed SST from the NOAA OI (centre panel) is continuous an overall mean can be calculated (thick green line) and the Southern Oscillation Index (SOI) is also shown for comparison in the lower panel.

The figure shows an overall warming of about 1 °C between 1982 and 2017, but with large year-to-year variability. The coolest years were 1982 and 1992, with warmer years in 2000-2001. The 5-year smoothed SST is correlated with the 5-year smoothed SOI prior to about 2005.

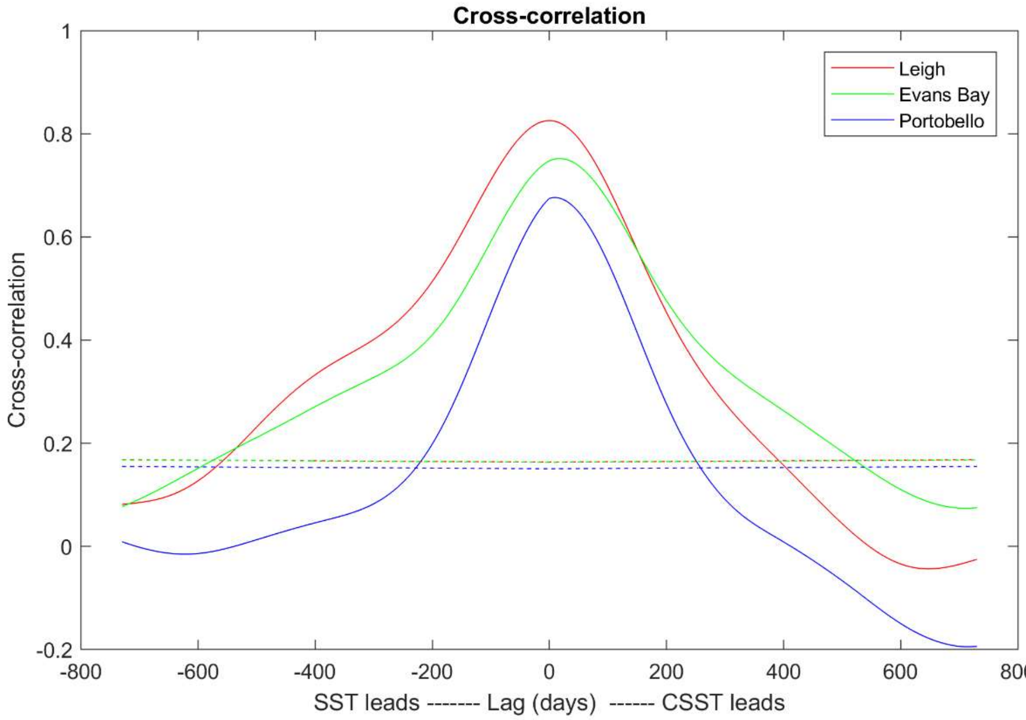

Figure 5-3: Cross-correlation between SST and CSST. Cross-correlation between the 1-year smoothed CSST and SST records for Leigh, Evans Bay and Portobello seen in lower panels of Figures 4-2, 4-6 and 4-10. Horizontal dashed lines are the respective significance levels. Correlations are considered significant when they exceed these levels (Sciremammano, 1979).

