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Variation and prediction of water temperature in York River estuary at Gloucester Point, Virginia

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VARIATION AND PREDICTION OF WATER TEMPERATURE IN YORK RIVER ESTUARY AT GLOUCESTER POINT, VIRGINIA

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ABSTRACT

A historical time series of daily water temperature measurements for Gloucester Point, Virginia (York River Estuary) during the period 1954 to 1977 is described by means of statistical techniques. A basic model which consists of trend, cyclical, seasonal, and irregular components is used to approach the nature of the water temperature variations. A simple sinusoidal curve is shown to describe the behavior of the annual component and accounts for more than 95 percent of the total variance either for an individual year or the 24 year mean record of water temperature. Consistent amplitude and phase angle were derived from Fourier analysis for the seasonal component of the water temperature. The variance spectrum technique which is based on the frequency domain is used to express significant "hidden" cyclical components which may not be apparent in the Fourier analysis. Four significant cyclical components extracted from the non-seasonal water temperature readings, with 22 year, 26 month, 14 month and 6 month periods might be related to solar activity. Two periods with large fluctuations of water temperature occurred before and after the stable years 1962-1970. This also might result from the intensity of sunspot activity. The lunar period fails to be a significant factor. The trend component is not obvious because most of the long term variation during this study period is contributed by the 22 year cycle.

The first order autoregressive process gives the best fit for the daily residual data after the fundamental harmonic and the record mean are removed. This predictive model, which consists of a deterministic portion (annual cycle) and a stochastic portion (non-seasonal component), can forecast the daily water temperature 12 days ahead theoretically.

There was no direct relationship between monthly mean water temperatures and monthly condition index values for oysters in the York River Estuary. Other features of these two time series appear to be correlated, perhaps because water temperature is a dominant factor during parts of the year and other factors control during the remaining seasons.

VARIATION AND PREDICTION OF WATER TEMPERATURE

IN THE YORK RIVER ESTUARY

AT GLOUCESTER POINT, VIRGINIA

INTRODUCTION

The increasing concern for our living environment makes it necessary to understand the characteristics of water quality, especially its effect for our people. One of the most significant parameters is water temperature because it can affect the growth and health of the biota. Therefore, the analysis of water temperature variations can provide worthwhile information for us concerning the nature of an estuary.

Beaven (1960) calculated the daily temperature and salinity values of surface waters of the Patuxent River estuary at Solomons, Maryland, and presented tables of average values for the twenty year period, as well as the daily fluctuations shown graphically with monthly means and ranges. Ritchie and Genys (1976) extended Beaven's information to the next ten years, and also established a fourth degree polynominal regression equation which can be used to predict the water temperature for any given day. Ward (1963) demonstrated that an empirical sine curve equation closely fits the annual variation of temperature of a stream, and that the nature of the sine curve does not change much from year to year.

Others have examined the characteristic of the residual that results when the seasonal variation is subtracted from the actual time series record. The information gained from the analysis can be used to develop models to predict water temperatures.

For this study we have used as the basic model, the concept that there is a dominant annual cycle. Superimposed on this annual cycle can be a long term trend, other cyclic variations and random or irregular components. If all four independent components were put back together, the result would vary much like an actual water temperature time series.

$$W = A + T + C + 1$$

where W = the variation of water temperature from some mean value

A = annual cycle

T = long term trend

C = cyclical variations

1 = irregular or random component

and all of the terms are functions of time.

The purpose of this study is to use a 24 year record of water temperature in the York River Estuary to determine the nature of each of these components. The location of the sampling station, data processing methods and the basic statistical results (means, ranges, etc.) are presented in Chapter I.

Chapter II includes harmonic analysis of the data to determine the characteristics of the annual cycle. The importance of higher order harmonics also was considered.

In Chapter III, the variance spectrum was calculated and used to investigate the cyclical components of the time series. The Box-Jenkins technique to develop a predictive model was examined in Chapter IV. This technique needs only three simple parameters to determine the stochastic or irregular portion of the record, once the deterministic, annual cycle has been removed.

The information gained from these analyses can be applied to many fields. When values are missing from historical records these techniques are useful to supply the missing data, and also to provide more accuracy and limit errors in predicting future values. Above all, it can provide good information for scientists studying the variation of biological growth with temperature changes. This knowledge of water temperature variations should be useful for aquaculture too. The application of the water temperature analysis to oyster condition index trends is given in Chapter V.

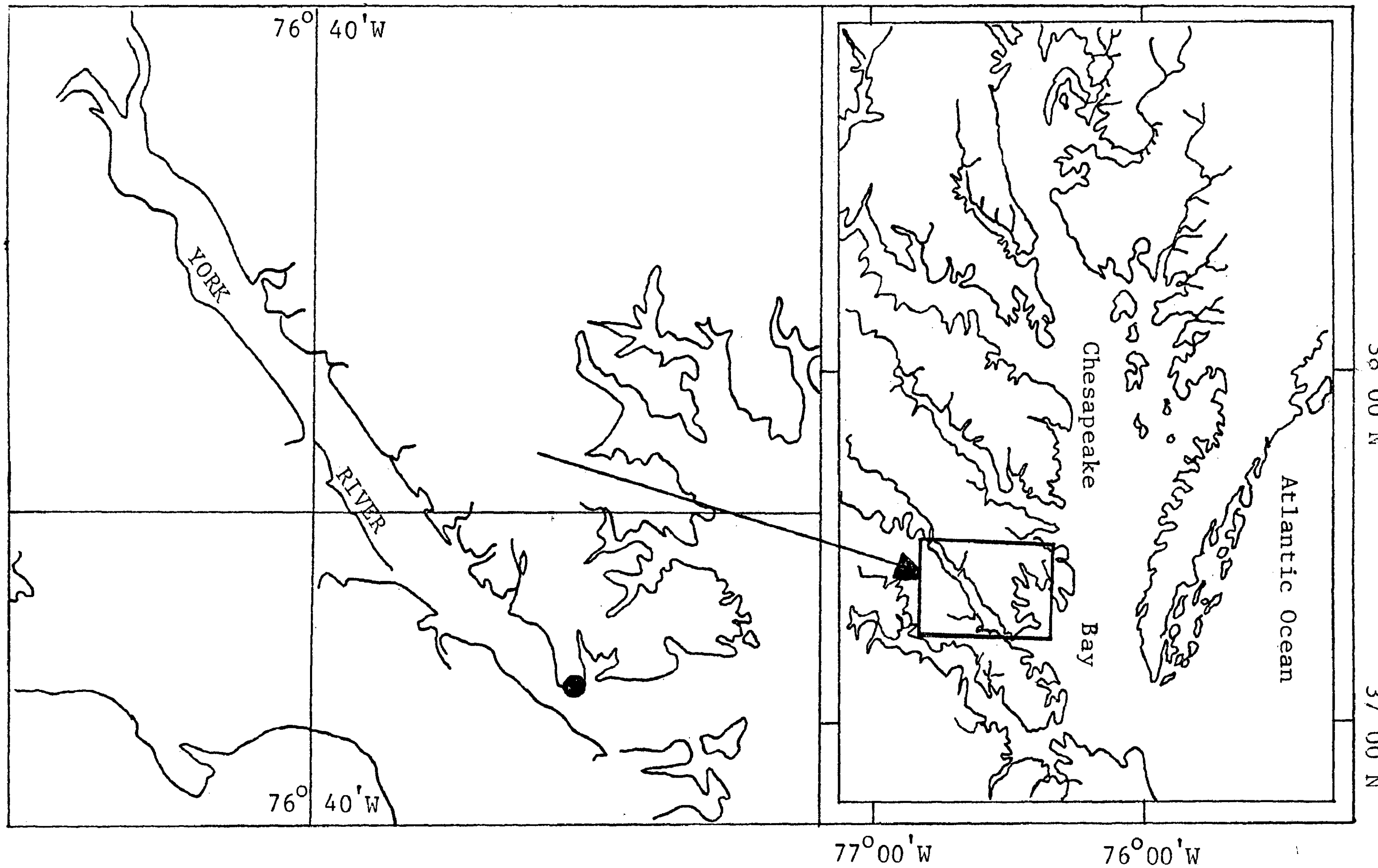
And finally, a discussion of the study's findings and conclusions are presented in Chapter VI and Chapter VII.

CHAPTER I

DESCRIPTION OF THE DATA

The York River is one of six major tributaries which enters Chesapeake Bay along its western shore (Fig. 1). The drainage area of the York River is about 6900 square kilometres (km^2) (Virginia Division of Water Resources, 1974) and lies entirely within the Commonwealth of Virginia. The York is formed at the town of West Point at the confluence of the Mattaponi and Pamunkey rivers. Tidal influences are observed over the entire length of the York River and extend about 96 kilometres (km) up the Mattaponi and 60 km up the Pamunkey. Its length from West Point to Chesapeake Bay is about 56 km. The average width of the York is about 3 km and the average depth about 6 metres (m), but depths range to over 26 m.

The Virginia Institute of Marine Science (VIMS) and The School of Marine Science, College of William and Mary is located at Gloucester Point on the north shore of the York River about 9.6 km from Chesapeake Bay at a narrow portion of the river channel. Water temperatures were monitored by VIMS at the end of a pier which extends about 116 m from the shoreline. The river width from the pier to



Figuare 1. York River Estuary and its relatively posiyion in Chesapeake Bay.

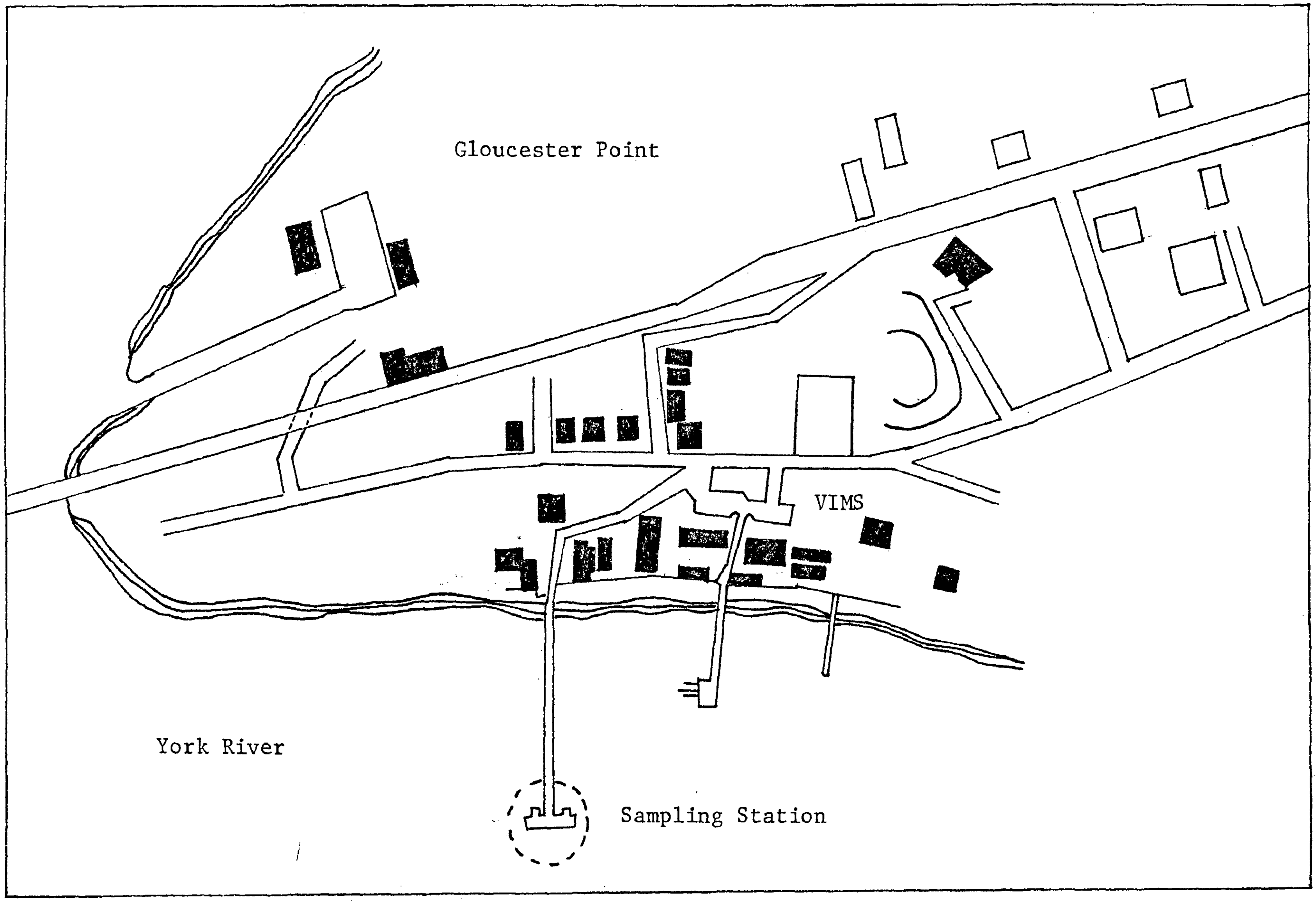


Figure 2. Location of water temperature sampling station.

the Yorktown monument on the opposite side is about 3.2 km. The exact location of this station is latitude of $37^{O}14.8'$ N and longitude of $76^{O}30.1'$W (Fig. 2).

Water temperature readings have been made at this location since 1947. A mercury maximum and minimum thermometer was used to measure the daily extreme temperatures. Since 1972, an Interocean Model 513 CSTD probe has been used. This instrument was designed to accommodate a variety of situations which arise in oceanographic and estuarine studies. It incorporates sensors to provide in situ measurement of conductivity, salinity, temperature, and depth. The sensors are located 2.2 m below mean low water; the river bottom is 4.2 m below mean low water. Temperatures were read to the nearest 0.1 of a degree centigrade (C). In order that the surface water temperature may be more accurately estimated, the probe is checked once a week for agreement with a mercury thermometer which is placed at the same level of water as the instrument. The mercury thermometers have a rated accuracy $\pm$ 0.25 C. It is estimated that the total error does not exceed $\pm$ 0.5 C.

There have been only a few instances when the instrument was inoperative; the missing data was supplied by an interpolation method. If the temperature data were abnormal, data from another instrument, a Foxboro Temperature Recorder, were used. For more lengthy periods with missing values, the data gap was left in the record. Data gaps are greatest for the years 1964, 1968, and 1972.

Although instantaneous readings were made prior to 1972, only the daily extremes were recorded. Since 1972, the average temperatures for each of 12 two-hour periods during that day are recorded as well. The daily extremes since 1954 and the two-hour average temperatures since 1972 are stored on punched computer cards at the VIMS Instrument Shop. Daily averages used in this study were the mean values for the daily extremes. The mean values for the 12 two-hour temperatures for the last six years also were calculated. Both were transferred to computer cards and stored in the William and Mary Computer Center library.

The daily average temperatures for the twenty-four years of record are given in tabular form in Appendix A. Statistics for each particular day of the year are given in tabular form in Appendix B. Normally, data for February 29 were ignored to simplify calculations. The twenty four year mean temperature for each day along with one standard deviation limits have been plotted (Fig. 3). Additionally, daily temperatures have been calculated using 7-day and 10-day moving averages of the twenty-four year means, and the 10-day moving average has been plotted (Fig. 4). The maximum and minimum daily temperatures, along with the year in which these occurred, have been listed in Appendix B.

The particular daily means of temperature ranged from 3.22 C to 26.92 C. Temperatures average around 3 C for

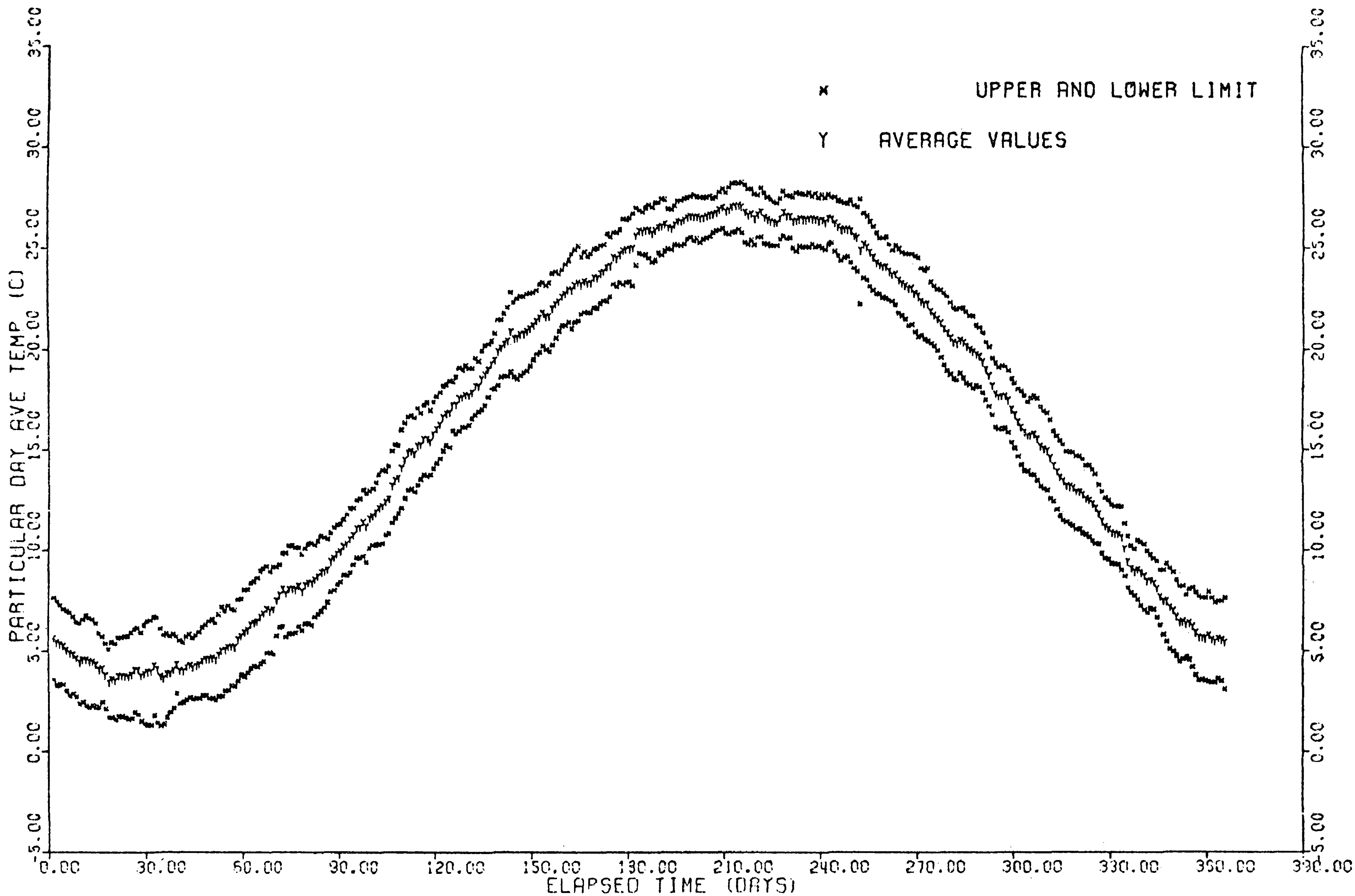


Figure 3. Mean daily average temperatures for 1954 to 1977 and ± 1 standard deviation.

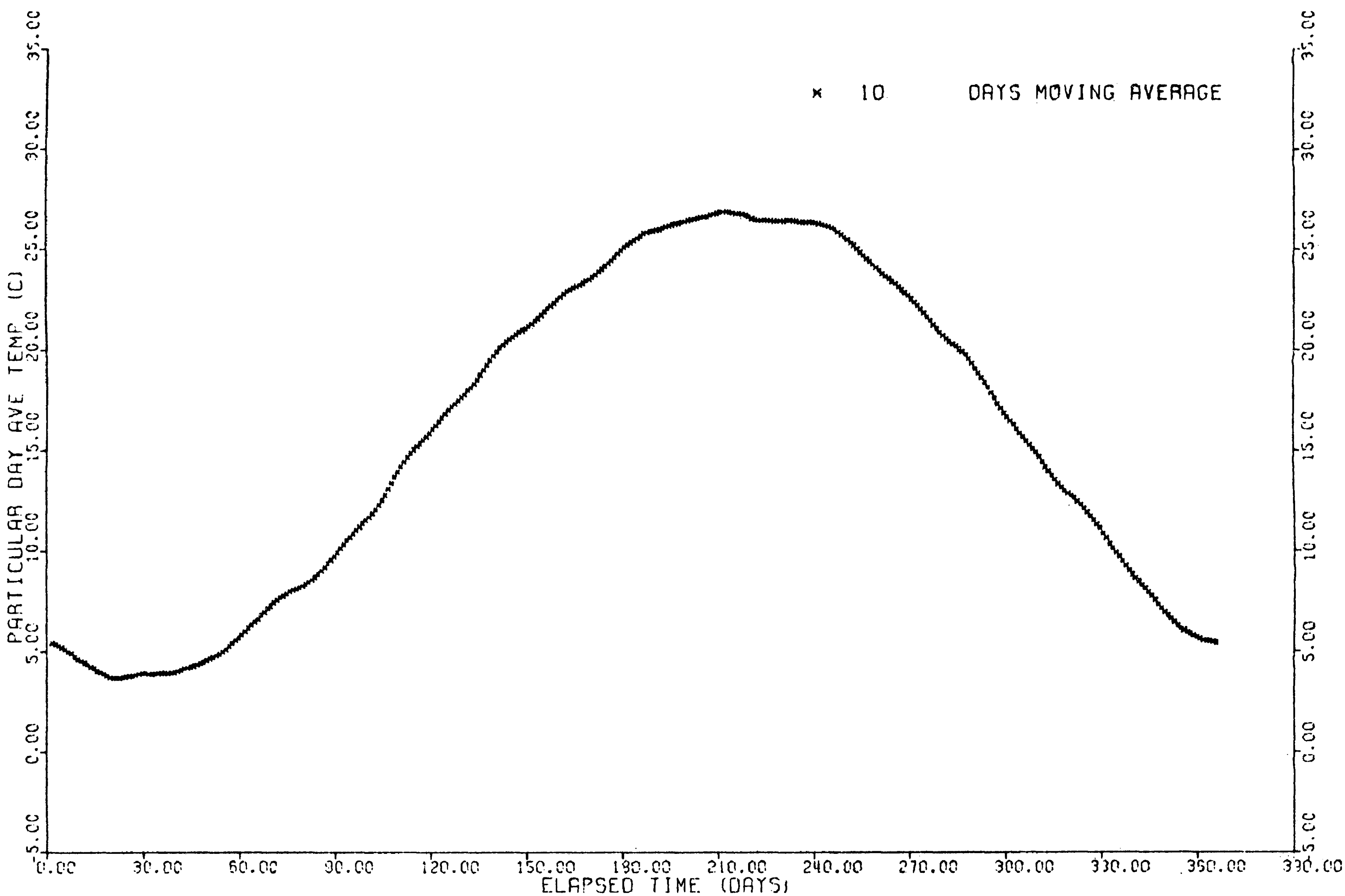


Figure 4. The 10 day moving average of 24 year mean daily average water temperatures.

about 25 days from January 15 to February 10. The coldest water temperatures occur during the middle or later part of January, and after six and one half months the warmest temperatures occur at the beginning of August.