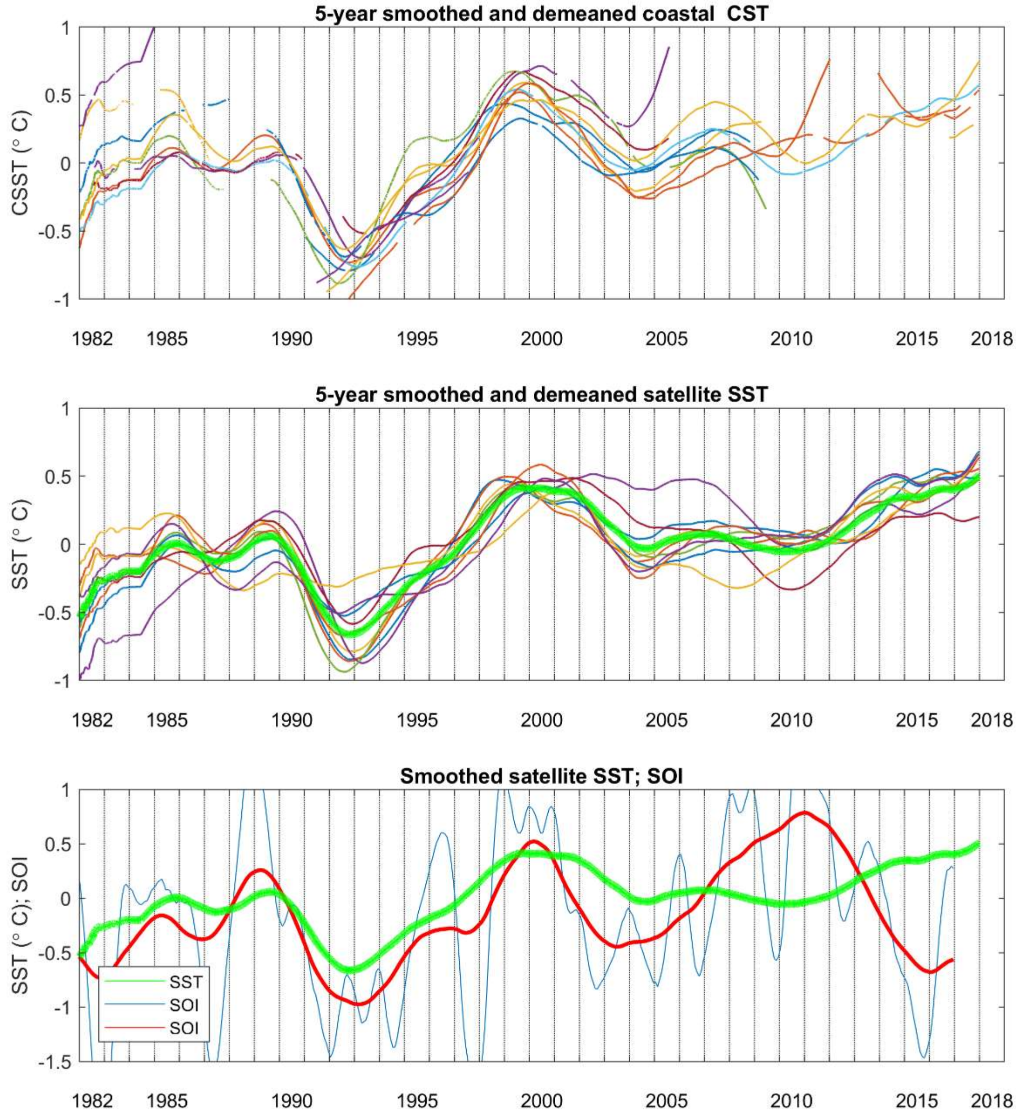

Figure 5-4: Low-frequency components of SST and CSST. Upper panel shows CSST from each site after the annual cycle and mean have been removed and the signal filtered with a 5-year running mean. Middle panel shows the 5-year smoothed SSST from each site after the mean and annual cycles have been removed. The thick green line shows the 5-year smoothed signal averaged over all SST sites. The lower panel shows the mean 5-year smoothed SST along with the Southern Oscillation Index (SOI) smoothed with a 1-year filter (blue) and with a 5-year filter (red).

5.3 Long-term trends

The two longest CSST records are from Portobello (from 1953) and Leigh Marine Stations (from 1967), and data from these sites have few gaps. However, as well as starting at various times, many of the other sites have been discontinued, for example, New Plymouth record extends only to 2009. Because of these varying record lengths and the intermittent nature of the coastal station records, it is difficult to directly compare long term trends from each site.

In contrast, satellite-based data extends back to 1982 for all the ocean sites, which allows for comparison of offshore trends around New Zealand from 1982. Three coastal sites have good coverage from 1982 and can be used to compare trends at the coastal sites with those offshore.

Therefore, we computed the long-term trends to 2017 for Portobello from 1953, Portobello and Leigh from 1967, Portobello, Leigh and Evans Bay from 1982, and all ocean sites from 1982.

Table 5.2 lists the slopes of the trends, their standard deviations in °C/decade and the significance levels. Trends are considered significant if their significance level exceeds 0.975. All trends are significant except CSST from the full Leigh record.