The standard deviation of the daily water temperature varied from 0.84 C to 2.58 C. Generally speaking, higher deviations occur during cold days and lower deviations occur during warm days (Fig. 3). However, highest value for the standard deviation occurred in the middle of September, although most days during that month have medium values.

The observed extreme daily average water temperatures ranged from a low value of -1.4 C on January 31 to a high value of 30.0 C on July 15 and 16 (Fig. 5). The days with highest extreme temperatures do not coincide with the days of the highest average temperature. The days with lowest temperature were a half month apart. From the middle of January through the middle of February, it is not uncommon for water temperatures to go below the freezing point. A few especially cold years, like 1977, produced many of the minimum values.

Sets of daily average temperatures were selected for each of the four seasons so that the probability distributions of values for the twenty-four years could be observed (Fig. 6). Generally, the data appear to be normally

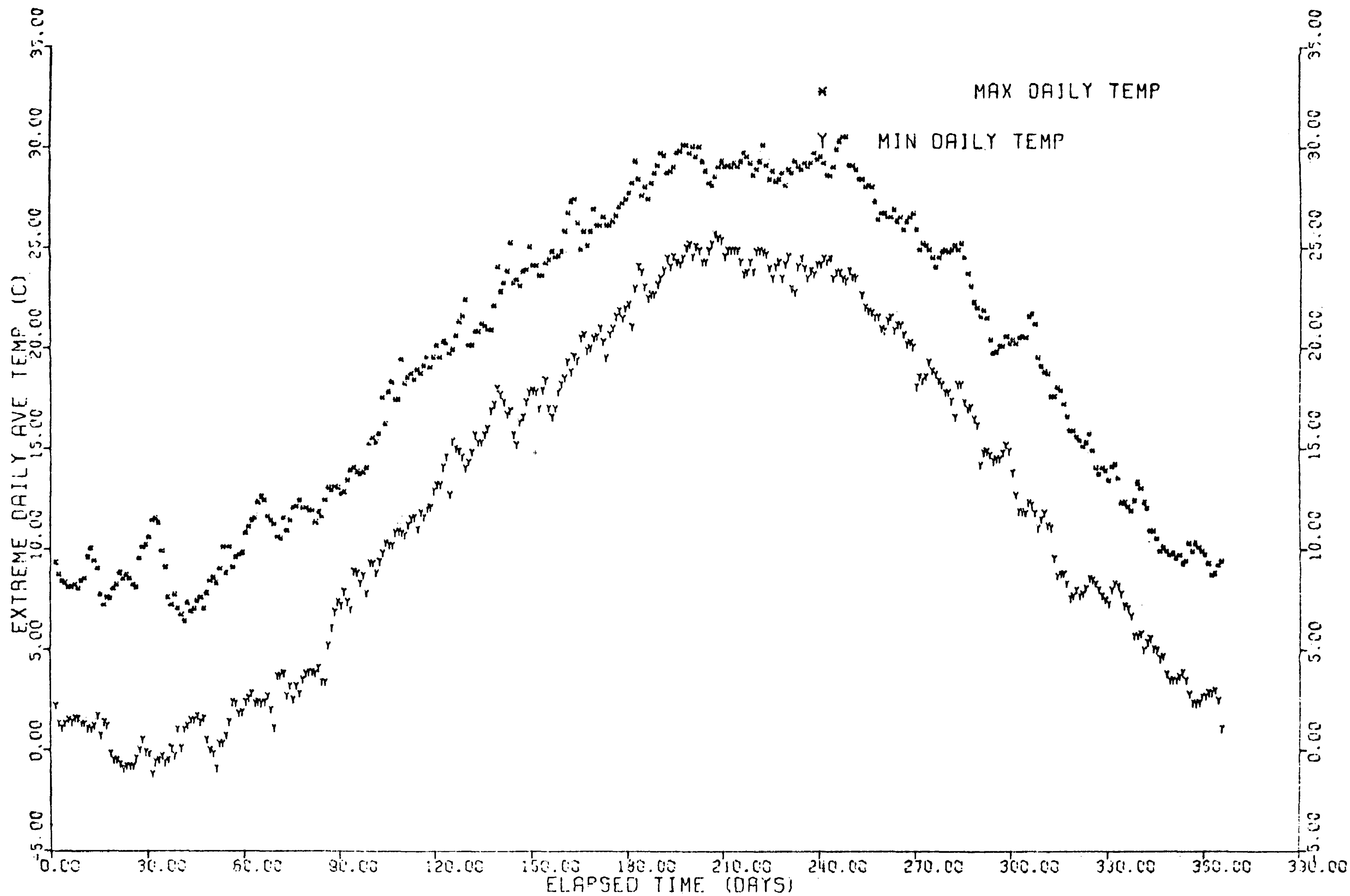


Figure 5. The extreme water temperatures for each calendar day for the years 1954 to 1977.

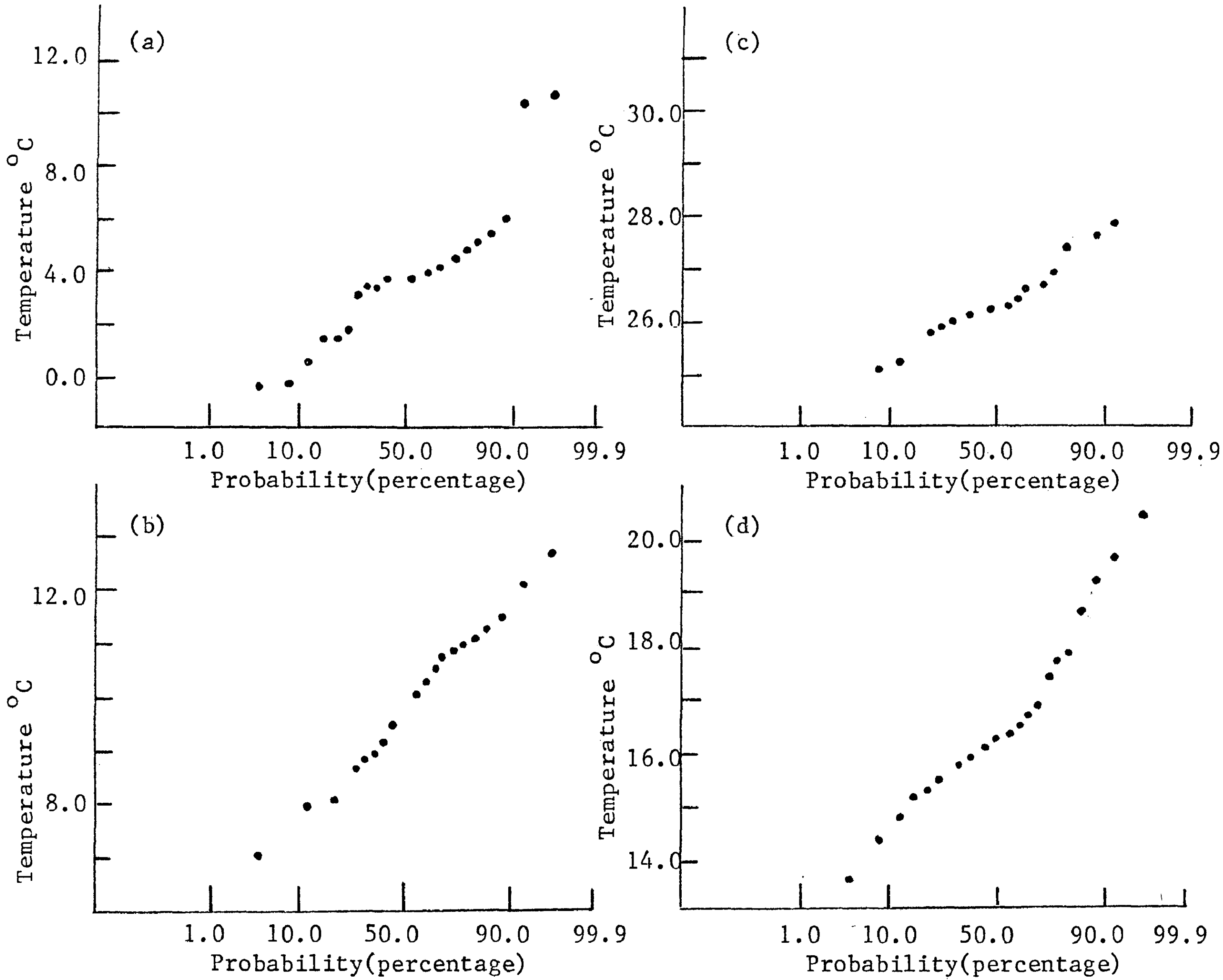


Figure 6. The probability distribution of one particular day for (a) the 30th day (winter), (b) the 90th day (spring), (c) the 199th day (summer), and (d) the 300th day (fall).

distributed but there may be a few outlying points. Because the sample size (N equals 24) is not large, the distributions cannot be described in detail.

Both the time series for individual years and the twenty-four year mean record were used in the analysis which is described in the following chapters.

CHAPTER II

HARMONIC ANALYSIS AND THE ANNUAL CYCLE

The techniques called time series analysis may be applied to sets of observations if these sets are dependent statistically. If a time series exhibits a strong characteristic for a given frequency, or even a set of frequencies, one style of analysis which can emphasize this periodicity is called harmonic analysis or Fourier analysis. It can separate the time series data into a set of sine wave signals, each having a given period and amplitude. As frequently used for water quality data, harmonic analysis shows the physically meaningful harmonics, which then can be subtracted from the original series. It is not necessary to include each harmonic and all harmonics need not be consecutive.

The seasonal or annual component refers to the identical or nearly identical pattern which a time series appears to follow during successive years. In other words, this seasonal behavior is the pattern observed within each year. The trend component indicates the evolutionary change that occurs in a time series over long time intervals. It is revealed primarily as a changing mean level around which the remaining components fluctuate with different degrees of regularity. The cyclical component describes successive advances and declines, and may include more than one cycle. In this chapter, the significance of these three components is investigated by harmonic analysis. The daily mean water temperature for each individual year is tested for the seasonal component. The twenty-four year daily mean series is examined to see if cyclical and trend components exist.

Kothandaraman (1971) reported that a single harmonic with a period of a year normally accounts for about 95% for the total variance of a water temperature record. Harmonic analysis can separate such cyclic variations from the observed record. If this is done, it is possible to investigate the nature of the non-cyclic variations, and it may be possible to construct a model which illustrates these non-cyclic variations. Thomann (1967) applied the general theory of Fourier and spectral analysis and presented the results of time variation for temperature and dissolved oxygen in the Delaware Estuary. The first harmonic included most of the total variance; the amplitude and phase angle were very similar for different transects through the whole estuary. Low-frequency phenomena dominated the residual spectra, especially for water temperature, with peaks in the area of 30 days. Long (1976) also did water temperature forecasting and estimation using Fourier

Series and Communication Theory techniques for a river with a constant thermal input from a power plant. He suggested that by using significant Fourier components he could make a meaningful prediction of daily average water temperature for up to 60 days ahead.

Other research has dealt with water temperature in the rivers or streams and the association with air temperature data. Kothandaraman (1971) investigated the nature of seasonal and non-seasonal variations in the daily mean river water temperature and developed a method to predict water temperature based on observed meteorological data. The resulting predictions had a standard error of estimate of about 1.1 C. Song (1973) postulated a model which includes variations due to atmospheric temperature fluctuation, and the seasonal variations of the water temperature as well as purely random fluctuations. Song and Chien (1977) analyzed some stochastic characteristics of the daily component of water temperature variations with respect to daily range, air temperature fluctuations, and watershed area. Linear regression models and autocorrelation and cross-correlation models were used.

Since it is already known that the annual water temperature cycle can be described roughly as a sine curve, it is reasonable to assume the Fourier analysis will provide meaningful information about the water temperature record.

Therefore, a fundamental formulation can be used to estimate amplitude and phase angle for the different components:

$$T = \overline{T} + \sum_{i=1}^{M} a_i \sin (b_i x + c_i) \qquad (2\text{-}1)$$

$$= \overline{T} + \sum_{i=1}^{M} A_i \sin b_i x + B_i \cos b_i x \qquad (2\text{-}2)$$

where $A_i = a_i \cos c_i$ $\qquad B_i = a_i \sin c_i$

then $a_i = \sqrt{A_i{}^2 + B_i{}^2}$ $\qquad c_i = \tan^{-1} \frac{B_i}{A_i}$

in which $\overline{T}$ is the average of the record

a_i = the amplitude of the ith harmonic

b_i = the frequency for the ith harmonic

c_i = the phase angle in radians for the ith harmonic

M = the number of harmonics

the phase angle c_i can be adjusted as follows:

$$c_i = \begin{cases} \tan^{-1} \frac{B_i}{A_i} & A_i > 0 \\ \tan^{-1} \frac{B_i}{A_i} + \pi & A_i < 0 \quad B_i \geq 0 \\ \tan^{-1} \frac{B_i}{A_i} - \pi & A_i < 0 \quad B_i < 0 \\ -\frac{\pi}{2} & A_i = 0 \quad B_i < 0 \\ -\frac{\pi}{2} & A_i = 0 \quad B_i > 0 \\ \text{arbitrary} & A_i = 0 \quad B_i = 0 \end{cases}$$

The coefficients in Eq. 2-1 can be determined using the least-squares method which would make the sum of deviations a minimum (after the harmonic coefficients A_i and B_i are calculated). These harmonic coefficients A_i and B_i may be given by:

$$A_i = \frac{2}{N} \sum_{x=1}^{N} Tx \sin b_i x \qquad (2\text{-}3\text{-}1)$$

$$B_i = \frac{2}{N} \sum_{x=1}^{N} Tx \cos b_i x \qquad (2\text{-}3\text{-}2)$$

where N = Total sample number

Tx = water temperature record at day x
x=1,2,...,365 for yearly data

These two values (A_i and B_i) can be estimated very accurately by the least-squares method, which saves some time compared to calculating the very big inverse matrix required to solve the set of linear equations if one needs to include higher frequency terms.

Harmonic analysis will be applied first to the twenty-four year mean record to show the variation of water temperature over the longer term. The second concern is to examine the variation of phase angle and amplitude year by year. Once the mean of the record and the amplitude and phase angle for each harmonic have been calculated, we can determine how many and which harmonics are needed. These can be selected with a useful calculator index, the variance accounted for by the given harmonic. From eq. (2-2) it is known that the variance accounted for by each given harmonic is equal to the half value of the amplitude squared ($Var_i = A_i^2/2$). From the percentage of total variance accounted for by that harmonic we can decide whether it is significant or not. For instance, the mean record for the twenty-four years has a first harmonic which accounts for 99.68% of the total variance. The second harmonic accounted for only 0.21% of the variance and none of the next 10 harmonics includes a portion greater than 0.02%. So, for many purposes, the first harmonic is sufficient to explain the trend of the average data, probably because many variations have been damped out through the twenty-four year averaging.

From the result shown above, the mean water temperature at the VIMS pier roughly can be described by a simple sinusoidal curve with a 365 day period, a 240° phase lag, an average temperature of 15.57 C and an amplitude of 11.59 C. Fourier coefficients were calculated by equation 3-3 for the first to the thirteenth harmonic. The principal results from the Fourier analyses of the temperature time series are presented year by year in Table 1. The first harmonic for each year's record has very limited phase angle variation but this is not true for higher harmonics. The first five harmonics accounted for most of the variance (Table 2). It can be noted that the second through fifth harmonics account for an additional 0.8 to 3.0 percent of the variance. Because the phase angles are scattered for successive years, random phenomenon are probably included in the record.

Table 1. Amplitude (C) and phase angle (radians) estimates for the first five harmonics of daily water temperature series for each year during 1954-1977.

Year	Average	First		Second		Third		Fourth		Fifth	
		Amp.	Pha.	Amp.	Pha.	Amp.	Pha.	Amp.	Pha.	Amp.	Amp.
1954	15.66	11.43	4.24	1.32	4.73	0.59	0.14	0.34	0.86	0.43	4.09
1955	15.55	12.16	4.23	0.95	4.85	0.23	3.33	0.42	0.03	0.54	1.94
1956	15.19	11.26	4.15	0.14	2.47	0.68	4.39	0.96	3.36	0.23	2.89
1957	15.46	10.85	4.24	0.74	4.95	0.78	1.80	0.33	5.31	0.99	3.43
1958	14.66	12.19	4.15	0.67	3.25	0.35	1.81	0.66	5.04	0.22	5.08
1959	16.61	12.41	4.20	1.27	4.53	0.53	6.19	0.15	3.32	0.18	2.74
1960	15.42	12.18	4.18	0.41	2.88	1.12	0.41	0.69	5.68	0.73	4.77
1961	15.55	11.96	4.13	1.09	4.57	0.32	3.86	0.77	3.50	0.49	1.70
1962	15.14	11.90	4.23	0.85	3.87	0.62	0.17	0.53	5.24	0.17	0.57
1963	15.06	12.07	4.20	1.00	3.84	0.82	3.44	0.31	5.75	0.57	5.85
1964	15.33	11.17	4.19	0.71	3.20	0.26	2.84	0.64	3.48	0.50	4.11
1965	15.13	11.30	4.15	0.25	3.31	0.83	1.00	0.20	3.36	0.47	2.40
1966	14.76	11.31	4.18	0.21	3.54	0.45	2.92	0.34	2.18	0.16	1.30
1967	14.73	10.73	4.18	0.74	6.25	0.09	5.44	0.58	0.88	0.41	6.09
1968	15.24	12.26	4.21	1.08	4.18	0.10	4.30	0.41	0.25	0.34	0.38
1969	15.05	12.34	4.22	0.58	3.50	0.21	0.40	0.36	6.22	0.64	4.96
1970	15.46	12.20	4.14	1.01	3.80	0.27	0.11	0.51	3.25	0.27	2.71
1971	16.47	11.76	4.13	0.90	4.25	0.54	5.13	0.11	2.23	0.29	1.24
1972	15.57	10.61	4.12	0.43	5.74	0.72	1.56	0.22	0.28	0.25	2.11
1973	16.53	11.52	4.12	0.43	4.94	0.25	0.65	0.43	2.32	0.21	4.01
1974	16.64	10.01	4.23	0.53	0.04	0.48	0.64	0.37	4.43	0.55	5.75
1975	16.84	10.95	4.14	0.42	1.17	0.94	5.86	0.93	4.90	0.75	0.37
1976	15.32	11.14	4.36	1.82	5.41	0.35	5.11	0.63	2.03	0.75	3.05
1977	16.30	12.98	4.27	1.50	4.24	1.27	2.87	0.77	2.77	0.42	3.76
mean	15.57	11.59	4.19	0.53	4.39	0.10	0.73	0.08	4.14	0.06	3.75

Table 2. Analysis of variance for water temperature data.

Year	Total Variance	1st Harmonic		2nd to 5th Harmonic		6th & Higher Harmonic	
		Var.*	%**	Var.*	%**	Var.*	%**
1954	67.97	65.39	96.20	1.21	1.79	1.37	2.01
1955	75.93	73.98	97.43	0.74	0.95	1.23	1.62
1956	66.00	63.51	96.22	0.73	1.13	1.76	2.65
1957	61.71	58.92	95.48	1.14	1.84	1.65	2.68
1958	76.27	74.40	97.55	0.52	0.70	1.32	1.75
1959	79.27	77.09	97.25	0.99	1.23	1.19	1.52
1960	76.91	74.29	96.59	1.23	1.60	1.39	1.81
1961	74.07	71.60	96.67	1.06	1.44	1.39	1.89
1962	72.76	70.85	97.37	0.71	0.99	1.20	1.64
1963	74.84	72.86	97.41	1.06	1.44	0.88	1.17
1964	63.86	62.42	97.74	0.62	0.97	0.82	1.29
1965	65.35	63.92	97.81	0.51	0.78	0.92	1.41
1966	65.62	64.01	97.55	0.21	0.30	1.41	2.15
1967	59.03	57.60	97.58	0.38	0.64	1.05	1.78
1968	76.82	75.19	97.88	0.75	0.97	0.88	1.15
1969	77.26	76.16	98.58	0.47	0.61	0.63	0.87
1970	76.09	74.45	97.85	0.73	0.96	0.91	1.19
1971	71.20	69.20	97.19	0.61	0.85	1.39	1.96
1972	57.65	56.37	97.78	0.41	0.79	0.87	1.49
1973	67.94	66.40	97.73	0.24	0.36	1.30	1.91
1974	51.70	50.10	96.91	0.49	0.95	1.11	2.15
1975	62.27	59.95	96.27	1.26	2.03	1.06	1.70
1976	65.21	62.41	95.29	2.21	3.40	0.86	1.31
1977	88.64	84.32	95.13	2.33	2.62	1.99	2.25

* The variance attributed to the specified harmonic

** The portion of the total variance attributed to the specified harmonic

It is interesting to see whether the 2-hour data would produce the same result. In order to better understand the variations derived from the different samples, one of the most complete data sets was chosen. There are measurement every 2 hours through the entire year 1974 except for July 23 & 24. Harmonic analysis was done for the daily averages (the mean value of the daily maximum and minimum), the 2-hour values, and the daily average of the 2-hour values. The last time series has a smaller portion of the total variance contributed by the first five harmonics and greater total variance. It is apparent that more variance is distributed to the higher harmonics (Table 3). Daily averages calculated in the two different ways showed similar results for each harmonic. This result gives us confidence that we needn't be concerned with the method of calculating the daily average values if we want to observe the long term tendency.

The harmonic analysis has been applied to the entire twenty-four year record. The period, amplitude, phase angle, variance and percent of total variance for all harmonics which have a percentage of variance more than 0.05 are shown in Table 4. Except for the first two, the lower order harmonics account for small variances. The 24th harmonic, the annual cycle, includes most of the variance of the record.

Table 3. The comparison of harmonic analysis for different sampling intervals of water temperature in 1974.

	1974	Daily Average (mean of max. and min.)	** Daily Average (2 Hr Value Avg.)	*2 Hr Values
	avg.	16.64	16.60	16.57
	total variance	51.70	51.48	52.23
First Har.	amp.	10.01	9.99	10.04
	phase angle	4.23	4.23	4.24
	variance	50.10	49.97	50.41
Second Har.	amp.	0.53	0.52	0.52
	phase angle	0.04	0.09	0.02
	variance	0.14	0.13	0.13
Third Har.	amp.	0.48	0.46	0.43
	phase angle	0.64	0.65	0.59
	variance	0.11	0.10	0.09
Fourth Har.	amp.	0.37	0.37	0.42
	phase angle	4.43	4.45	4.50
	variance	0.07	0.07	0.08
Fifth Har.	amp.	0.55	0.53	0.55
	phase angle	5.75	5.78	5.74
	variance	0.15	0.14	0.15

** 365 daily averages are calculated by each 2 hr value for that day

* There are 365x12=4320 each 2 hr values for that year

Table 4. The harmonic analysis of 24 year daily mean water temperature record.

Number of Harmonic	Period (day)	Amplitude (C)	Phase Angle (radians)	Variance (C^2)	Percentage of Variance
1	8760	0.53	2.15	0.14	0.21
2	4380	0.45	3.78	0.10	0.15
8	1095	0.31	2.35	0.05	0.07
10	876	0.38	0.13	0.07	0.10
12	730	0.33	2.73	0.05	0.08
13	674	0.38	2.72	0.04	0.06
21	420	0.43	4.37	0.09	0.13
22	398	0.30	5.88	0.04	0.06
23	381	0.31	6.01	0.04	0.07
24	365	11.59	4.19	67.22	95.84
45	195	0.25	4.30	0.03	0.05
47	186	0.26	5.42	0.03	0.05
48	183	0.53	4.40	0.14	0.20

Another way to use harmonic analysis to determine the relative importance of different periodic components is to use the corresponding amplitudes. The half value of the sampling number multiplied by the corresponding amplitude squared is named the "intensity" for that frequency $I(f_i) = \frac{N}{2}\ (\text{amplitude})^2$. When those intensities are plotted against their corresponding frequencies, the figure is called a "periodgram", which shows the relative amount accounted for by a frequency band. This method was applied to the residual daily water temperature record (original series minus the annual cycle) to find the important cycles. In Figure 7, the intensities for the first 50 frequencies are shown. Some obvious peaks occur in this figure. However, the very strong fluctuation in this figure makes it hard to distinguish which ones are important. Many isolated peaks may or may not show their significance in a practical situation. Fishman (1969) has pointed out that this method was inadequate for estimating the relative importance of periodic components for a wide variety of phenomena. The two principal reasons for this inadequacy were first, the departure of the fixed period from reality. Many phenomena do exhibit recurrent behavior, but few show any regular periodic appearance. The second reason the periodgram failed stems from the inordinately large number of periodic components that are suggested as being important. It was hardly possible to reconcile all these peaks with what was actually observed. This implies

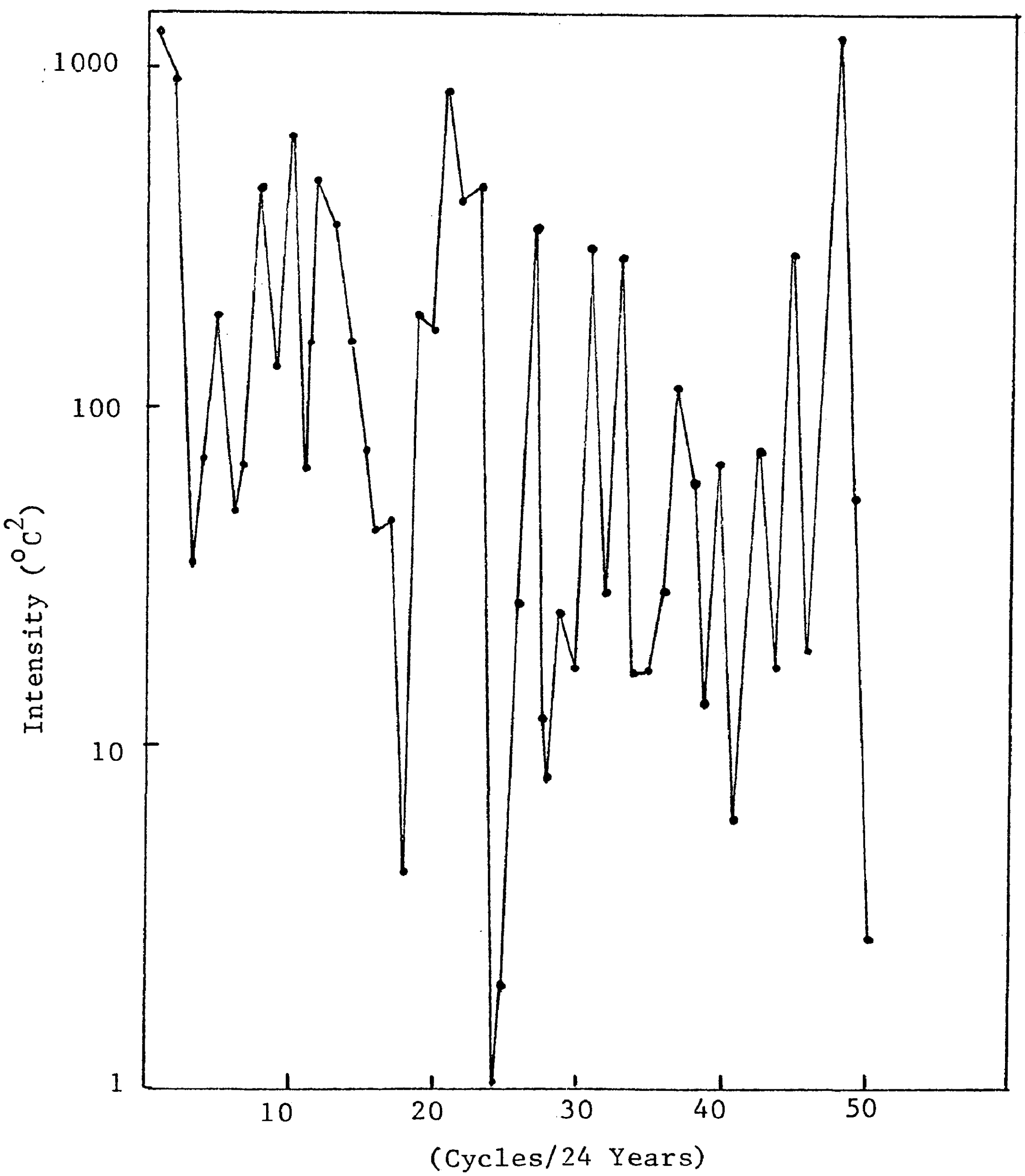


Figure 7. Periodgram for the water temperature residual series(mean and first harmonic removed).

that if some phenomenon is not an integer harmonic of the fundamental period, the calculated intensity peak will disappear. Therefore, the variance spectrum is needed to make up for these disadvantages.

In summary, the harmonic analysis has shown that the annual cycle of water temperature accounts for more than 95 percent of the total variance for either an individual year, the twenty-four year record or the twenty-four year mean. The amplitude and phase angle for the yearly harmonic were stable from year to year. The higher order harmonics (second or higher) show great variation in both amplitude and phase angle from one year to another. However this technique fails to explain the importance of phenomena for which the period is not an integer harmonic of the fundamental period of the record. This is especially true when a band of frequencies, rather than a single frequency, is important.

CHAPTER III

THE CYCLICAL AND TREND COMPONENTS OF WATER TEMPERATURE VARIATIONS

It is desirable to know the importance of the cyclical and trend components. The trend component indicates the evolutionary change that occurs in a time series over long time intervals. It is revealed primarily as a changing mean level around which the remaining components fluctuate with different degrees of regularity.

The cyclical component describes successive advances and declines, and may include more than one cycle. Because cycles may be superimposed, it is difficult to observe them by visual inspection of the time series. They may or may not follow exactly similar patterns after equal intervals of time.

In this chapter, those significant components will be described by variance spectrum. In addition, after some significant components have been found, we will seek to define the causal relationships with some physical phenomena such as solar activity. Such a study may lead to an improved understanding of the different physical processes and their role in determining the variation of water temperature.

Finally, a table will show the intensity of those components which contribute to this twenty-four year record.

In the last chapter some relationships between the various harmonics and water temperature variations were presented. But if there are important frequencies which are not harmonically related to the length of the series, then we must find another method to analyze those variations. An appropriate tool to solve this problem is called power spectrum or variance spectrum. The power spectrum curve shows how the variance is distributed with frequency. The way from the time domain of the variance to the frequency domain is the Fourièr transform of the autocovariance function. In other words, the variance spectrum is the transformation from a time-based to a frequency-based distribution through the autocovariance-function. Low frequency pass filters or high frequency pass filters can be used to choose the frequency needed.

In statistical theory, the correlation between neighbors with different spacing plays an important role and describes the behavior of a time series. The covariance between Z_t and Z_{t+K}, the values separated by K intervals of time, is called the autocovariance of lag K and is defined by

$$R(K) = \sum_{t=1}^{N-K} \frac{(Z_t - \overline{Z})(Z_{t+k} - \overline{Z})}{N-K} \qquad (4\text{-}1)$$

where $R(K)$ = autocovariance coefficient at lag K

$\overline{Z}$ = the mean value of record

Z_t = the record value at time t

Z_{t+K} = the record value at time t+K

The autocovariance coefficient plotted against the corresponding lags is called the autocovariance function. Zero lag (K=0) indicates the autocovariance coefficient is equal to the total variance (i.e., $R(o) = \sigma_a^2$). The ratio of autocovariance coefficient and total variance is called autocorrelation coefficient. If both functions are positive, it means that the physical process described has a degree of positive tendency. If it has a negative value, it implies that opposite tendency will follow with a time lag of K units. If the first autocovariance value is positive this indicates that high (or low) values of temperature will tend to persist on the following day. If the autocovariance is negative, high values of temperature would be followed by low temperature values one day later, and vice versa.

Wastler (1963) described the mathematical basis for an application of spectral analysis. He states that the Fourier cosine transform is computed as

$$V_r = \Delta\tau\left(R(o) + 2\sum_{g=1}^{m-1} R(g)\cos\frac{gr\pi}{m} + R(m)\cos r\pi\right)$$

where r = 0,1,2,...m

$$\Delta\tau = \begin{cases} \frac{2}{m} & r=0,m \\ \frac{1}{m} & 1 \le r \le m-1 \end{cases}$$

where V_r = the estimated power spectrum

R(m) = the autocovariance function with m day lags.

When these estimated values are plotted against the frequency, it makes apparent the dominant periods for this time series. The area under this curve equals the total variance of the record. Actually the estimated function is not always the best approach of the spectrum. It usually is transformed by a linear filter to smooth it and focus on the low frequency or high frequency values which one needs. The highest frequency of estimate which limits the events seen by a given sampling frequency is known as the Nyquist frequency (i.e., $f_N = \frac{1}{2}\,\Delta t$). In other words, the highest frequency cannot exceed half the sampling frequency. Although power spectrum has a characteristic to discover a hidden significant frequency, it is not able to measure the phase angle for that frequency.

Figure 8 indicates the autocovariance function of the twenty four year record after removing the 24th harmonic and record mean. The 24th harmonic, the annual cycle, removed 95.84 percent of the total variance. This figure shows the relationships for the first 720 lags. The first 80 autocovariance coefficients have decreasing positive values with an exponential decay. After that the autocovariance coefficients show approximately a sine wave form with damped amplitude and with increased lag. Since the autocovariance function has big positive values every 180 lag number (e.g., 180,360,540,etc.), the record probably contains a half year cycle. The first 217 autocovariance

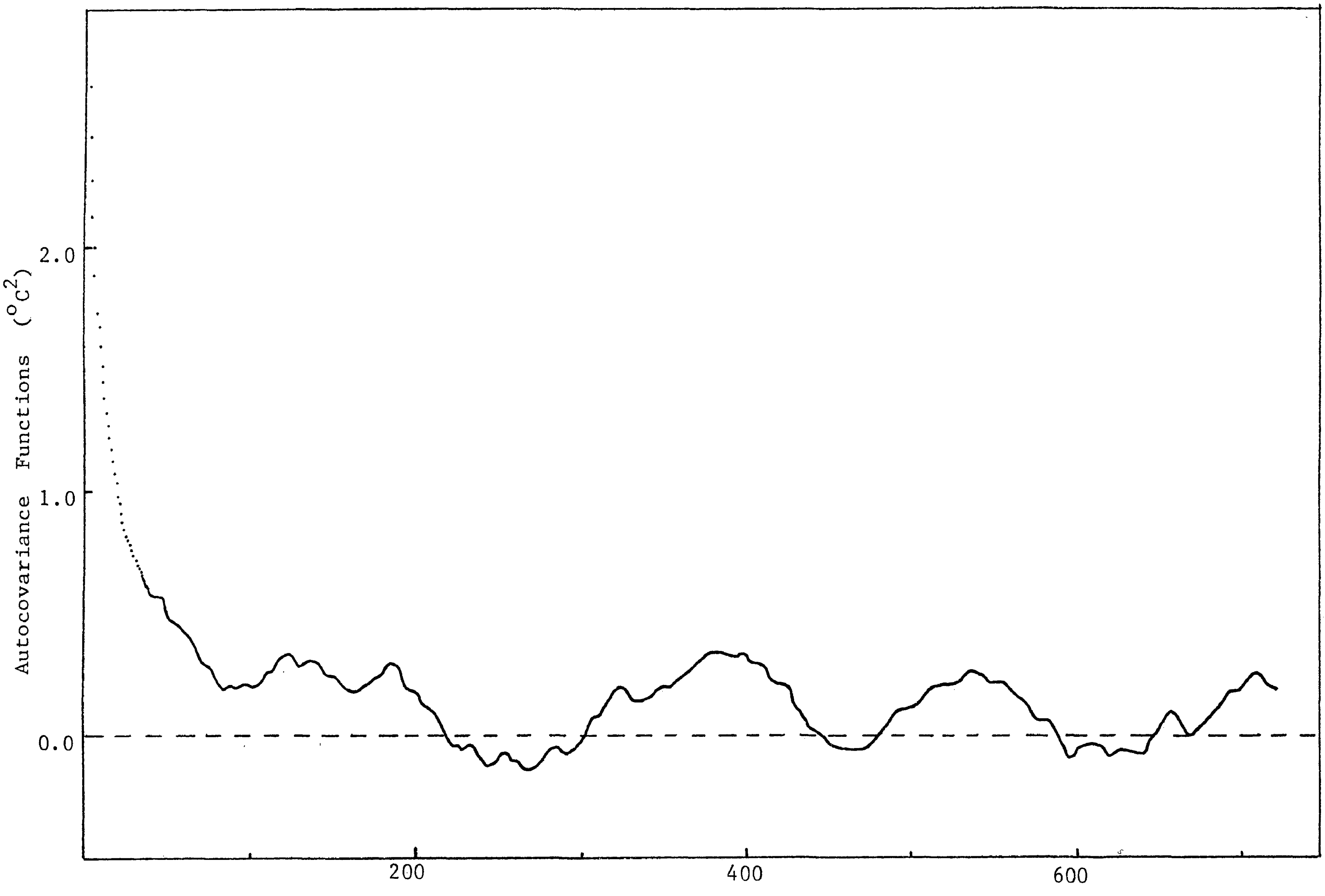


Figure 8. The autocovariance function of the 24 year daily mean series with the annual harmonic and record mean removed.

coefficients have positive values which means that temperature readings will follow the same tendency for these lags. The highest values of the later autocovariance coefficients appear at 378 day lag (positive) and 268 day lag (negative). This figure provides useful information to point out the relative tendency of water temperature residuals series.

With the variance spectrum technique it is possible to determine weak cyclical components for a particular time series record. If these cycles express sufficient regularity in their respective periods of oscillation, one would expect to observe local peaks and large values of variance in the vicinity of their corresponding frequencies. The narrower the peak, the more regular and discernible the cycle will be. The cyclical component often is so irregular that the corresponding spectrum shows only a concentration of variance over the entire low frequency range (Fishman, 1969).

In order to determine the significant peaks and periods with period less than two years, the maximum lag number is chosen as 365. In other words, the residual variance (annual component removed) will contribute over a frequency from 0 to 365 for this twenty-four year record. Gunnerson (1966) stated that significant values at zero frequency are a measure of the variance associated with secular variations which are revealed as long term increases or decreases. In addition, he mentioned that some random of nonrecurring phenomena are contained in the zero frequency variance. Therefore, it is highly significant that variance at zero frequency is in accord with the presence or absence of significant trends.

The variance spectrum of the residual daily temperature series for periods less than 2 years is shown in Figure 9. The dashed line represents the original estimated spectrum and the solid line indicates the smoothed estimation. Semi-log paper is used so that the high frequency band can be exhibited more clearly. Several peaks (182.5, 60-66, and 23.5 days) are apparent. However, a significance test with the 95 percent probability limits indicates that only the semiannual cycle is important. It should be mentioned that the absence of the peak at a very low frequency (i.e. period longer than half-year) doesn't mean the absence of a cyclical phenomenon for that range. To increase the resolution, one must either increase the maximum lag number (i.e. a wider range is observed) or filter out the high frequencies. The second approach (Thomann, 1967) was used to compute the monthly residual mean, which results in a new residual series of 288 months (24 years).

In order to gain more information from this record, the variance spectrum of the monthly mean of the residual series was computed with the maximum lag number equal to 144. In other words, the first value has the period of twenty-four years. The results (Fig. 10) show only four peaks above

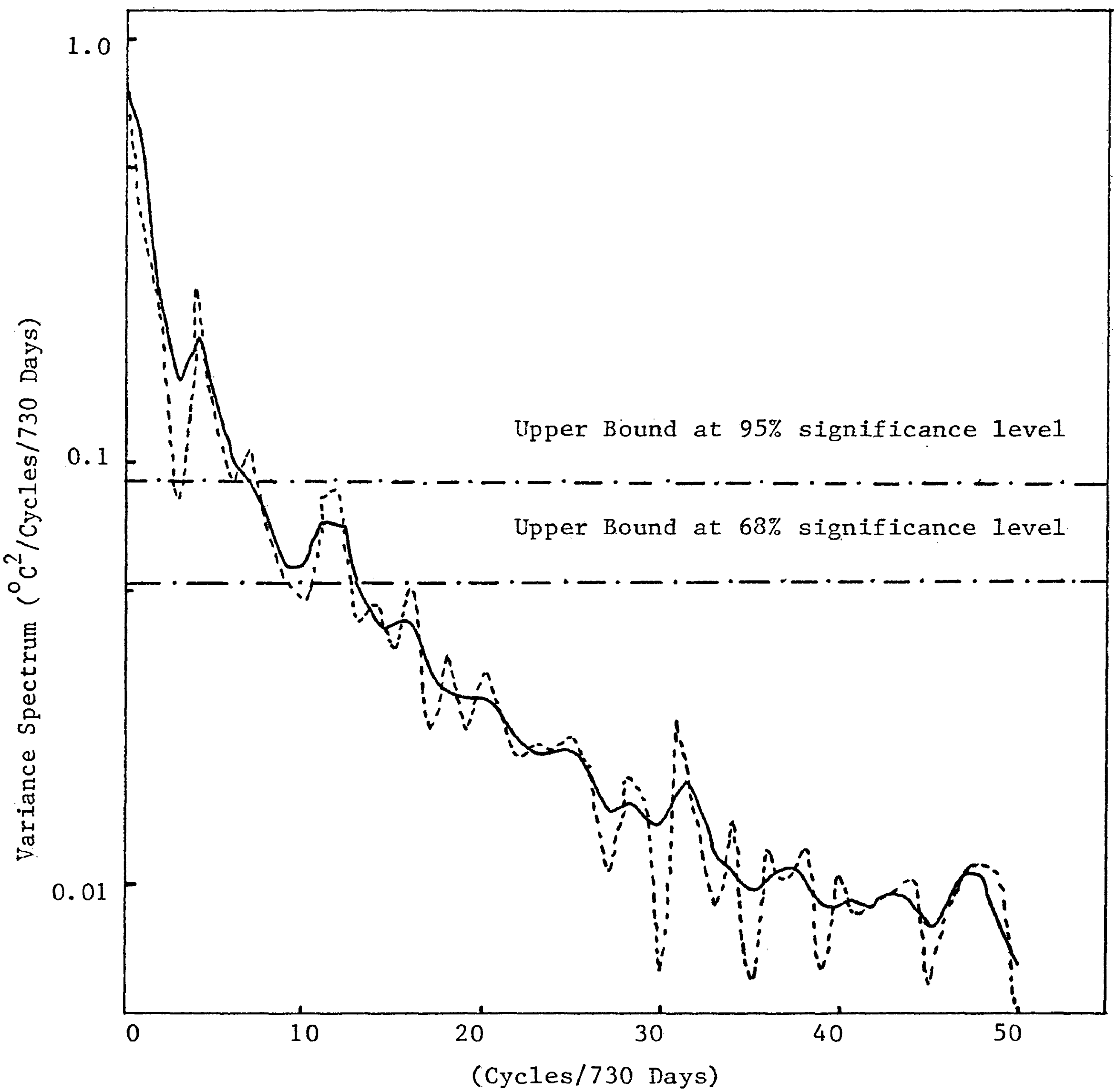


Figure 9. The power spectrum of the residual temperature series (annual cycle and mean removed) for periods less than 2 years.