The trends indicate that CSST at Portobello Marine Station has been rising at a mean rate of 0.12 °C/decade since 1953, and 0.089 °C/decade since 1967. Examination of the Portobello time series (Figure 4-10) shows a series of warm years in the late 1960's and early 1970's that explain why the rate is lower for the shorter record.

The trend in CSST at Leigh Marine Station from 1967 is not significant. This means that any trend in CSST at Leigh over this time period is masked by the year-to-year variability, as found by Shears and Bowen (2017).

The trends in CSST at Portobello, Leigh and Evans Bay from 1982 are significant and have a mean slope of 0.154 °C/decade.

The trends in SST at all sites from 1982 are significant, and their slopes range between 0.209 and 0.392 °C/decade with a mean value of 0.269 °C/decade, and a standard deviation of 0.06 °C/decade.

There is no clear dependence of these trends on latitude with Ahipara, Leigh and Tauranga having the same range in slopes (0.311, 0.242, 0.210 °C/decade) as Jackson Bay, Portobello and Bluff (0.331, 0.231, 0.294 °C/decade).

However, the west coast sites have higher slopes than east coast and there is a suggestion that the trend is dependent on longitude (Figure 5-5), with Napier being an outlier. Why Napier should be an outlier is not clear, but the other trends suggest a higher rate of warming on the west coast of New Zealand.

Table 5.2 Long-term trends in surface sea temperature and their significance for each site. Trends for Portobello, Leigh and Evans Bay from 1953, 1967 and 1982 were computed from the coastal site. Trends for the sites labelled with SST were computed from the ocean site. Trends are considered significant if the significance level of the slope is greater than 0.9725. If the trend is considered not significant it is labelled as No in the last column.

Site	Trend slope ± s.d (°C/decade)	Student's t level	Significant
Portobello from 1953 CSST	0.12 ± 0.02	1.000	Yes
Portobello from 1967 CSST	0.09 ± 0.03	0.999	Yes
Leigh from 1967 CSST	0.01 ± 0.03	0.656	No
Portobello from 1982 CSST	0.15 ± 0.05	0.998	Yes
Leigh from 1982 CSST	0.12 ± 0.05	0.990	Yes
Evans Bay from 1982 CSST	0.20 ± 0.05	1.000	Yes
Ahipara SST	0.31 ± 0.08	1.000	Yes
Leigh SST	0.24 ± 0.09	0.997	Yes
Tauranga SST	0.21 ± 0.08	0.995	Yes
Napier SST	0.39 ± 0.09	1.000	Yes
New Plymouth SST	0.27 ± 0.09	0.998	Yes
Wellington Evans Bay SST	0.22 ± 0.09	0.990	Yes
Wellington Lyall Bay SST	0.22 ± 0.09	0.989	Yes
Lyttleton SST	0.21 ± 0.08	0.992	Yes
Jackson Bay SST	0.33 ± 0.09	0.999	Yes
Portobello SST	0.23 ± 0.08	0.999	Yes
Bluff SST	0.29 ± 0.09	1.000	Yes

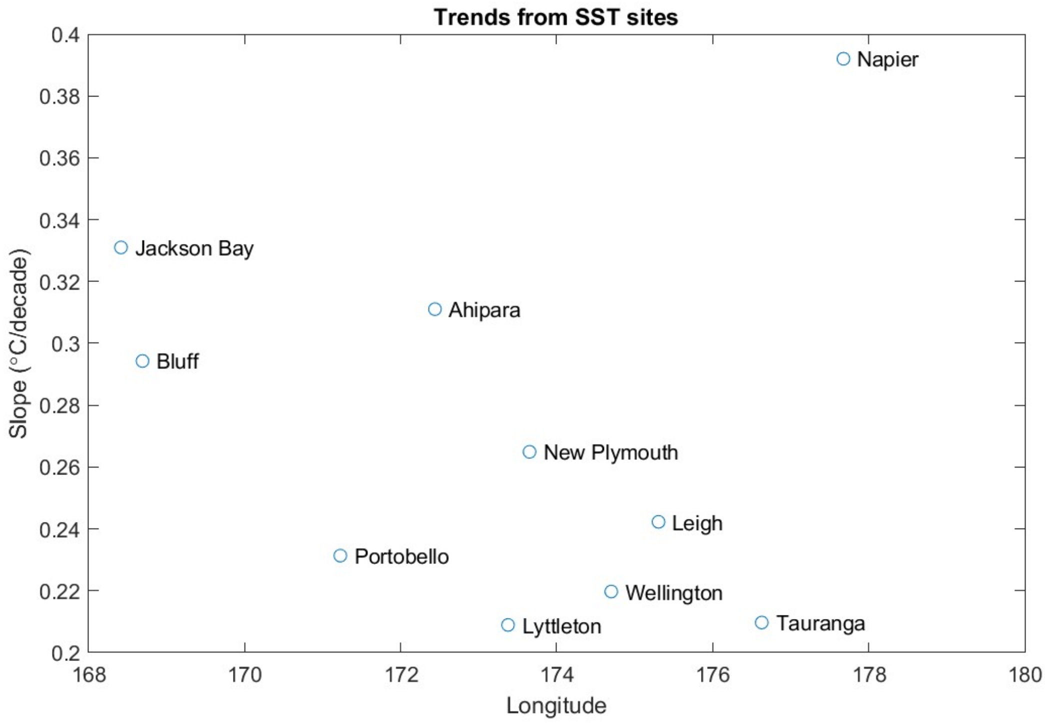

Figure 5-5: Slopes of trends in SST plotted vs Longitude. Slopes of the trends (°C/decade) from the SST sites since 1982 plotted as a function of site longitude.

6 Discussion

There are many processes which affect CSST, including the daily and annual cycles of solar heating and cooling, the influence of offshore waters in heating or cooling the coastal region, tides, and wind-driven mixing and upwelling of deeper, colder water (Chiswell & Schiel, 2001). There may also be year-to-year variability in CSST associated with larger scale phenomena such as ENSO.

The dominant signal in CSST is the annual cycle of solar heating and cooling, with maximum monthly CSST usually occurring in February, and minimum monthly CSST occurring in July.

Hourly changes in CSST result from both daily heating and cooling, and tides.

Mesoscale variability (i.e., temperature changes occurring over days to weeks) reflects the influences on CSST of such processes as local weather, wind-driven upwelling of cold water into inshore regions. This mesoscale variability can be quite large, for example, Figure 3-1 illustrates about 5°C change in daily-mean CSST at Ahipara over the space of 2-3 weeks. This event is about half the annual range in CSST.

As one would expect there is a latitudinal gradient in mean CSST with mean CSST about 17 °C at Ahipara and 12 °C at Bluff.

However, there is no latitudinal gradient in the overall range in CSST (i.e., difference between warmest and coldest CSST). For example, Ahipara and Jackson Bay, have about 11°C range, whereas Portobello and Napier have about 15-16°C range in CSST (Figure 5-2). In Wellington, the range is ~13.5°C within Evans Bay, but ~11°C in Lyall Bay, whereas the mean temperatures are within 0.5°C for these two sites. This reflects the fact that the summer to winter range in CSST is more likely to be influenced by local geography than the large-scale oceanographic circulation (see Lima & Wethey, 2012), with enclosed waters having larger variability than open waters.

Similarly, while the amplitude of the annual cycle of SST in offshore water decreases going south, there is no clear latitudinal gradient in the amplitude of the annual cycle of CSST at the coastal sites (Figure 5-2). It is likely that local heating in summer and/or cooling in winter is much more extreme in enclosed bays than in the ocean offshore, for example, Lyall Bay in Wellington has an annual range of about 2 °C, whereas Evans Bay has an annual range of about 4 °C.

Once the annual cycle and mean temperature are removed from each site, the variations in CSST with periods of a year or more follow remarkably well the long-term variations in offshore SST. This observation is consistent with the findings of Bowen *et al.* (2017) who suggest that coastal sea surface temperature is significantly correlated with the arrival of barotropic Rossby waves over the latitudes of New Zealand, so that deep isotherms fluctuate coherently around the country.

Peak cross-correlation between CSST and SST is highest at Leigh and lowest at Portobello (Figure 5-3). Whether the lower values at Portobello reflect a decrease in correlation with latitude, or whether they reflect the fact that the coastal site at Portobello is more disconnected from the open ocean than at the other sites cannot be determined because of gaps in the records from the other sites.