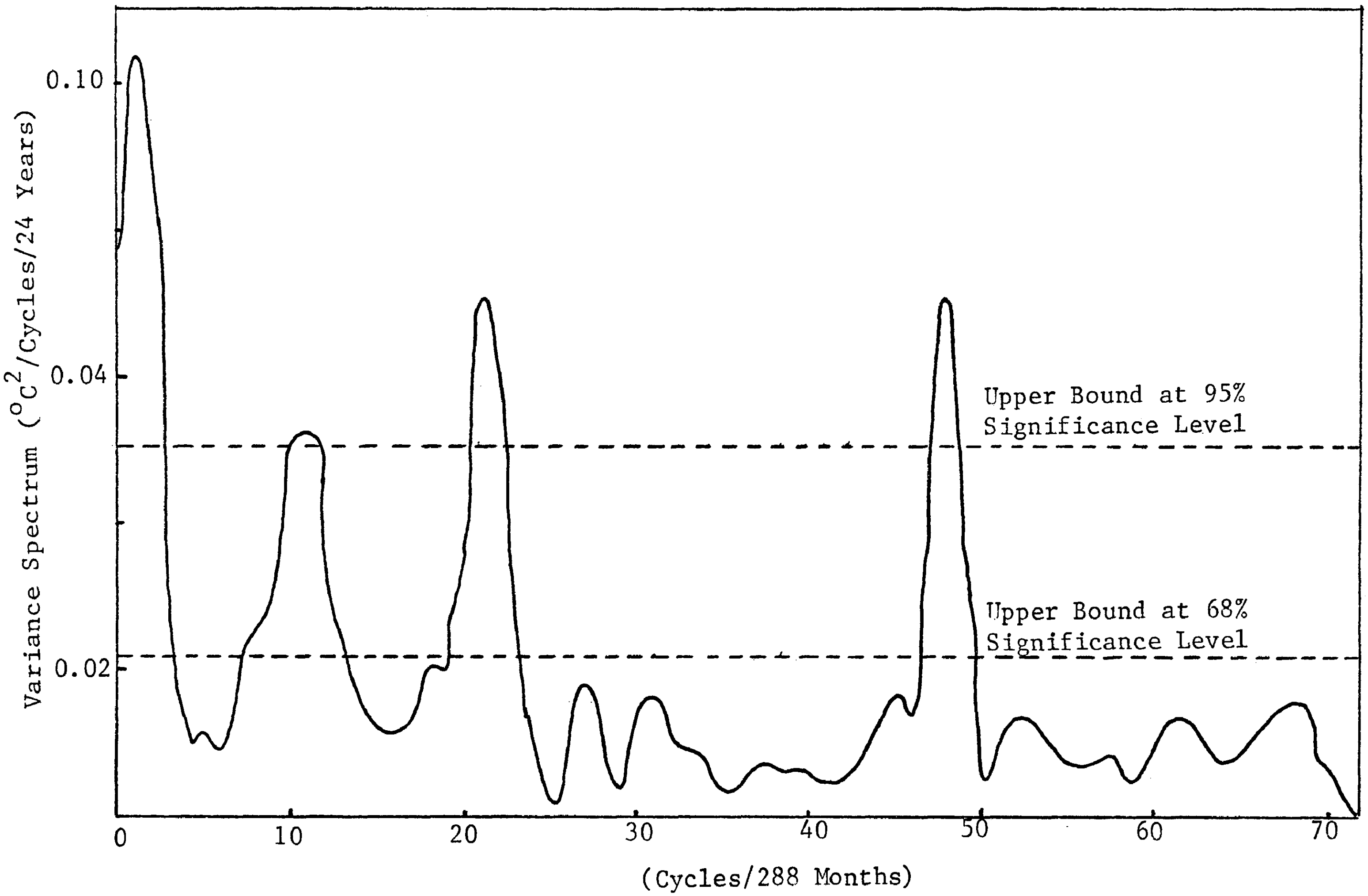


Figure 10. The power spectrum of average monthly residual temperature series.

the 95 percent significance level with periods of 24 years, 26 months, 14 months and 6 months. Note that the biggest peak of this figure has no definite period since the second frequency (i.e. 12 year period) also accounted for a large portion of the variance.

The trend component is not obvious in this long-term cycle if it does exist. The variance accounted for by the zero frequency has a nonsignificant value (less than 0.1 percent of total variance). Therefore, it can be concluded that most of variance at very low frequency is contributed by the cycle with an approximate 24 year period. The trend component almost can be ignored in this record or it can be regarded as a very slight increase in the mean value.

Another simple and fast method to show this long-term cycle is to use the 12 month moving average to filter out short term cycles; the variance spectrum was calculated for the new series (Fig. 11) and only 2 peaks remained after this process. In Figure 12 the 12 month moving average and its smoothed curve are shown. Except for the mid-portion of the series, strong apparent variations of water temperature occur. From the end of 1972 to the middle of 1976 is seen as a relatively hot period. A feature of the period from 1962 to 1970 is a mean temperature about 0.5 C below the overall record mean of about 15.5 C.

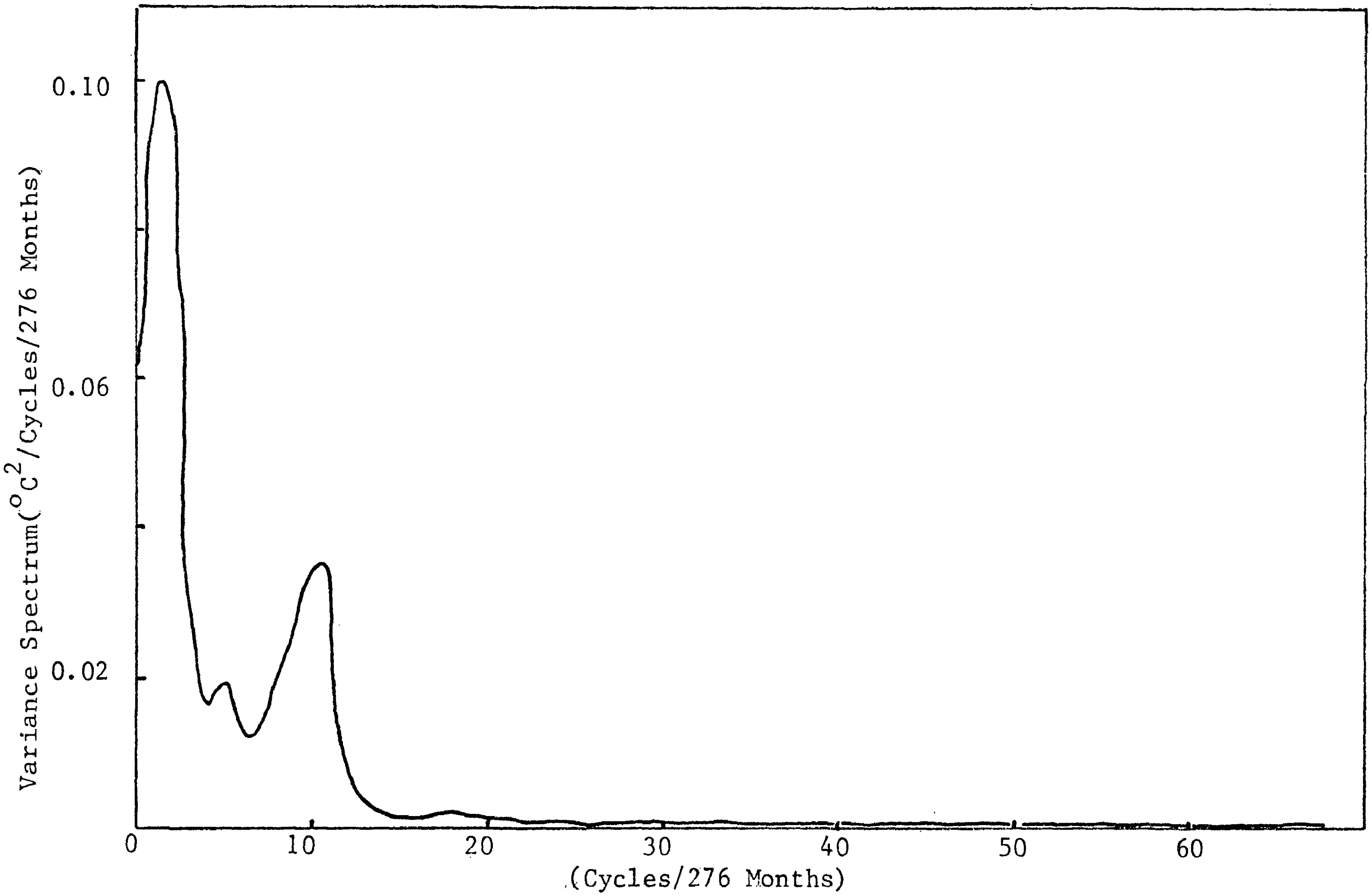


Figure 11. Variance spectrum of the month moving average temperature series.

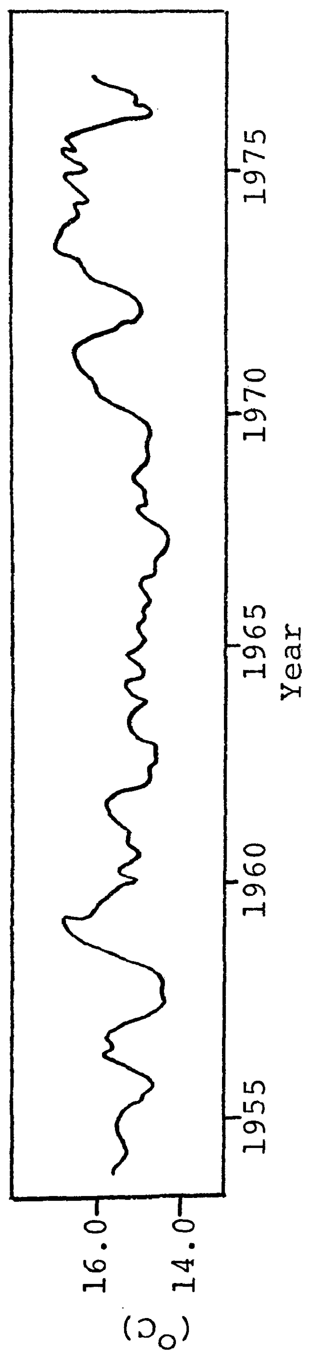


Figure 12. The 12 month moving average for the monthly mean water temperature series.

In summary, the variance spectrum has shown that there are several important cyclical components of water temperature and that the trend component is very weak. Those results are summarized in Table 5.

Factors Controlling the Cyclical Components

Since some important signals have been noted in the variance spectrum, it is possible to seek some physical phenomena which might cause this behavior. The sunspot cycle often is regarded as one of the basic mechanisms which can affect phenomena such as the air temperature on earth. The lunar cycle might be another factor which produces fluctuations. In this study, we have concentrated on those "external" factors of recurring nature which may affect the water temperature record. The stages of investigation which follow will be: 1) the periodic behavior of sunspot numbers, 2) sunspot and/or solar cycle effects on the variability of water temperature, and 3) fluctuations on lunar cycle expected to be seen in the water temperature record.

(1) Sunspot Behavior

A sunspot is "A temporary cool region in the solar photosphere that appears dark in contrast to the surrounding hotter photosphere" (Kaufmann, 1975). Counts of the number of sunspots visible at any given time have been recorded since the time of Gallileo (1610). By the mid-1800's, it had become clear that the number of sunspots varies periodically. The

Table 5. The total variance of 24 years water temperature series contributed by the trend, cyclical, seasonal, and irregular components.

Component	Period (year or month)	Intensity (percentage of total variance)
trend	not obvious	less than 0.10
cyclical	around 24 years	0.44
	26 months	0.21
	13-14 months	0.30
	6 months	0.24
	around 2 months	0.06
seasonal	12 months	95.84
irregular	----------	2.81

sunspot cycle is defined as being from one minimum to another for the sunspot number. The yearly mean sunspot number for years 1850 to 1973 is shown in Figure 13. An 11 year period has occurred, and the number reached a record high value in 1959. However, the occurrence of maxima is not strictly periodic and there often is a delay in the maximum (or minimum) based on the distribution of sunspots in solar latitude and the magnetic field characteristics (Zirin, 1966). Some scientists believe the solar cycle has a 22 year period because the magnetic field reverses each 22 years. Each sunspot cycle may express different activity; therefore each has been given a number beginning with the middle 1800's. Recently, the sunspot maxima have occurred in 1948, 1959 and 1970, and the minimum values in 1954, 1964 and 1976.

The periodicity of sunspots number is of interest to many researchers. Sugiura (1977) analyzed the Zurich sunspot record for the years 1800-1975 using the power spectrum method. Several apparent peaks for this record were at periods of 10.9, 5.1, 3.4, 2.0, 1.8 and 1.3 years. Some additional minor peaks were noted from monthly data of sunspots for years 1954-1977 (Fig. 14) at 2.0, 1.4 (17 months), 1.1 (13 months) and 0.96 (11 months) year periods.

Many investigators have described the solar-terrestrial relationship using air-temperature records. Shan (1966) used the power spectrum analysis to show that for the air

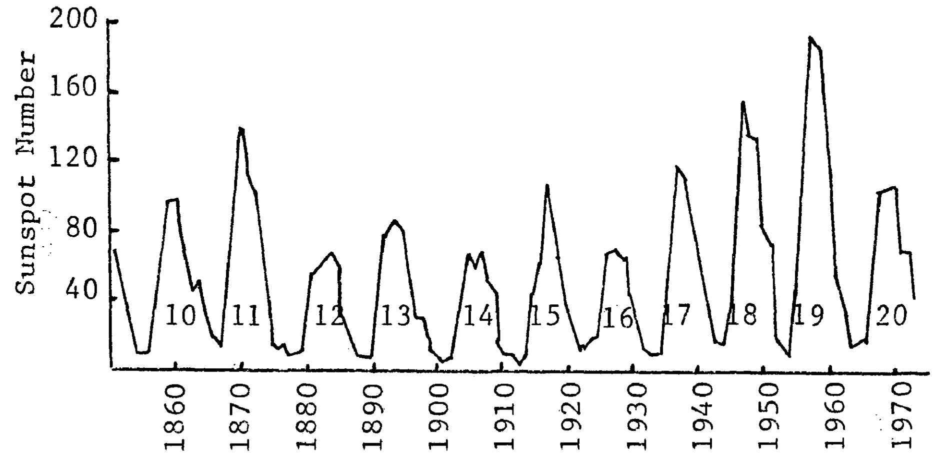


Figure 13. The number of sunspots per year from 1850 to 1973 and the sunspot cycle numbers.

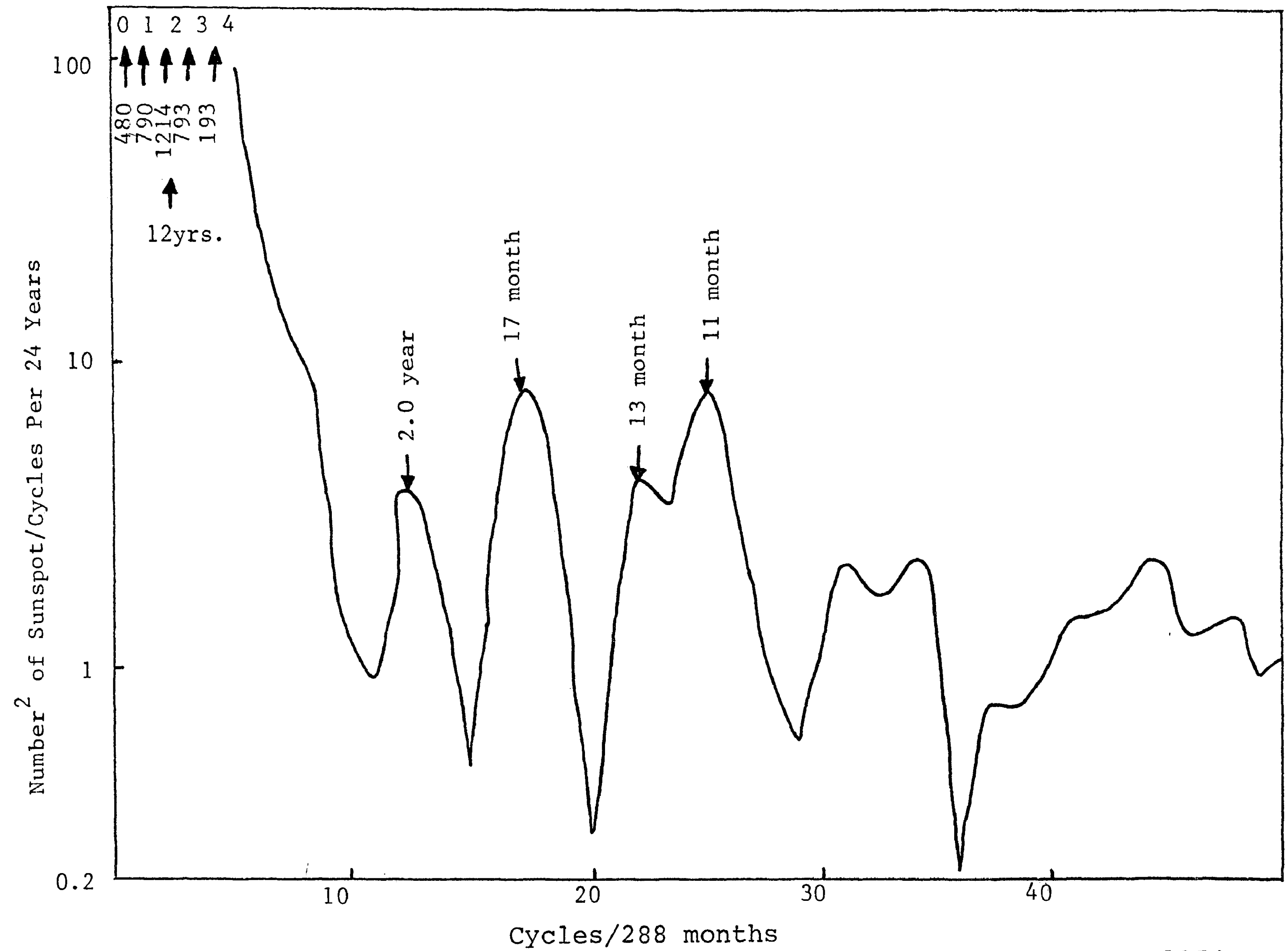


Figure 14. The variance spectrum for sunspot numbers for years 1954-1977.

temperature series at three different cities which had monthly records for over 50 years, the only significant energy in these spectrum appears at the period of 12 months. No significant energy was found corresponding to any known sunspot periodicity. Currie (1974) found the solar cycle signal in power spectra surface air temperature data from the North American continent, and showed that the period of 10.6 $\pm$ 0.3 years did exist. Gerety (1977) pointed out that cross-spectral computations, using the time series of Zurich sunspot numbers and seasonal temperature and precipitation records, indicate that these series are uncorrelated at individual stations with short-term records and when grouped together into latitude bands. Recently researchers have been concerned that volcanic dust might affect the temperature record (Schneider 1975, Mass 1977).

After Kalinin (1954) mentioned that a quasi-periodic geometric variation with a period of about 2 years, and the discovery of an oscillation of the zonal wind component in the equatorial stratosphere of slightly more than 2 years in length by Reed and Rogers (1962), many researchers began to reexamine the periodic behavior of sunspot cycle. Shapiro and Ward (1962) pointed out the possibility of a spectral peak at the period of 25 months and suggested this cycle might be attributed to the solar ultraviolet radiation. Shan and Godson (1966) have shown the existence of the 26 months oscillation in the equatorial stratosphere. Currie

(1973) interpreted the spectral peak near 2.15 year, as the ninth and fifth harmonics of the double solar cycle and the sunspot cycle in the geomagnetic horizontal and vertical components. Sugiura (1977) demonstrated the existence of highly correlated quasi-biennial variations in the geomagnetic field and in solar activity.

According to above information, it can be concluded that the solar activity, such as the double sunspot, sunspot and quasi-biennial cycles, might affect terrestrial features.

(2) The Sunspot Cycle and its Effect on Water Temperature

(a) Double-Sunspot Cycle: 22 years

It has been shown that the water temperature residual record for years 1954-1977 has a significant component with period around 24 years. This relation is examined by calculating the correlation coefficient between yearly mean water temperature and sunspot number (Fig. 15). The coefficient is so low (-0.223) that it is concluded that there is no direct influence from sunspot activity on water temperature. More precisely, there is no strong linear correlation between these yearly data, although it is possible that the non-linear effects exist. Perhaps, as Schneider (1975) noted solar radiation does not have a linear relationship to sunspot number. He emphasized that solar radiation increases with sunspot number, but eventually reaches a maximum and subsequently decreases.

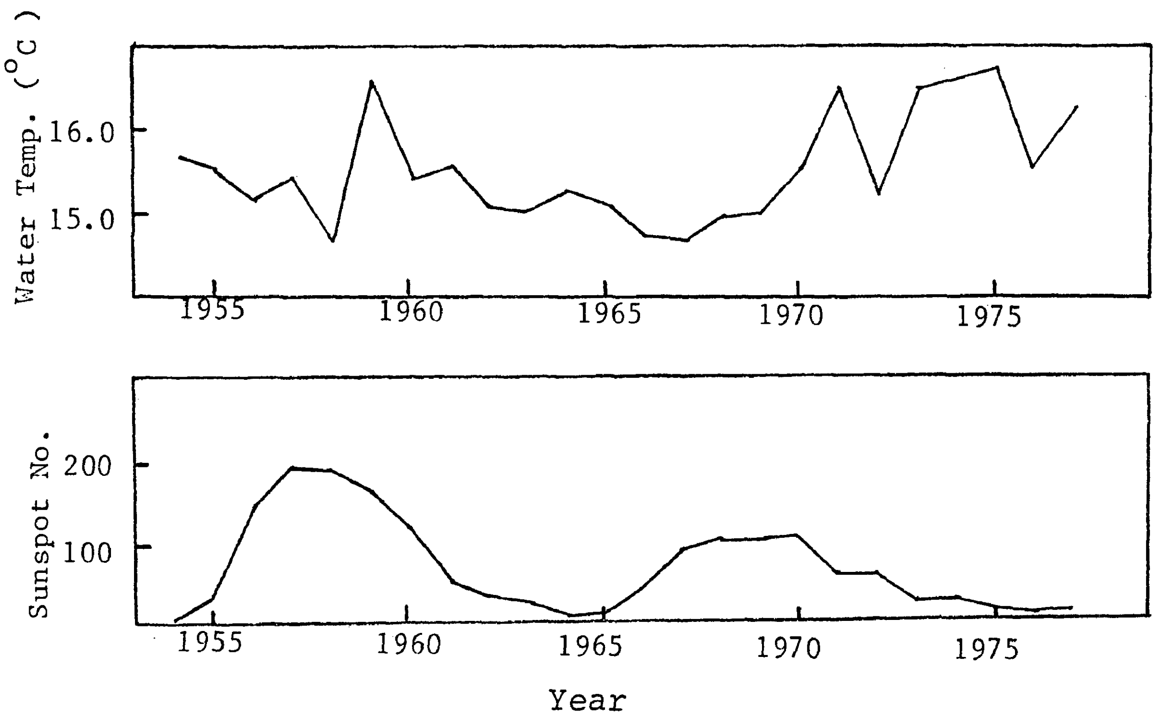


Figure 15. Yearly mean water temperature and sunspot number. (The correlation coefficient is -0.223).

In order to define the variation of water temperature at the same period as the solar cycle (22 years), the variance spectrum method again is used to examine the significance of the water temperature oscillation. The variation of water temperature for years 1954-1975, 1954-1964, and 1964-1975 is shown in Figure 16. Those peaks thought to be significant in sunspot records exist during all three periods. The size of the 22 year peak suggests that the solar cycle can effect water temperatures. In fact the variance accounted for by the 22 year peak is more than that accounted for by the 24 year peak previously.

Water temperature variations might be related to the double-sunspot cycle. Chernosky (1966) suggested that the last half of an even-numbered sunspot cycle is more active than the first half, and that the converse is true for the odd-numbered cycles. The years 1962-1969 had more stable behavior of water temperature and, perhaps, this might be attributed to reduced sunspot activity.

(b) Sunspots Cycle: approximately 11 years

In Figures 10 and 16a, the second frequency (period around 11 years) has high values. With the limited length of record, though, it is hard to determine whether it contains both long cyclical component or not. However, as an additional tool in evaluating the reality of the result, the 24 year record was re-analyzed by variance spectrum in 10 and 12 year segments. Those 2 segments of water temperature

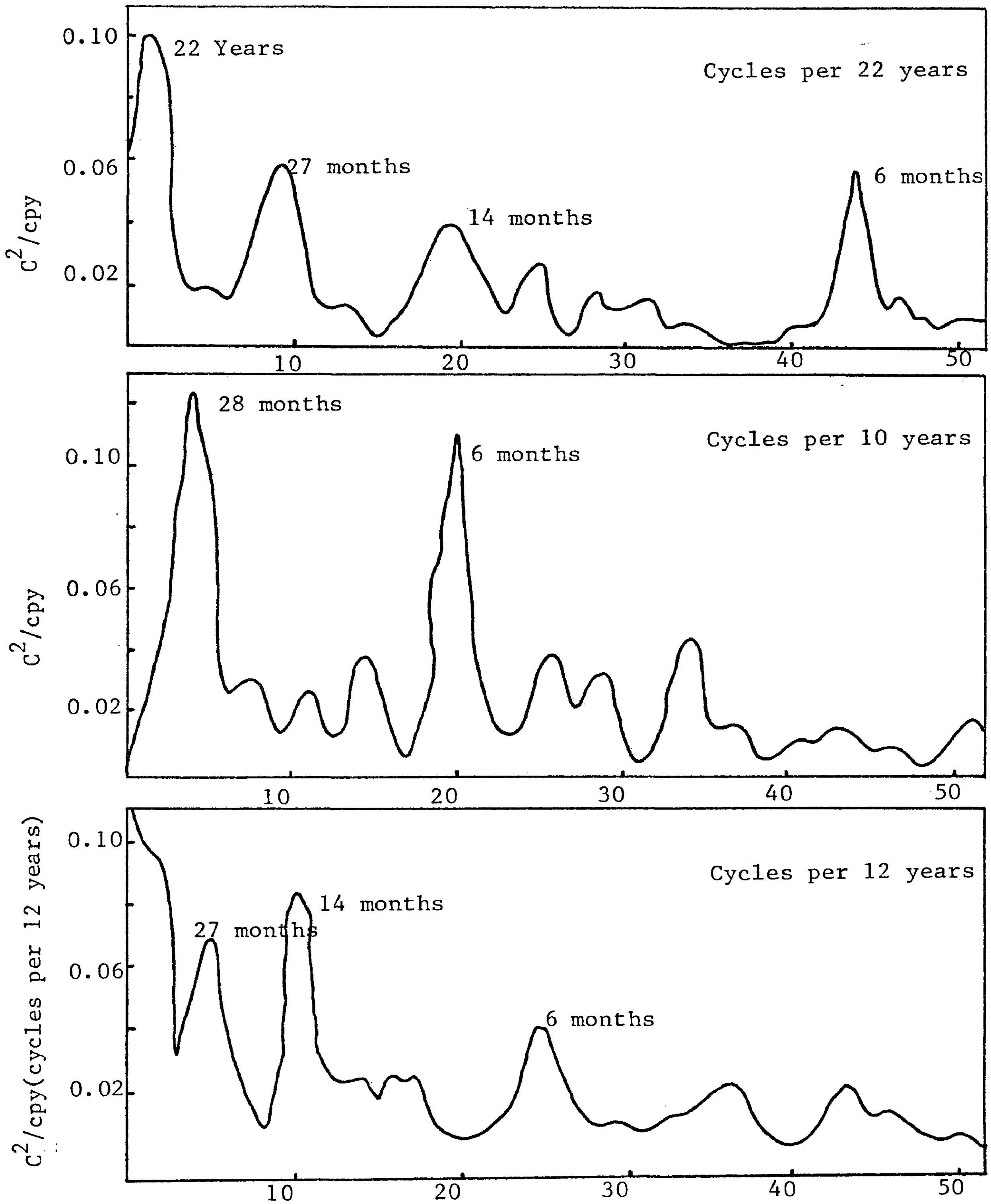


Figure 16. The variance spectrum of water temperature residual series for years (a) 1954-1975, (b) 1954-1964 and (c) 1964-1975.

record are chosen to correspond with the sunspot cycles in 1954-1963 and the following 12 years. If in both records the first frequency accounted for significant variance, it means that those two sunspots cycles affect the water temperature individually. Non-significant variance was accounted for by the first frequency for the first 10 year period (Fig. 16) but the first frequency accounted for more variance during the second segment of the record. Therefore, apparently there is no significant variation of water temperature corresponding to individual sunspot cycles.

(c) Semiannual Variation: 6 months

The semiannual variation is not explained well by the spectrum of sunspot numbers. Chernosky (1966) investigated the effect of double sunspot cycles on terrestrial magnetic activity during 1884-1963. He stated that the semiannual maxima in geomagnetic activity may be due either to the earth's heliographic latitude or to the sun's geographic latitude. He suggested that the semiannual variation is very little in evidence at the odd-even number minimum (such as occurs between the 19th and 20th sunspot cycles) but is well developed at the even-odd number minimum. If the water temperature is affected similarly, this semiannual variation should be greater during the years 1954 and 1976 than around the years of 1964-1966. The amplitude of the semiannual variation of water temperature and the annual sunspot number for years 1954-1977 are presented in Figure 17. The semiannual

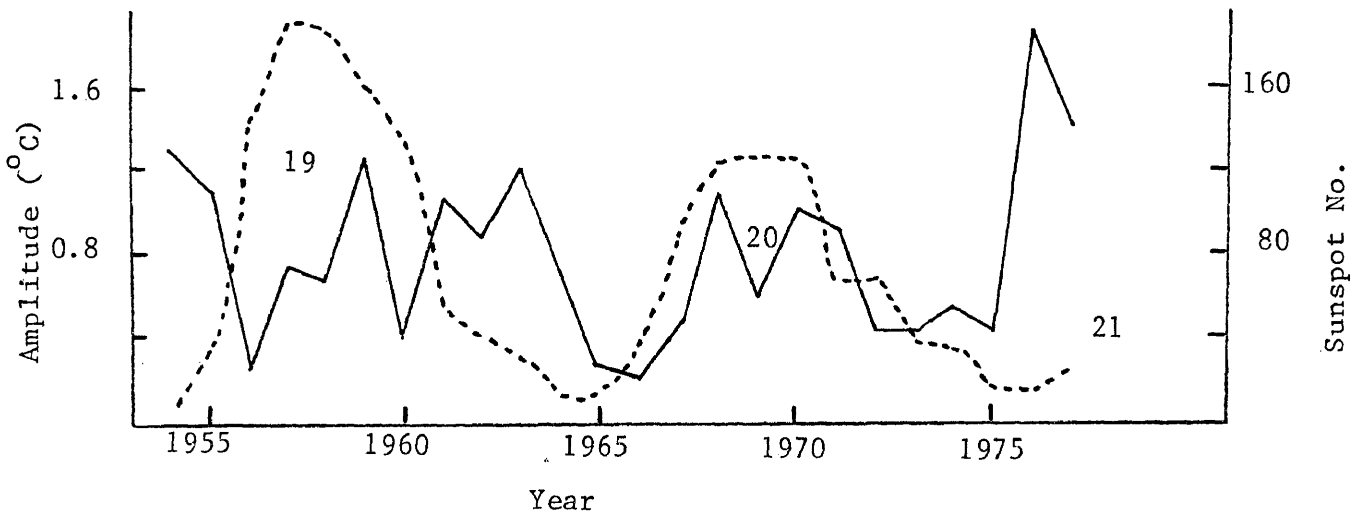


Figure 17. Amplitude of the semiannual component (solid line) and sunspot number (dotted line) during years 1954 to 1977.

component was stronger in the years of 1954, 1955, 1976, and 1977 than the years of 1965 and 1966. But this fails to explain the variation for rest of years. Chernosky (1966) also suggested that in general, the odd-number sunspot cycle has more semiannual variation than even-number sunspot cycle. Perhaps this provides a partial explanation as to why the half-year variation of water temperature appears bigger during the 19th sunspot cycle than during the 20th sunspot cycle (see Fig. 16).

(3) The Lunar Cycle.

Since the earth's rotation around the sun has a large impact on the water temperature record, perhaps the lunar cycle affects the water temperature, too. The lunar month is defined as the "synodic period which starts at new moon and ends approximately 29.53 days later at the next moon". Here, the variance spectrum is again used to examine this effect (Lund, 1965). A segment of the variance spectrum showing the frequency ranging from 30 to 60, with lag number equal to 720 fails to show any significant peak corresponding to the lunear period (see Fig. 18). The lunar period again fails to be important when the maximum lag number is chosen to be 118.

In summary, the cyclical portion of the water temperature record contains a 22 year cycle, a 26 month 'quasi-biennial'

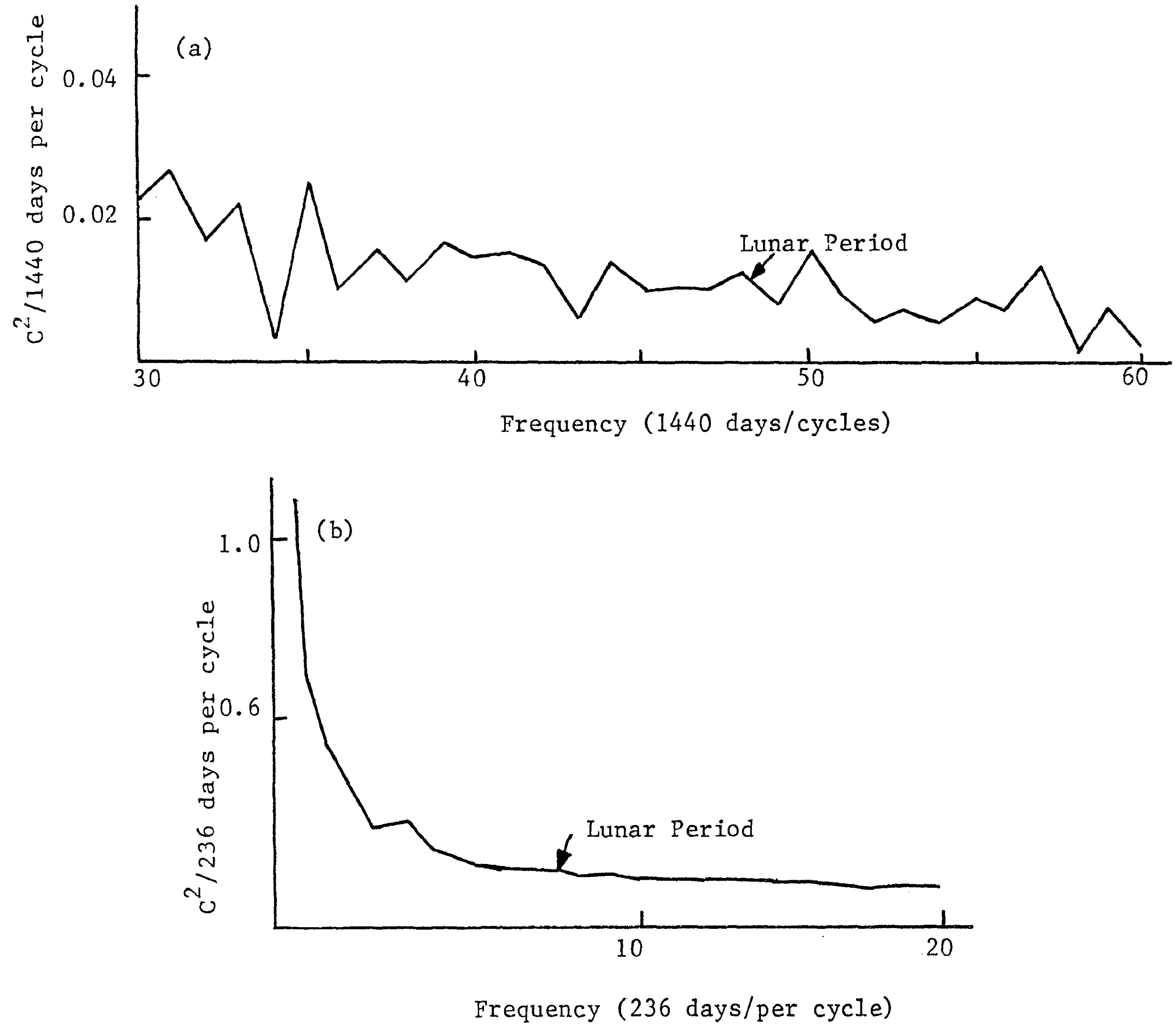


Figure 18. Variance spectra of the water temperature residual series with lags of a) 720 and b) 118.

variation, a 14 month variation and semiannual oscillations. All of those variations might be attributed to solar activity which shows similar cyclical variations. However, the daily water temperature series does not show any significant oscillation with the lunar period.

CHAPTER IV

THE IRREGULAR COMPONENT AND A PREDICTIVE MODEL

In Chapter I the long term, average values for each calendar day were presented. In Chapter II, harmonic analysis was used to demonstrate that most of the total variance for yearly series and the mean long term record is due to the annual cycle (the first harmonic). This changed slightly from year to year, because the first harmonic cannot account for random events. Also because the cyclical components discussed in Chapter III have not been defined explicitly, one cannot predict the influence of these components on future water temperature readings. One solution is to make a mathematical model which contains as many components as possible. However, the result can be very complicated and confusing. In this chapter, a simple formulation of the non-seasonal component (after the annual component and record mean are removed from the original series) will be described.

This formulation is based on the Box-Jenkins (1970) technique and provides a structured stochastic model to simulate the annual trend and the irregular components of the water temperature variation. This kind of model possesses a minimum number of parameters, may describe the stochastic process with maximum simplicity, and can include most of the total variance. The ability of this simple model to incorporate the variance of the York River water temperature time series record will be determined.

Many researchers have used stochastic and/or deterministic processes to describe the characteristics of water quality data sets. Almost all of the methods emphasize the behavior of past time series. But we also are concerned about the future readings for time dependent data. The Fourier series and the power spectrum techniques express the behavior based on the frequency domain of the time series. The Box-Jenkins method attempts to fit a model by expressing the time series as an output function which has a random input and consists of several transfer functions. This model not only can tell us something about the nature of the system generating the time series but also can be used to obtain forecasts of the future values.

The autoregressive, integrated, moving average model (ARIMA) used in the Box-Jenkins method will be explained in a later section of this chapter. We also will examine water temperature forecasts for 3 days or longer and evaluate extending the forecast to one year. The reliability of the predictions which have specified probability limits will be discussed.

Carlson and Watts (1970) have illustrated the method of identifying the appropriate form of the general autoregressive moving average model (ARMA) by use of the same autocorrelation function (ACF) used in the Fourier series analysis. In this technique the values of the parameters for the suggested model of each series are estimated and the results checked to suggest further modification of the model. McMichael and Hunter (1972) developed a model for temperature and flow in rivers using the Box-Jenkins method. This kind of model divides each data set into a deterministic and a stochastic portion. From the viewpoint of numerical analysis, it is preferable to either a purely stochastic or a purely deterministic model. It is noted that a small number of parameters in this model can substitute for and contribute a greater portion of the response than a large number of amplitude and phase angle parameters in a Fourier series. Albert and Yu (1976) examined the stochastic structure of some water quality time series. They found that the ARIMA model could provide very satisfactory results and that a first order autoregressive model produces a 99 percent reduction in the variance of the original data. A mixed first order autoregressive and first order moving average model was preferred for this data set. Huck (1974) used the Box-Jenkins method to model chloride and dissolved oxygen data. It was found that the best representation for the chloride data was an autoregressive model and dissolved oxygen was best described by a moving average process.

In this study, the York River water temperature data have been used to establish a deterministic-stochastic model using the Box-Jenkins parametric model. The deterministic portion was decided first; this portion was assumed to be the fundamental annual harmonic plus the record mean. It is necessary then to specify the order of the autoregressive model and the moving average model after observation of the autocorrelation function values and the changes in the variance of the residual series. The ARIMA process was used to fit the stochastic process. The three stage iterative procedure consisted of identification, estimation and evaluating the accuracy of model (Box and Jenkins, 1970).

Model identification includes use of the data and information on how the series was generated, and evaluating the appropriateness of the several kinds of parametric models available. Model estimation includes obtaining sets of coefficients, using different methods to approach the real data, and making the sums of square errors as small as possible.

The last step is to check the adequacy of the model and determine how it can be improved and corrected if it is inadequate. Each of these steps is described in detail in Appendix C.

Four models were selected as ones which can reasonably simulate the data. The choice was based on 1) highly similar coefficients, 2) very close values of the ratio of the sum of the residual to the initial sum of squares, 3) approximately the same Q value, and 4) inclusion of about the same amount of total variance. The characteristics of the four models are summarized in Table 6 and described in greater detail in Appendix C. Considering the principle of simplicity, Occan's Razor, the best choice is the (1,0,0) model.

ARIMA Type	Parameters	Fitted Model	Percentage of Total Variance
(1,0,0)	$\phi_1=0.91875$	$(1-0.91875B)\tilde{Z}_t = a_t$	99.4179
(2,0,0)	$\phi_1=0.91019$ $\phi_2=0.00919$	$(i=0.91019B-0.00919B^2)\tilde{Z}_t = a_t$	99.4180
(1,0,1)	$\phi_1=0.9199$ $\theta_1=-0.008$	$(i-0.9199B)\tilde{Z}_t =(i+0.008B)a_t$	99.4179
(0,2,1)	$\theta_1=0.99$	$\nabla^2\tilde{Z}_t=(1-0.99)a_t$	99.4259

Table 6. The Final Estimation for Each Possible Model.

The behavior of the (1,0,0) model can provide some understanding of the stochastic processes affecting water temperature. It implies that the deviation from the annual cycle is dominated by the deviation for antecedent neighbors and those residuals have decreasing correlation from near to far neighbors. In mathematical words, deviations from the annual cycle will decrease with exponential decay.

Once the best fit model has been selected, the forecast function can be derived using relations between present and past observed values. The minimum square error is expected to explain how accurate this model is.

One of the basic concepts of the forecast model is that the present disturbance value, $\tilde{z}_t = y_t - \tilde{y}_t$, might be expressed as a set of linear functions of weighted present and previous shocks that is:

$$\tilde{z}_t = \underline{\overline{\psi}}_o \, a_t + \underline{\overline{\psi}}_1 \, a_{t-1} + \underline{\overline{\psi}}_2 \, a_{t-2} + \ldots. \tag{4-1}$$

The coefficient of a_t, $\underline{\overline{\psi}}_o$, is always regarded as 1. If $\tilde{z}_{t+\ell}$ is the value observed ℓ days ahead and $z_t(\ell)$ is the forecast value with ℓ day lead time, the purpose of this exercise is to reduce the error between $\tilde{z}_{t+\ell}$ and $z_t(\ell)$. That is:

$$\begin{aligned}\tilde{z}_{t+\ell} &= a_{t+\ell} + \underline{\overline{\psi}}, \, a_{t+\ell-1} + \underline{\overline{\psi}}_2 \, a_{t+\ell-2} + \ldots. \\ &= (a_{t+\ell} + \underline{\overline{\psi}}, \, a_{t+\ell-1} + \ldots + \underline{\overline{\psi}}_{\ell-1} a_{t+1}) \\ &\quad + (\underline{\overline{\psi}}_\ell \, a_t + \underline{\overline{\psi}}_{\ell+1} a_{t+1} + \ldots) \\ &= e_t(\ell) + z_t(\ell)\end{aligned} \tag{4-2}$$

If the series of equation (4-2) is divided into two portions, that is the part of the shocks that have not happened yet and those shocks which have happened, then the disturbance ℓ units ahead is composed of the forecast function corresponding to the lead time ℓ. The forecast error can be regarded as the output from a set linear filter, whose input is a set of white noise with ℓ shocks. (See Appendix C-1 for details).