There is also a complicated influence on SST around New Zealand from large-scale Pacific oscillations. SST around New Zealand was cooler than normal during the major El Niños (negative SOI) of 1982/83 and 1992 to 1995, and warmer than normal during the La Niñas of 1988-1989 and 2000-2001, but after 2005 there appears to have been little impact of ENSO on the 5-year smoothed SST, which instead showed a slow increase despite the large oscillations in SOI associated with the 2010-2011 La Niña (positive SOI) and the 2015-2016 El Niño.

A recent paper by Shears and Bowen (2017) suggest that the low-frequency variability in SST in the Tasman Sea is related to the curl of the wind stress. How this is related to the large-scale atmospheric cycles such as the Southern Oscillation is not fully understood.

The low-frequency signals in SST and CSST show about a 1 °C increase since 1982, although coolest and warmest years throughout the region were in 1992 and 2002, respectively.

The trends show CSST and SST warming at all sites. There may be a difference between the offshore SST and coastal CSST since the results for the sites where we can directly compare SST and CSST trends (Leigh, Evans Bay and Portobello from 1982) show lower trends in CSST than in SST.

The longest CSST record is from Portobello Marine Station, and this shows a reliable 0.12 ± 0.02 °C/decade increase in CSST since 1953. Our value is slightly higher than, but is statistically consistent with that obtained by Shears and Bowen (2017) of 0.1 ± 0.05 for the years 1953 to 2016.

Our analysis of the SST records from 1982 shows no relationship between SST trend and latitude. However, the west coast sites tend to have higher trends than the east coast sites with Napier being an outlier. This observation is result is consistent with Shears and Bowen (2017) who looked at trends in SST since the 1950's from three sites (Maria Island, Portobello and Leigh), and found the long-term rate of warming off eastern Tasmania (Maria Island) was about 0.20 °C decade^{-1}, compared to about 0.10 °C decade^{-1} for Portobello, and not significant at Leigh. They also found that warming trends over the satellite era (1982–2016) for these sites were greater than the longer-term trends.

Shears and Bowen (2017) attributed this to changes in the regional-scale circulation resulting from increased wind stress curl in the South Pacific subtropical gyre. What may be happening is that increases in the strength of the trade winds in the tropics, and/or increases in the westerly winds at more southern latitudes lead to increased flow of warmer water southwards in the East Australian Current along the Australian coast. This in turn leads to warming, but at a lower rate, off the west coast of New Zealand, and at a yet lower rate off the east coast of New Zealand. How much of the warming around New Zealand is due to such a wind-driven process, and how much is due to other factors such as large-scale global warming is yet to be determined.

It should be noted that the extensive marine heat wave seen around New Zealand from late 2017 into early 2018 will have little impact on the calculation of trends, because at the time of this analysis, the NOAA OI product was available only until the end of 2017.

There are many reasons to measure coastal SST at as many sites as possible, for example to anticipate the local impact of any harmful invasive species. Discussion of these reasons is beyond the scope of this document. However, for the purpose of evaluating potential long-term climate changes in the marine environment, the high correlation between sites means that impacts of climate change are likely to be well determined from a relatively small number of sites around the country. Given the existing long-term records at Leigh, Evans Bay and Portobello, it is clear that these sites should be maintained with highest priority. Together these sites provide representative CSST across New Zealand, but biased to the east coast. Thus, Jackson Bay should also be maintained with high priority to provide CSST representative of the west coast of the country.

At present, coastal sites are instrumented with self-contained thermistor loggers that are deployed for up to a year or more before being recovered (for example, the most recent Leigh data at time of writing this report is from August 2017). This has the problems that data are not real time and exposes the data to the risk that instrument failure or loss can lead to significant data loss.

We recommend that the four critical sites be upgraded to real-time logging instrumentation, with backup, linked to a coastal SST network so that data can be viewed in near-real time. A lower level of priority can be set for the other sites – although, again, there are other reasons for measuring CSST than climate change, and other factors such as local requirements and local logistics, that need to be taken into account before providing a priority list.

7 Acknowledgements

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