From equation (4-1), since each current disturbed value can be expressed as weight $\underline{\overline{\psi}}$ on a set of shocks.

$$\tilde{z}_t = \underline{\overline{\psi}}(B)\ a_t \tag{4-3}$$

where $\underline{\overline{\psi}}\ (B) = \underline{\overline{\psi}}_o + \psi_1 B + \underline{\overline{\psi}}_2 B^2 + \ldots$

The ARIMA model is:

$$\phi(B)\nabla^d\ \tilde{z}_t = \theta(B)\ a_t \tag{4-4}$$

If equation (4-3) is substituted into equation (4-4) the result is:

$$\phi(B)\nabla^d\underline{\overline{\psi}}(B) = \theta(B) \tag{4-5}$$

For a (1,0,0) model, based on equation (4-5)

$$\nabla^d = 1 \quad \theta(B)=1 \qquad \therefore\ \phi(B) = (1-\phi B)$$

$$(1-\phi B)(1+\underline{\overline{\psi}}_1 B + \underline{\overline{\psi}}_2 B^2 + \ldots) = 1 \tag{4-6}$$

Comparison of equations (4-5) and (4-6) shows that the same power of B has the same coefficients on both sides.

$$\underline{\overline{\psi}}_1 - \phi = 0 \qquad \underline{\overline{\psi}}_1 = \phi$$

$$-\underline{\overline{\psi}}_1\phi + \underline{\overline{\psi}}_2 = 0 \qquad \underline{\overline{\psi}}_2 = \underline{\overline{\psi}}_1 \cdot \phi = \phi^2$$

$$-\underline{\overline{\psi}}_2\phi + \underline{\overline{\psi}}_3 = 0 \qquad \underline{\overline{\psi}}_3 = \underline{\overline{\psi}}_2 \cdot \phi = \phi^3$$

$$\therefore\ \underline{\overline{\psi}}_j = \phi^j \quad j \geq 1$$

The ℓ term ahead for (1,0,0) model is:

$$(1-\phi B)\ \tilde{z}_{t+\ell} = a_{t+\ell}$$

$$\tilde{z}_{t+\ell} - \phi\tilde{z}_{t+\ell-1} = a_{t+\ell}$$

when $\ell=1$ $\quad \tilde{z}_{t+1} - \phi\tilde{z}_t = a_{t+1} \quad \tilde{z}_{t+1} = e_t(1) + \hat{z}_t(1)$

$$= a_{t+1} + \hat{z}_t(1)$$

$$\therefore\ \hat{z}_t(1) = \phi\tilde{z}_t$$

when $\ell=2$ $\quad \tilde{z}_{t+2} - \phi\tilde{z}_{t+1} = a_{t+2} = \tilde{z}_{t+2} - \hat{z}_t(2) - \phi a_{t+1}$

$$= \hat{z}_{t+2} - \hat{z}_t(2) - \phi(\tilde{z}_{t+1} - \phi z_t)$$

$$\therefore\ \hat{z}_t(2) = \phi^2 z_t = \phi\hat{z}_t(1)$$

Therefore, it could be concluded that this forecast model might be expressed in the following form for different lead time but with the same origin:

$$\hat{z}_t(1) = \phi\tilde{z}_t \qquad (4\text{-}7)$$

$$\hat{z}_t(\ell) = \phi^{\ell}\tilde{z}_t = \phi^{\ell-1}\hat{z}_t(\ell-1) \qquad \ell\geq 2 \qquad (4\text{-}8)$$

Thus, tomorrow's water temperature can be predicted as:

$$\hat{z}_t(1) = \phi\tilde{z}_t$$

$$\begin{aligned}\hat{y}_t(1) &= \tilde{y}_{t+1} + 0.91875 \cdot (\tilde{y}_t - y_t)\\ &= \big(\alpha_1+\alpha_0 \sin(w(t+1) + 4.1956) - 0.91875 \\ &\quad \cdot \sin(wt + 4.1956)\big) + 0.91875\ y_t\\ &= 1.264 + 11.5953 \cdot \sin\big(w(t+1) \\ &\quad + 4.1956) - 0.91875 \cdot \sin \\ &\quad (wt + 4.1956)\big) + 0.91875\ y_t \qquad (4\text{-}9)\end{aligned}$$

where, y_t = today's temperature reading

$\tilde{y}_{t+1}$ = annual harmonic corresponding value at day t+1

$\tilde{y}_t$ = annual harmonic corresponding value at day t

Because the forecast error is expected to have minimum mean square, an expected value equal to zero is the best. The theoretical error for ℓ lead time is:

$$\nabla = (\overline{\Psi}_0^2 + \overline{\Psi}_1^2 + \overline{\Psi}_2^2 + \ldots + \overline{\Psi}_{\ell-1}^2)\ \delta_a^2$$

where δ_a^2: the residual variance after model was fitted

$\overline{\Psi}_j$: the coefficients of weight on j, j=0, ..., ℓ-1

Thus the difference between the observed disturbance and forecast function ℓ days later is bounded within the square root of ∇ times ε, the corresponding value of the normal distribution (e.g. for the 50 percent probability limit, ε=1.96 etc.)

$$\tilde{Z}_{t+\ell} = \hat{Z}_t(\ell) \pm \varepsilon\left((\overline{\Psi}_0^2 + \overline{\Psi}_1^2 + \ldots + \overline{\Psi}_{\ell-1}^2)\,\delta_a^2\right)^{\frac{1}{2}} \qquad (4\text{-}10)$$

$$\delta_a^2 = 0.4879 \qquad \overline{\Psi}_0=1 \qquad \overline{\Psi}_1^2= (0.91875)^2, \ldots$$

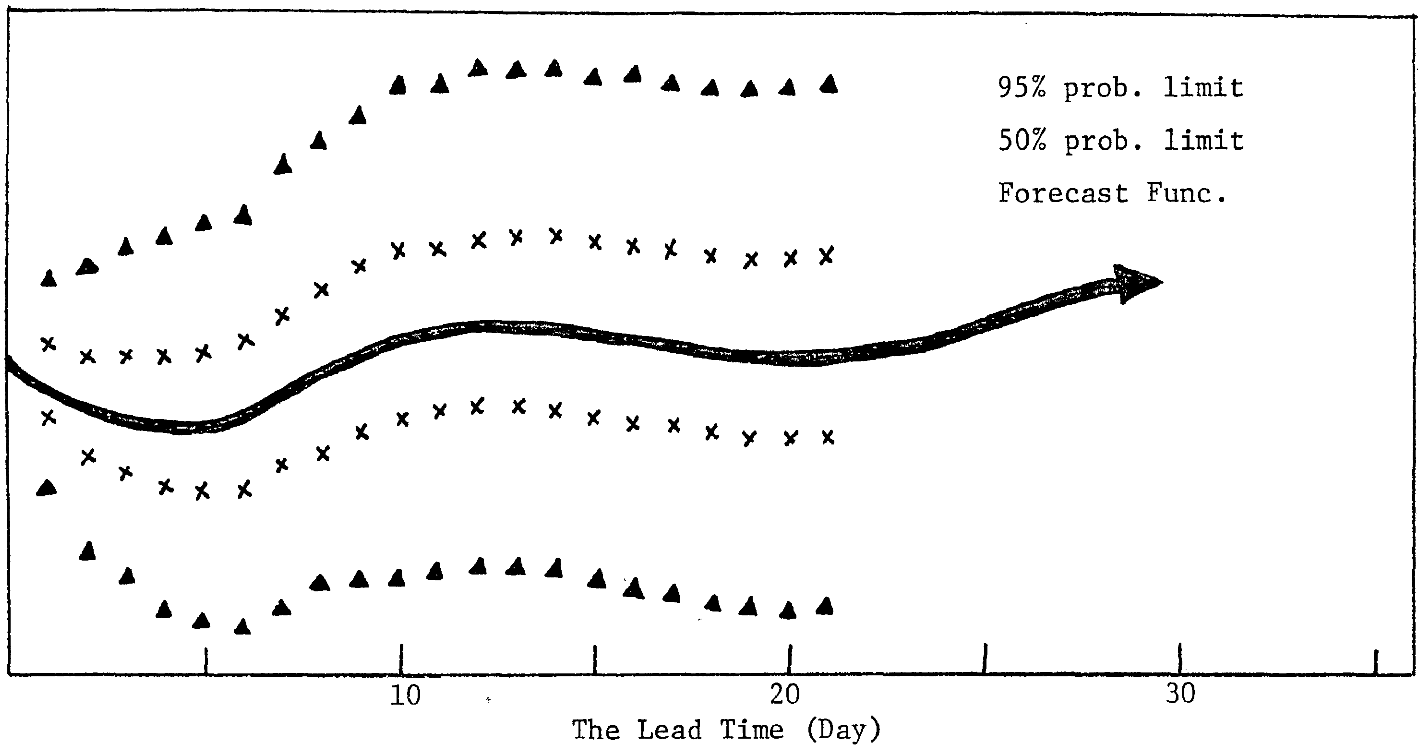
The square root of forecast error variance actually can be indicated as the summation of a geometric series with ϕ^2 factors.

$$\overline{\Psi}_0^2 + \overline{\Psi}_1^2 + \ldots + \overline{\Psi}_{\ell-1}^2 = 1 + \phi^2 + \phi^4 + \ldots + \phi^{2(\ell-1)} \qquad (4\text{-}11)$$

Table 7 includes the first 20 forecast errors for water temperature data. The forecast error will increase with forecast lead time. It is found that the rate of increase approaches zero at about the fifteen days lead time. Actual temperature data and 1 day, 2 day, 3 day forecasts for 1976 are compared in Figures 19 to 21. These figures show that there is little difference between the forecast series and the actual function.

It is worthwhile to note that with a longer forecast period, the "shift" phenomenon is more obvious. The deterministic portion (seasonal component) of this model is assumed to be a sine curve when the corresponding value of the sine function is decreasing, the predicted value is bigger than the actual value, and the contrary result occurs when the slope of the sine function is increasing. The reason might be that the water temperature annual cycle is not perfectly described by a sine curve. So, we can modify the short term forecasts by this general rule: from July 20 to January 20, the forecast value should be reduced a bit to approximate actual values more closely. During the other half of the year, prediction should be modified in the other direction. In the summer, the variation of water temperature is quite small, thus the prediction then is superior to other seasons.

In Chapter III examination of the autocovariance function has shown that the water temperature record includes



Lead Time	1	2	3	4	5	6		8	9	10	11	12	13	14	15	16	17	18	19	20
50% Limit Error	0.43	0.59	0.69	0.77	0.83	0.87	0.91	0.94	0.97	0.99	1.00	1.02	1.03	1.04	1.05	1.06	1.07	1.07	1.07	1.07
95% Limit Error	1.25	1.74	2.00	2.23	2.40	2.54	2.65	2.74	2.81	2.87	2.92	2.96	3.00	3.03	3.05	3.07	3.09	3.10	3.11	3.12

Table 7. The first 20 forecast errors for $(1-0.91875\ B)\ \tilde{Z}_t = a_t$ model of water temperature prediction.

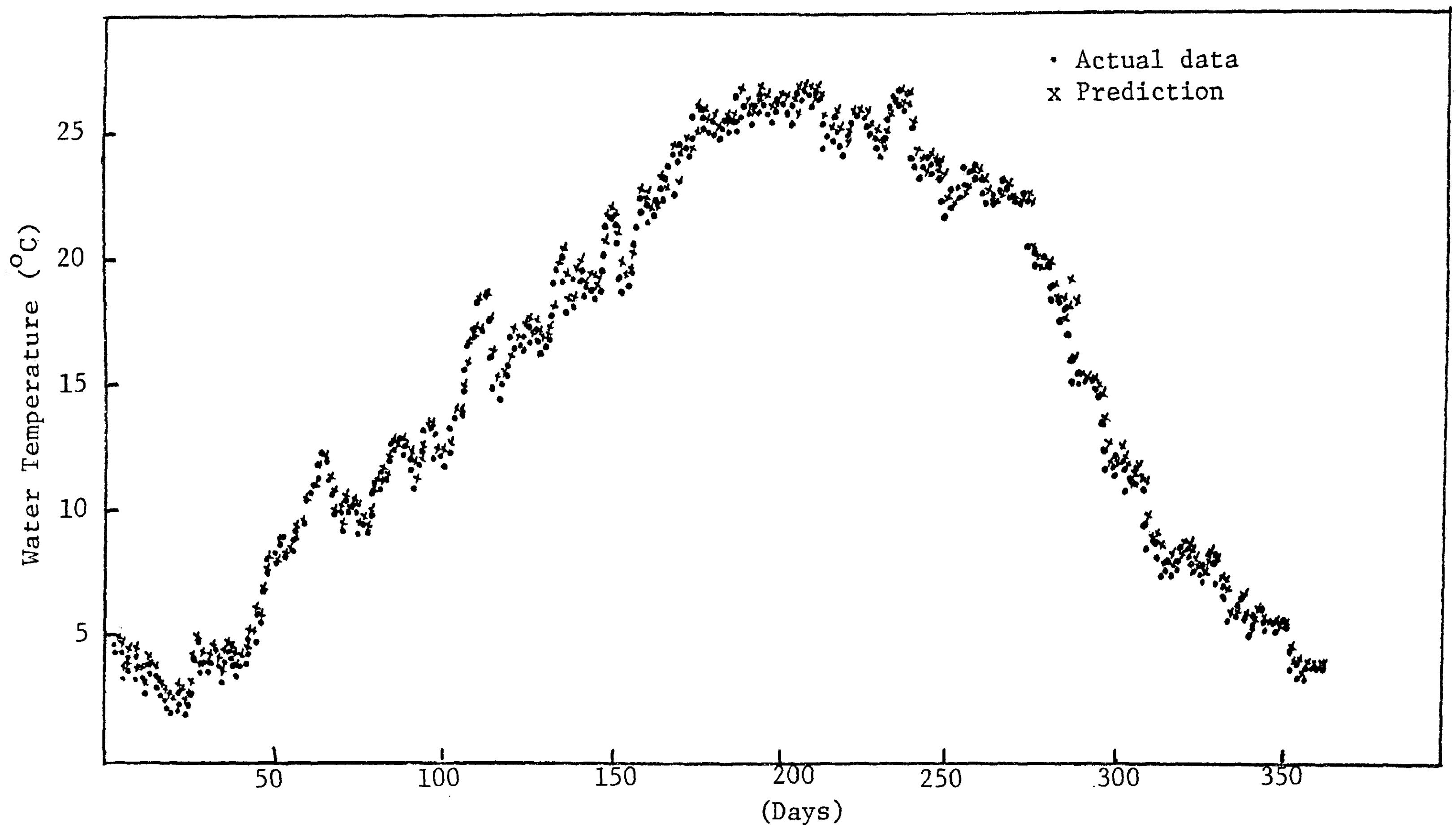


Figure 19. One day ahead prediction versus actual water temperature data in 1976.

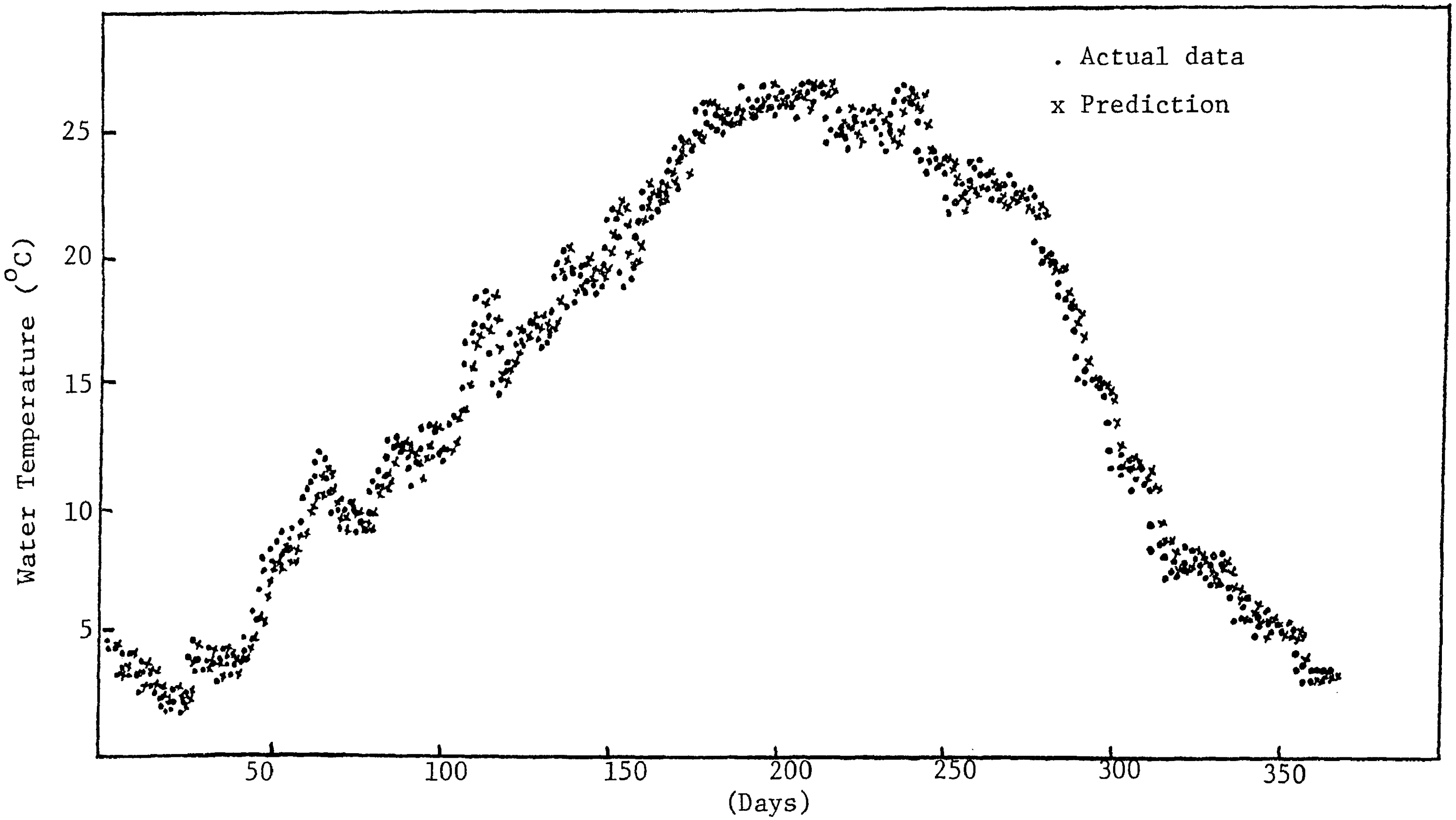


Figure 20. Two day ahead prediction versus actual water temperature data in 1976.

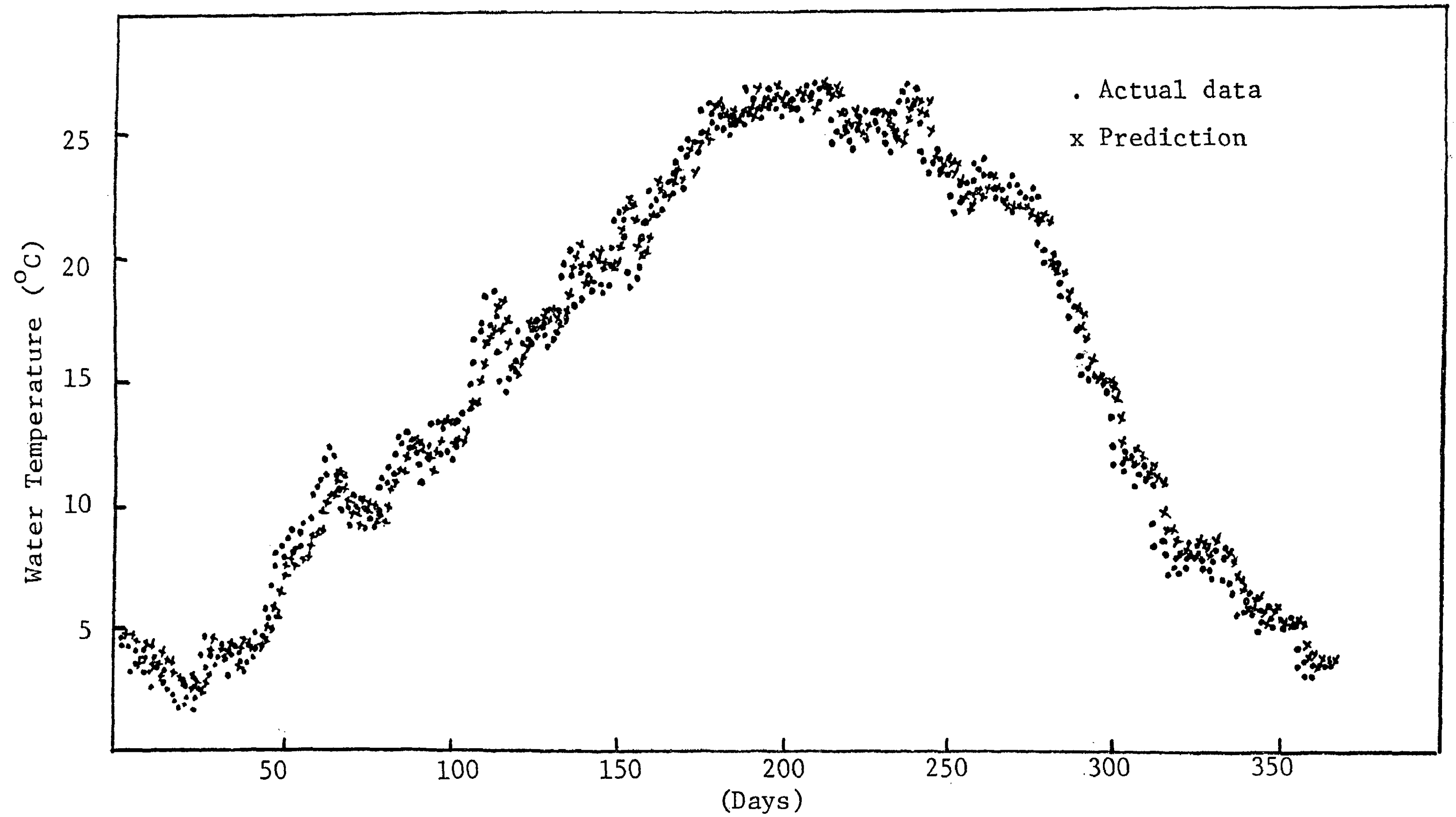


Figure 21. Three day ahead prediction versus actual water temperature data in 1976.

the half-year cycle and this phenomena might be explained by geomagnetic field variation. Perhaps then the deterministic portion ought to contain both the annual and the semiannual variation. However, from Chapter II, it is seen (Table 1) that the amplitude and phase angle varies yearly for semiannual component. In other words, the semiannual component will change with time. This might conflict with the purpose of a deterministic function, which is to define a response function which is easy to calculate and accurate for any point in the time interval. Another reason why this shift phenomenon occurred is that the actual data used to compare with the predictions have a large fluctuation of semiannual nature. Table 1 indicates that the year which was used (1976) had the largest semiannual fluctuation (amplitude=1.8°C) for the period 1954-1977.

In order to improve the predictions when the semiannual fluctuation is strong, the deterministic portion of the model of water temperature can be modified to contain both the annual and semiannual cycles. The autocorrelation function for the residual series when the half-year cycle is eliminated is a function with exponential decay (see Fig. 22). The best fit model is still the first order autoregressive process (1,0,0) except the coefficient is changed to 0.91231. That model is:

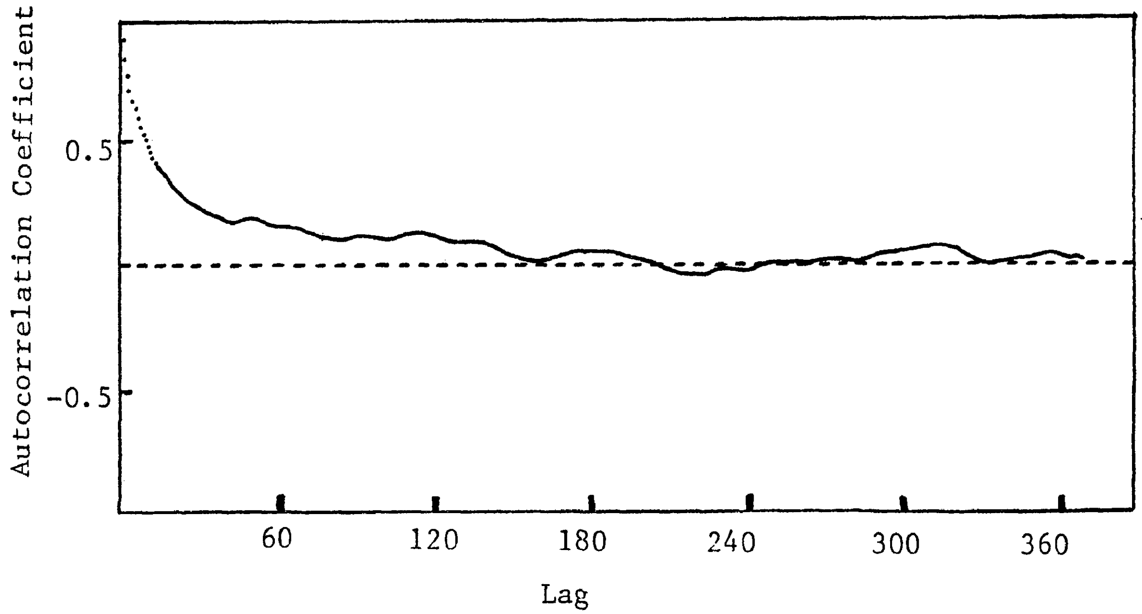


Figure 22. The autocorrelation function after the annual and semiannual components and mean are removed.

$$\hat{y}_t(\ell) = \tilde{y}_{t+\ell} + \phi^{\ell}(y_t - \tilde{y}_t)$$

$$= \alpha_0 + \alpha_1 \sin(w(t+\ell)+ \alpha_2) + \alpha_3 \sin(2w(t+\ell) + \alpha_4)$$

$$+ (0.91231)^{\ell}(y_t - \alpha_o - \alpha_1 \sin(wt + \alpha_2) - \alpha_3 \sin (2wt + \alpha_4))$$

where

ℓ = the number of ℓ days ahead of prediction

ϕ = the coefficient of the first order auto-regressive process

α_3 = the amplitude of semiannual variation

α_4 = the phase angle of semiannual variation

The rest of parameters are the same as mentioned previously.

For this modified model, 1) two more parameters need to be estimated, 2) the residual variance only changes 0.01 (0.40971 to 0.39984), and 3) the ratio of the variation is large (480:1). Hence, due to the simplicity and the above tiny differences, it is suggested that this semiannual variation can be ignored for most predictions.

The relationship between actual data and the predictive function are summarized in Table 8. The total variance for actual data and predictions are very close. The one day prediction error is bounded by the 50 percent and 68.28 percent probability limits, while the other two predictions have errors near to one standard error. In addition, although the predictions have greater total difference than actual data for the entire year, the sums of those predictions are almost the same. Therefore, for short term predictions, the deviation between actual data and the sine curve usually can be ignored.

Predictions for three arbitrarily selected original points are shown in Figure 23. None of the values for the first fifteen days is outside the 95 percent probability limit and only a few are near the 50 percent probability limit. The predictions are for winter, spring and summer.

Longer simulations of water temperature data using <u>one known data point</u> are shown in Figure 24. Because the forecast error will be constant after about 15 days lead time, the predictive function will follow the harmonic curve. The equations (4-8) and (4-9) explain this phenomenon.

$$\hat{z}_t(1) = \phi\tilde{z}_t$$

$$\hat{y}_t(1) = \tilde{y}_{t+1} + \phi(y_t - \tilde{y}_t) \tag{4-12}$$

$$\hat{z}_t(\ell) = \phi^{\ell}\tilde{z}_t \qquad \ell \geq 2$$

$$\hat{y}_t(\ell) = \tilde{y}_{t+\ell} + \phi^{\ell-1}(\hat{y}_t(\ell-1) - \tilde{y}_t)$$

$$= \tilde{y}_{t+\ell} + \phi^{\ell}(y_t - \tilde{y}_t) \tag{4-13}$$

From equation (4-13), today's prediction is the deterministic value plus ϕ times the difference between yesterdays reading and its harmonic value. With an increasing prediction period, the power of ϕ will increase too (equation 4-14). But if ϕ is less than 1, somedays later this exponential term will equal or be very close to

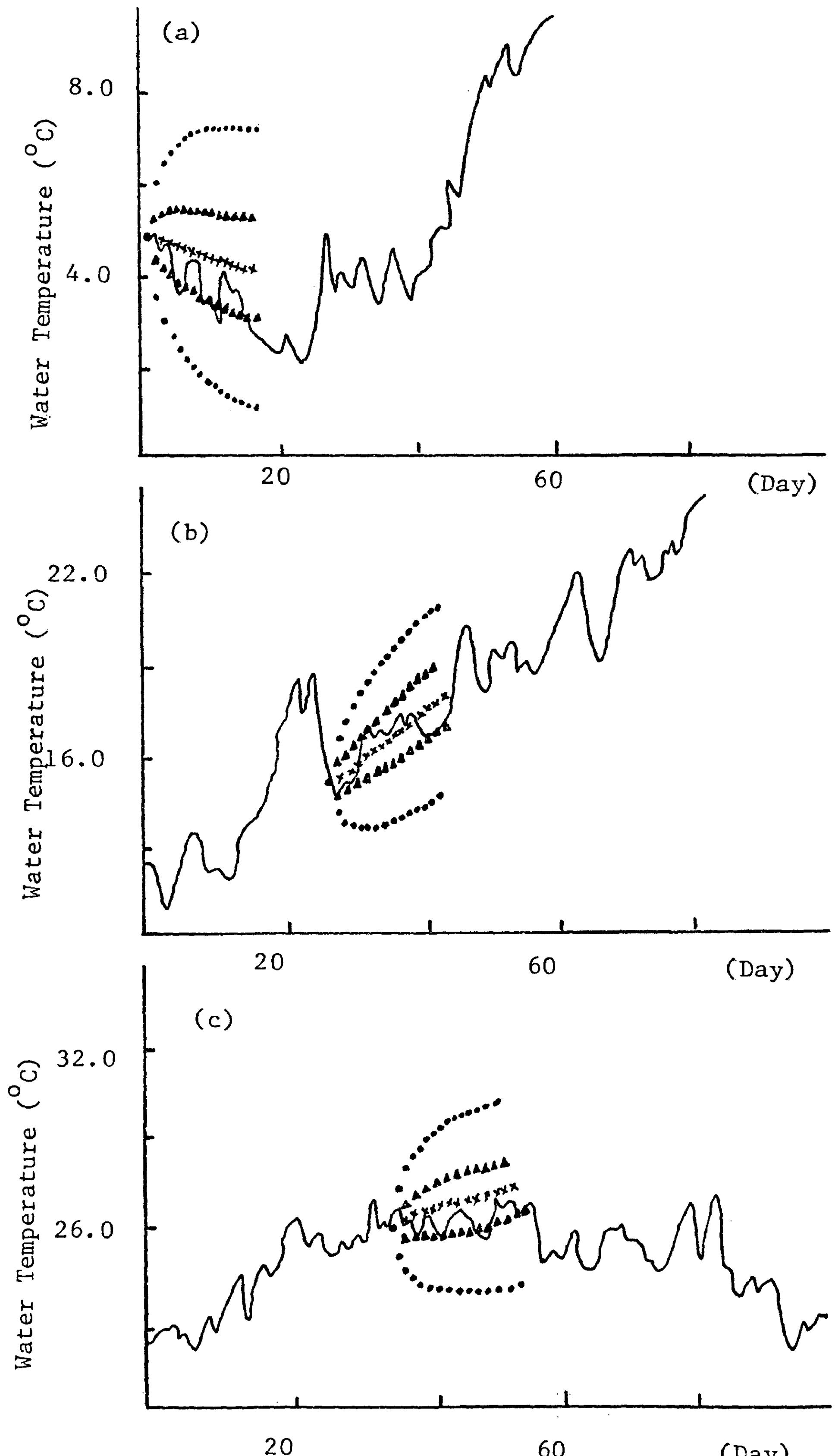


Figure 23. Fifteen day forecasts for given a) winter, b) spring and c) summer days.

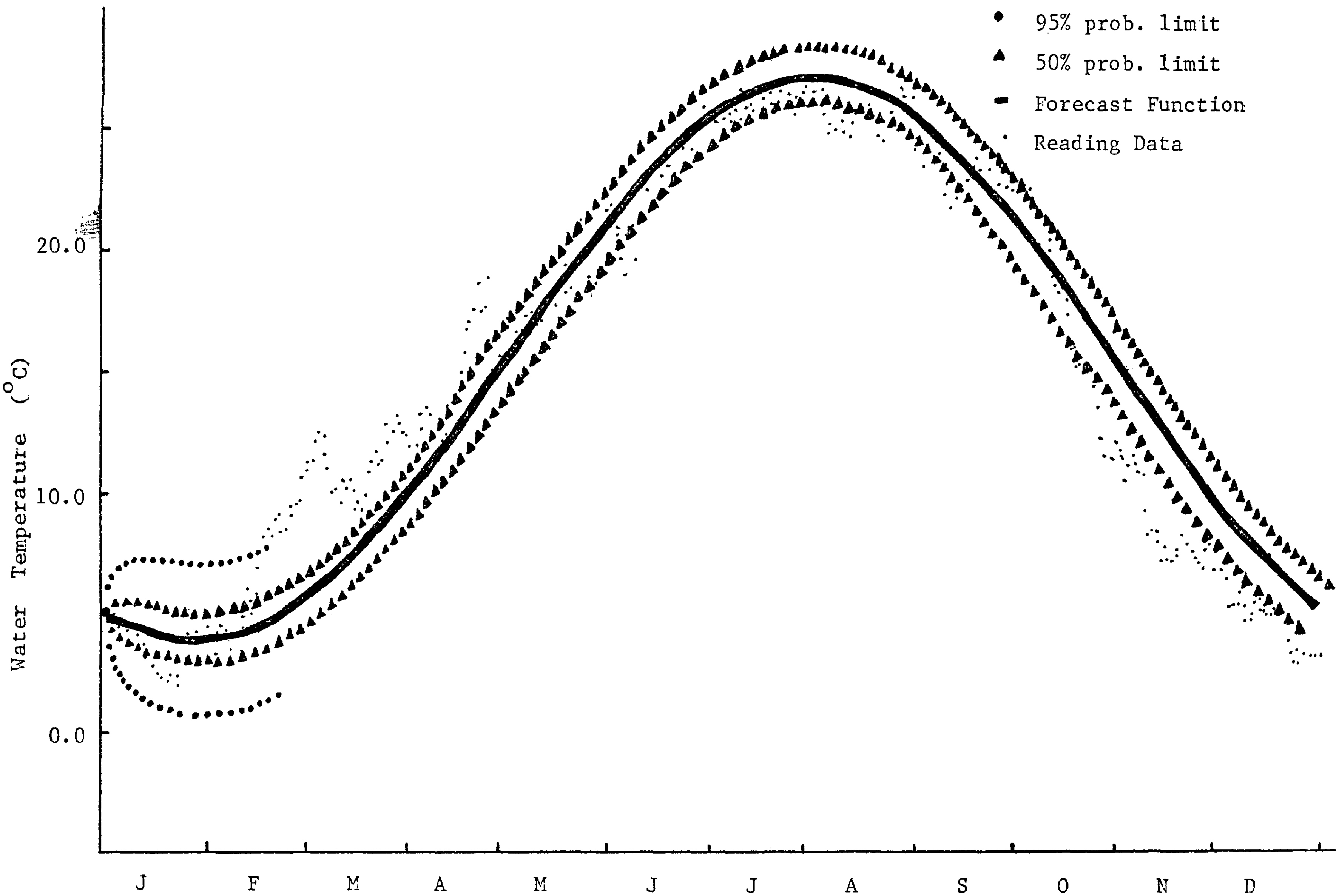


Figure 24. One year forecasting of water temperature and probability limits.

zero. That means the predicted value is dominated by the deterministic portion of the model and the influence of the autoregressive operator disappears. Thus for long term predictions when the temperature readings are not modified by future shocks, the predictions will return to the deterministic routine sooner or later. For higher order autoregressive operators, the function goes back more slowly.

In summary, the Box-Jenkins technique can provide a daily water temperature predictive model. The best fit for the non-seasonal component of the York River water temperature record is the first order, autoregressive process. This model gives good results for short term predictions up to about 15 days ahead.

NOTATIONS FOR CHAPTER IV

a_t: white noise process at time t (shocks at time t)

B : backward shift operator

d : order of differencing operator

e_t: normal random deviate

$e_t(L)$: error of estimate of forecast made at time t with lead time L

L: lead time for forecast

P: order of autoregressive process

Q: estimate of statistic

q: order of moving average process

γ_K: estimate of autocorrelation coefficients at lag K

ε: normal deviate corresponding to probability level

y_t: series of daily mean water temperature at time t

$\tilde{y}_t$: annual harmonic corresponding value for day t's water temperature

F: forward shift operator

Z_t: observed value of series at time t

$\tilde{Z}_t$: the deviation from mean of a series (or from a defined deterministic function) at time t

$\hat{Z}_{t(L)}$: forecast at time t of Z_{t+L} (L unit forecast ahead from time t)

θ: moving average coefficient

δ_a^2: sample variance of a time series

ϕ: autoregressive coefficient

ϕ_{KK}: kth-order partial autocorrelation function

$\underline{\overline{\psi}}_j$: jth weight when autoregressive process is expressed as weight infinite sum of previous shocks

∇^d: dth-order backward shift operator

μ: mean of the entire series

π_j: jth weight when moving average process is expressed as weighted infinite sum of previous disturbances

$\theta_q(B)$: polynomials of order q for a moving average process

$\phi_p(B)$: polynomials of order p for a autoregressive process

(p,d,q): autoregressive integrated moving average process (a series can be expressed by pth order autoregressive process, dth difference operator and qth order moving average process)

ACF: autocorrelation function

PACF: partial autocorrelation function

$S(\phi,\theta)$: sum of square when a series does exist autoregressive process with coefficient ϕ and moving average process with coefficient θ

N: the number actually accounted for estimate coefficient

α_0: series mean of water temperature

α_1: amplitude of water temperature series is fitted to annual sine curve

α_2: phase angle of water temperature series is fitted to annual sine curve

w: frequency (in here, $w = \frac{2\pi}{365}$ of water temperature data is fitted to a annual sine curve

CHAPTER V

AN APPLICATION: THE RELATIONSHIP BETWEEN WATER TEMPERATURE AND THE CONDITION INDEX OF OYSTERS

The variability of water temperature plays a very important role in maintaining the normal existence and the growth of aquatic biota. Many different impacts have been documented for changing water temperature (Arnold, 1962). It is known that temperature requirements are different for each stage of the growth cycle. In addition, natural reactions, such as diseases and competition, can become more important when coupled with water temperature stress. Because organisms can be affected by the variation of water temperature in these many ways, it attracts us to investigate the relationship between these factors and daily mean water temperature.

The oyster is one of the most important seafood products of the York River estuary. If we pay attention to the quality of the oysters, this will show us the best time for harvesting. Scientists have designed a method to express the meat quality of oysters termed the Condition Index (CI). This relative value can compare changes in yield from time to time or location to location for oysters. It is defined as the ratio of dry weight of the oyster meats in grams to the size of the shell cavity in cubic centimeters. It is known that the higher values for condition index indicate greater amounts and quality of meats for any given bushel (Haven, 1962). The C.I. of oysters ranges from 3.0 to 12.0 and is classified by three groups based on quality. A "poor yield" is classified as values between 3.0 to 5.5 and "good yield", 7.6 and over. Values between those two classes are regarded as average quality. Meat quality of York River oysters has been average or below average, if all stations are considered. The average was 6.2 for the years 1955-1971.

Monthly C.I. of oysters have been measured since the end of 1969 to the present for three important estuaries in Virginia. The seasonal and long term tendency of that index number can provide information for the harvest of the future. The Pages Rock sampling station in the York River is near Gloucester Point and a complete data set exists for this station. The C.I. of oysters measured at Pages Rock for years 1970-1977 is shown in Figure 25. Two apparent peaks occur, one in late spring and the second in early fall. The yearly average increased in the period 1974-1976 but dropped back to a low level in late 1976. An especially low average of C.I. of oysters occurred in 1973.

Water temperature might be one factor which affects growth and mortality of oysters. Hence, in order to know the relationships between the temperature and C.I. series, the cross-correlation function was used.

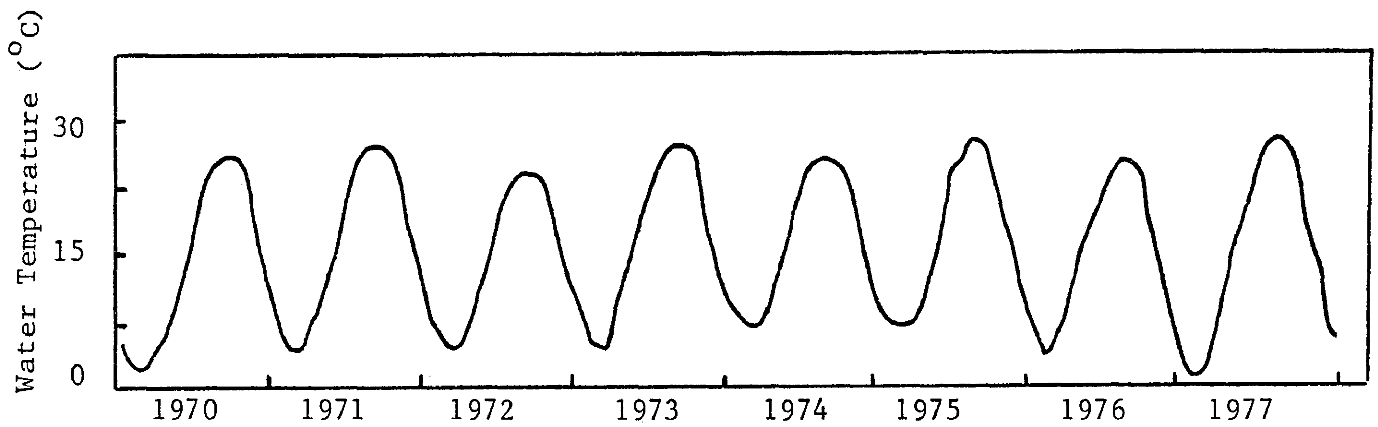


Figure 25a. Monthly mean water temperature at Gloucester Point sampling station in the York River Estuary.

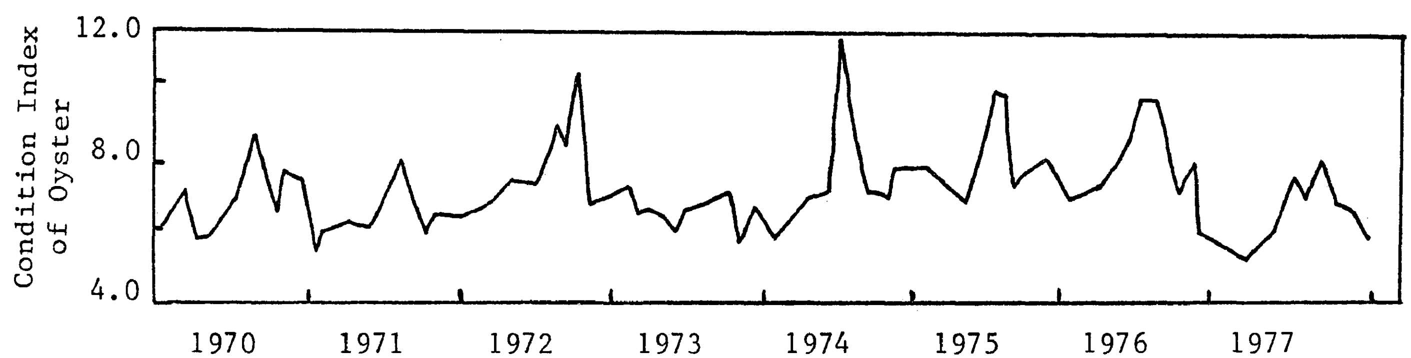


Figure 25b. The condition index of oyster measured at Pages Rock in the York River Estuary.

One can observe (Fig. 25) that the trend of the former is more regular than the latter. Since both trends are expressed as annual cycles, the monthly deviation from particular monthly mean of this period can more clearly reveal this relative relation (see Fig. 26). There appears to be no significant corresponding relationship through the entire trend. Plots of pairs of corresponding temperature and index deviations (Fig. 27) show that each section has almost the same number of pairs. That means that even if a direct relationship does exist, the coefficient will be very low. Besides, it is necessary to consider that the water temperature might affect the C.I. several months later. Cross correlations for lags of 0 to 3 months are 0.053, 0.114, 0.146 and 0.182 respectively. Even though there is an increasing tendency, they are all so small that it is not reasonable to make a regression equation. Values increased to about 0.33 for lags up to 12 months, although such long term influences do not appear to be reasonable. In conclusion, monthly mean water temperatures are not good indicators of monthly C.I. of oysters.

Arnold (1962) also has pointed out that aquatic organisms can acclimate to higher or lower water temperature and the former is easier than the latter. The sensitivity or tolerance of aquatic organisms to temperature changes (or levels) also varies with age, size and season. Hence, it is possible to seek some relative variations of water temperature through

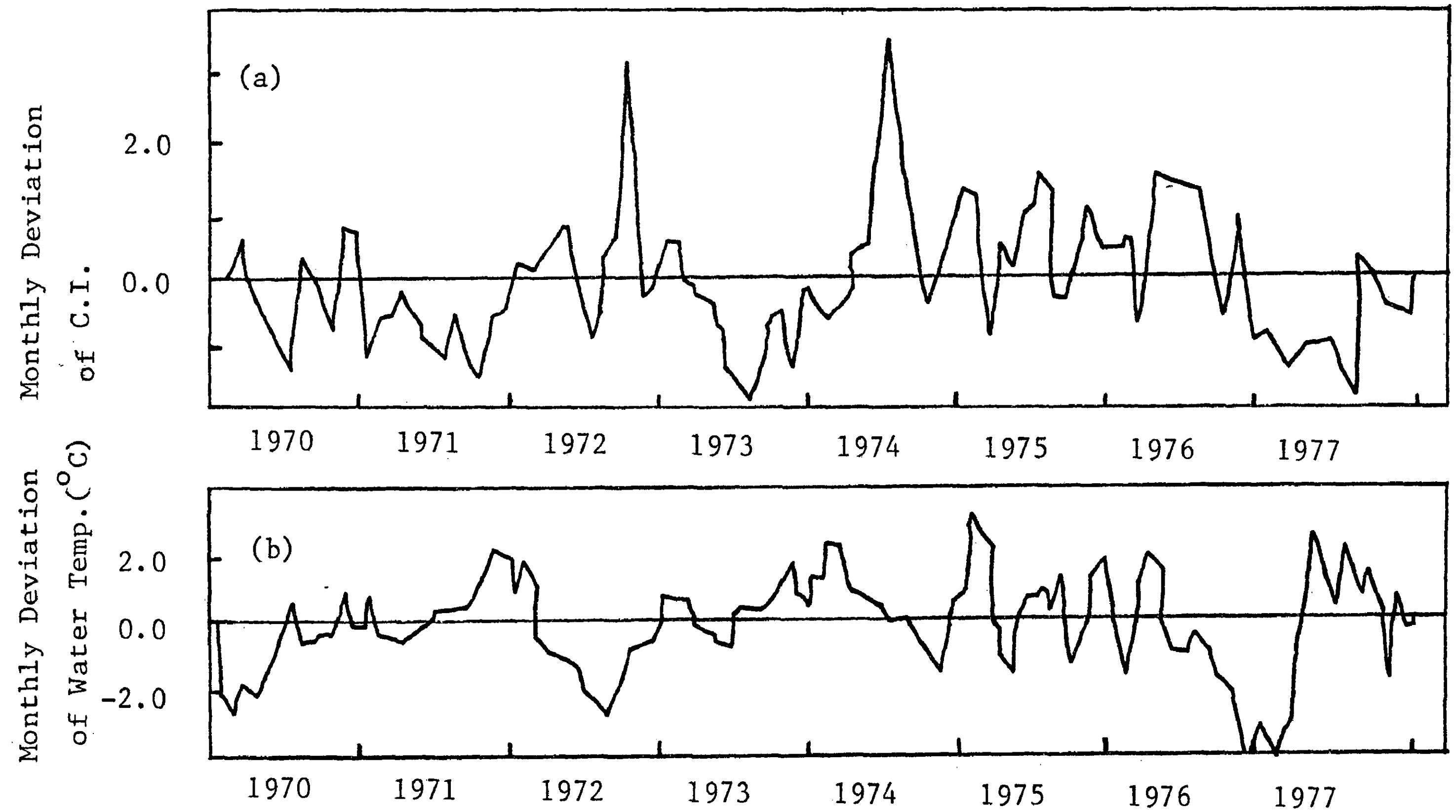


Figure 26. Shows (a) Monthly deviations of condition index of oyster at Pages Rock from the particular monthly mean during 1970-1977 and (b) Monthly deviation of water temperature at VIMS pier from the particular monthly mean during 1970-1977.

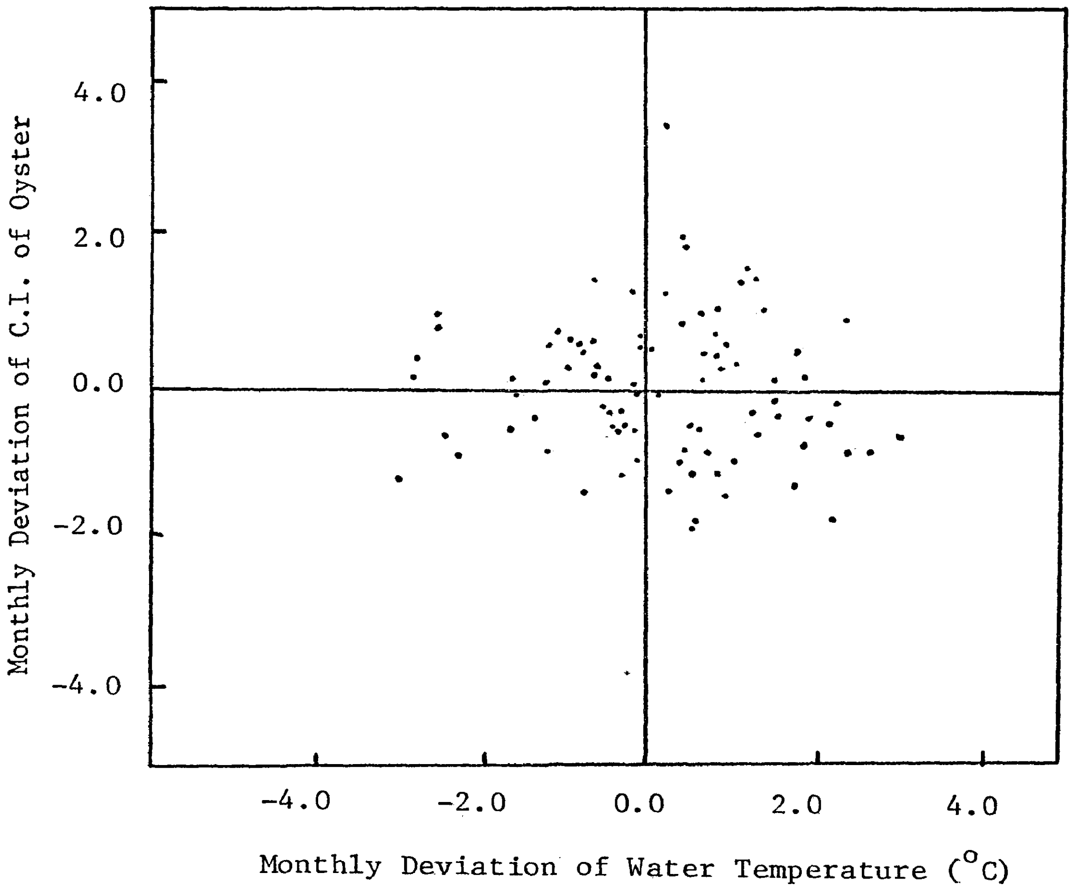


Figure 27. The monthly deviation of water temperature and the corresponding monthly deviation of condition index of oysters for 1970-1977.

two successive index numbers. Several general rules are:

1. The obvious peak of this index always occurs in June or July when the monthly mean water temperature is around 24C. This was true in the years 1970, 1974, 1975 and 1976 for which the index number was over 9 (Fig. 25). The years 1971, 1973, and 1977 did not have the high peak, perhaps because of hotter weather in July (average temperature over 26C). Day to day fluctuations also might affect the C.I.. The change in condition index of oyster from March to July versus the number of days when water temperature was in the range of 21C-25C is shown in Figure 28. The purpose is to see whether the increase of C.I. during late spring and early summer is related to the accumulated reaction of water temperature in a given water temperature range. The correlation coefficient is moderate (0.561). Slow acclimatization of the oyster to increased water temperature might be the reason for this moderate correlation.

2. Some minor peak usually occurs in September or October when the water temperature has dropped back to the range around 20C but this increase is slight.

3. Each major peak is very sharp. This might be explained that the oysters acclimate more easily to increasing water temperatures. However, the oysters require more dissolved oxygen at higher water temperatures. This may

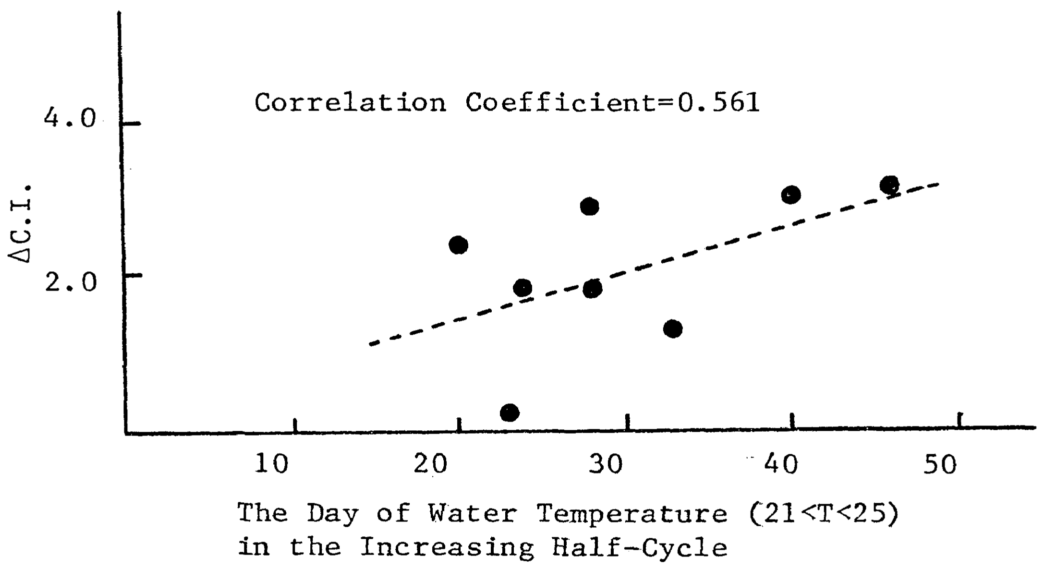


Figure 28. The change in C.I. of oyster versus the number of days the water temperature ranged from 21C to 25C for the months March to July.

control the upper temperature which can be tolerated by oysters and explain why there is a marked drop of the C.I. in late summer.

4. The C.I. during the winter does not always decrease after the oysters have acclimated to the lower temperatures. The C.I. value may increase slightly, e.g. years 1970, 1971, 1972, 1974, and 1977.

5. The water temperature of around 10C is critical for oysters. If the spring is cold (water temperature less than 10C-11C through March), the C.I. will decrease. This indicates that for the oyster to be kept in cold water is disadvantageous. The relationship between water temperature during the previous winter and the condition index in March is shown in Figure 29. If this relationship does exist, one would expect a warm winter to result in a higher C.I. value in March. In Figure 29-A the minimum water temperature observed during the previous winter is plotted versus the March C.I. A correlation coefficient of 0.735 was calculated. Both the number of days with temperature below 10C and "degree-days" for T<10C were examined. The better correlation, r=0.723, was for the degree-days (Figure 29-B). However the small number of data points (8 points) does not allow us to define these relationships as clearly or precisely as we might like. The correlations are reasonably good for both indicators of the previous winter's coldness.

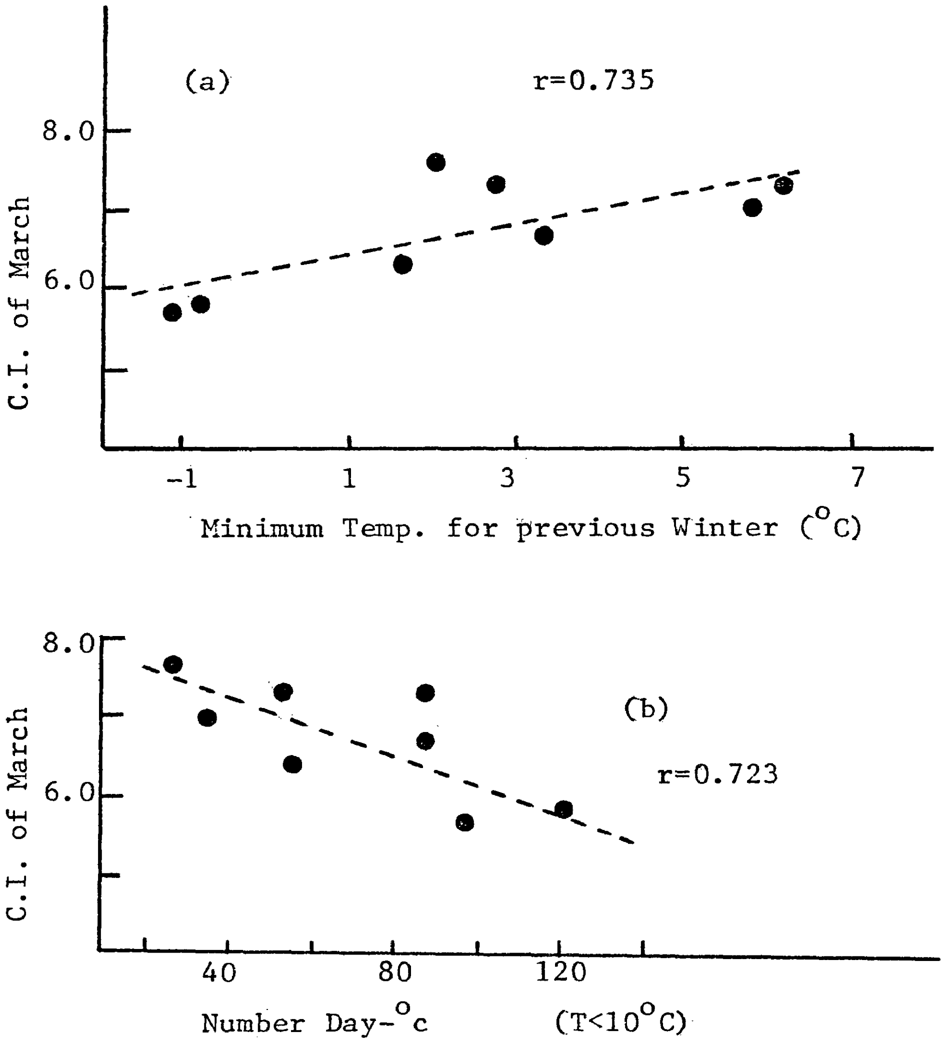


Figure 29. March Condition Index versus a) minimum temperature for the previous winter and b) number of degree-days below 10C for the previous winter.

In summary, there is no direct relationship between the monthly variation of water temperature and condition index of oyster. It might be because those relations between the acclimatization of the oyster and water temperature are not linear. Besides, many other factors, such as dissolved oxygen levels, quantity and quality of food available, also affect the health and growth of oysters. However, the ideal conditions to maintain high value of C.I. seem to follow this rule: warm winter, early spring, short summer and long autumn. More frequent sampling for C.I. value is needed to define the relationship with water temperature precisely.

CHAPTER VI

DISCUSSION

(a) How to achieve a more satisfactory result using the basic model.

The four basic components of the water temperature time series (annual, trend, cyclical and random) have been derived. However, in order to reach a more satisfactory result for any given time series, some characteristics of the techniques used in this study need to be discussed and specified. Note that all of these four components will not occur for every time series, depending on the length of the record and the sampling interval. In this discussion it is assumed that a time series is long enough to contain all four components.

In general, the presence of a trend in a time series usually makes it difficult to examine the behavior of the remaining cyclical, seasonal and irregular component, especially for economic time series (Fishman 1969). If some obvious trend can be seen from the plotting of the time series, this component needs to be extracted first. The difference operator usually is used to solve this problem. The effect of this operator is to reduce a process from non-stationary sequences to a stationary process. The order of the difference operator which is required to eliminate the trend component is related to the degree of the polynomial equation which best describes this trend behavior. In general, if the nth differences are zero on the average, then the trend will follow a polynomial of degree (n-1). For instance, if a straight line gives the best description, then the first differences (difference operator used once) will have a non-zero average, but the second differences will fluctuate around zero. In this study, a very strong annual cycle does exist, but the yearly mean doesn't show any apparent trend, (slope=0.072). Besides, it was found that the average nearest to zero occurs at the first difference.

The next step is the choice of an appropriate function which can present the general behavior of the seasonal and cyclical components. Fourier analysis usually is suitable because many periodic functions share, more or less, the properties of sinusoids. Another advantage of Fourier analysis is that the amplitude doesn't change with the initial point of the sampling interval. The disadvantages were noted at the end of Chapter II. It appears that if the Fourier analysis is performed before the variance spectrum is calculated, more information can be extracted.

More detailed knowledge of the cyclical behavior of a time series, however, can be reached solely by variance spectrum. Once an especially strong cyclical component occurs, it will "block" the rest of the recurring behavior which may or may not be significant. In order to be certain of the regularity of a seasonal component or cyclical component, an analysis of segments of the time series is required to show the consistency of each cyclic component. The broad features of a cyclical component can be seen from each segment from Fourier analysis or the variance spectrum. It is not necessary to expect that each cyclical behavior will be repeated and have the same magnitude. However, this analysis can tell us if each component changes with different time intervals. If so, one might seek the cause of this change. For instance the approximately equal amplitudes and phase angles show the annual component of the water temperature record to be stable. However the first 12 years of the record behave differently at low frequency than the following 12 years of this 24 year record, although both the 24 year period and the 12 year period express high values in the variance spectrum.

The moving average and seasonally adjusted method also can be used to eliminate the effect of cyclic behavior in a time series. But the disadvantages for both is that the intensity of that cyclical behavior is not always known. Except for definite recurring phenomena that are known, the weighted moving averages or filters must be chosen correctly. Besides, big errors can occur when the time series is short.

Even with an increased understanding of a time series, sometimes it is hard to understand its nature totally. Another, or a longer, time series might provide an explanation for the behavior of this series. "Multiple time series analysis" seems to be necessary for a very thorough and complete investigation.

(b) The advantages of a deterministic-stochastic model over a purely stochastic model

The Box-Jenkins technique can provide predictions from a simple parametric model which is generated by the ARIMA process and is suitable for many time series. This method can reduce effectively most of the total variance from a time series. However, few investigators have discussed the question of the limits of the predictions and the structure of the model. In order to explain this, it is necessary to indicate the advantages of a deterministic-stochastic model.

Many time series do not have an obvious deterministic function. Therefore, a predictive model can be made only if the whole series is regarded as the stochastic process. The ARIMA process still can provide a satisfactory result. However, this kind of model might be related more to previous disturbances than the combined deterministic-stochastic model. For instance, McMichael and Hunter (1972) derived a stochastic model using the daily mean water temperature. The characteristic of their model is that today's disturbance (here, the disturbance is the reading subtracted from the mean value of the series) is related not only to yesterday's disturbance but also with that for the same day last year. In practice, the disturbance which occurred last year is unlikely to have any affect this year. The strong yearly cycle needs to be substituted, otherwise this series will remain non-stationary. A serious disadvantage of purely stochastic models is that the forecasting error is related to the standard deviation of the time series. Especially for recurring time series, the forecasting error will be large. The prediction also is limited by different situations (such as seasonal fluctuations) and affected by too many terms.

This should be taken as the deterministic function. Then a model can be selected for the remaining, stochastic component. The stochastic model will provide information on the behavior of the time series.

CHAPTER VII

CONCLUSIONS

The basic conceptual model of the water temperature record which has been used in this study consists of a trend component, a cyclical component, a seasonal component and an irregular component each of which has been described. The important findings are as follows:

(a) Long term trend component:

This component is not strong enough to express its behavior in this 24 year, daily mean water temperature series. It is known that the degree of difference operator and the variance accounted for by the zero frequency in the variance spectrum show the strength of this trend component. With a zero order difference operator, the trend component accounted for less than 0.1 percent of the total variance. Most of the variance at low frequency is contributed by a cyclical component with a period of 22 years.

(b) Cyclical components:

Recurring cycles have been found in this daily mean water temperature record with the major periods being 22 years, 26 months, 14 months and 6 months. All four periods are characteristic of solar activity. The lunar period

(29.53 days) was not significant for this series. If these recurring phenomena are due to solar activity, an interesting exercise would be to derive a rule which can describe roughly the behavior of water temperature within a double-sunspot cycle. It is important to emphasize that the cyclical components do not always have the same intensity throughout a long time series period. For example the greatest semiannual variation of water temperature occurs around the even-odd sunspot minimum. The activity of quasi-biennial oscillation is similar. The 14 month oscillation is stronger during an even-numbered than during an odd-numbered sunspot cycle. In fact, its intensity during an even-numbered sunspot cycle is stronger than the biennial and semiannual variations.

The suggested interaction between sunspots and water temperature is as follows:

1) Solar activity is greatest during the first and last five or six years of the 22 year solar cycle. Correspondingly, the water temperatures will show greater variation during those periods (e.g. 1954-1959 and 1971-1976 of this series) than during the rest of the cycle (e.g. 1960-1970).

2) At the even-odd minimum in the sunspot cycle both the biennial and the semiannual variations tend to a maximum (e.g. years 1954, 1976, 1977).

3) The 14 month oscillation of water temperature has a stronger behavior during an even-numbered sunspot cycle.

(c) Seasonal or annual component:

This component is so stable that it shows almost identical amplitude (11.59 c) and phase angle (240 degree) year by year. Over 95 percent of the total variance is accounted for by this component for individual years and the 24 year mean series. The higher order harmonics (periods less than one year) do not show consistent amplitude or phase angle. For this reason, the annual component needs to be extracted first; then the more information can be extracted from the residual water temperature record.

(d) Irregular (random) component: The remaining component which is left after removing the above three components from the original series is regarded as the irregular component. This component has no observable pattern and is regarded as the purely random phenomena.

(e) Non-seasonal component:

In order to predict the future reading accurately (especially for the short term future), the non-seasonal component can be assumed as the stochastic portion. Using the Box-Jenkins technique a first order autoregressive process was found to give the best fit predictive model for this time series. Both portions, deterministic and stochastic, accounted for over 99.5 percent of the total variance of the original water temperature series. Reasonable prediction can be made for 12 days ahead using this model, if one standard deviation is taken as the termination point for the forecasting error.

Appendix A: Daily average water temperature at VIMS pier for years 1954-1977.

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1954

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	5.5	3.8	8.7	10.7	18.9	23.0	25.0	26.6	25.4	24.3	14.4	9.0
2	6.2	4.1	8.0	10.9	20.2	22.1	26.0	27.0	25.1	23.7	14.1	8.8
3	6.0	3.7	7.6	10.8	20.1	22.9	25.9	26.3	24.7	23.9	12.8	8.5
4	5.8	4.7	6.6	9.1	19.4	22.7	25.5	26.5	25.4	23.8	12.4	8.2
5	5.7	4.0	6.5	10.0	18.2	21.6	26.2	26.5	25.7	24.3	12.6	8.0
6	5.7	3.8	7.3	10.7	18.3	21.8	25.7	26.0	26.6	24.1	12.2	6.7
7	5.0	3.7	7.6	12.4	18.0	21.8	25.5	25.5	27.0	22.2	11.6	4.8
8	5.1	3.7	7.3	12.3	18.2	22.4	25.4	26.0	27.3	20.9	11.8	5.2
9	5.0	4.0	7.4	12.6	18.3	23.3	24.6	25.2	27.2	21.3	11.9	5.4
10	5.5	4.0	7.5	13.2	20.0	23.0	24.6	26.0	26.5	21.7	11.1	5.5
11	4.7	4.9	7.6	12.9	17.1	23.2	24.3	25.3	25.4	21.5	11.3	4.8
12	4.3	3.9	7.5	13.0	17.2	24.3	23.9	24.4	24.6	22.1	11.5	4.4
13	3.2	2.7	7.3	13.8	16.9	24.2	24.4	24.6	24.0	22.2	11.0	4.5
14	2.7	3.4	6.9	13.7	15.8	24.6	25.7	25.1	24.7	22.6	11.1	4.7
15	3.2	5.5	7.2	14.3	15.5	25.7	24.5	24.6	24.4	19.4	11.0	5.1
16	3.6	6.4	7.2	15.1	16.5	24.4	25.0	25.5	24.3	****	11.0	5.0
17	3.5	6.7	7.1	14.7	17.2	23.6	25.0	25.7	24.6	****	11.6	4.6
18	3.5	7.0	7.8	14.0	17.4	22.9	25.0	25.0	24.7	****	12.2	5.4
19	3.5	6.9	8.3	15.2	17.9	21.7	25.1	25.1	24.4	19.0	12.9	5.3
20	4.6	7.2	8.3	17.2	17.8	23.3	25.7	26.0	24.3	18.2	12.7	4.7
21	5.1	7.2	7.6	17.3	17.2	24.0	25.3	26.0	24.6	17.6	12.6	4.0
22	3.7	6.6	8.2	17.7	17.6	24.7	25.4	25.4	23.6	17.2	11.9	3.6
23	3.0	6.9	8.2	17.9	18.1	24.4	25.4	24.8	23.2	17.2	11.2	2.6
24	2.8	6.9	9.0	18.6	18.9	24.4	25.5	25.5	23.2	17.1	11.1	3.2
25	3.2	7.1	9.7	18.6	18.6	24.6	25.8	26.2	22.9	17.1	10.5	3.8
26	3.7	6.9	9.6	19.0	19.7	24.7	26.2	26.1	22.7	17.1	10.0	3.7
27	4.4	7.5	10.1	19.4	20.3	25.6	26.5	26.2	22.6	17.3	9.7	3.6
28	3.6	8.4	10.4	18.2	21.1	23.5	26.9	26.5	22.9	16.8	10.1	4.4
29	3.6		10.8	17.9	21.9	23.0	27.0	26.4	23.7	16.5	9.9	5.0
30	3.6		11.1	18.0	21.4	23.9	27.5	25.5	24.3	15.8	8.9	5.9
31	3.8		11.0		22.1		27.9	25.2		14.9		6.1
AVG	4.3	5.4	8.2	14.6	18.6	23.5	25.6	25.7	24.7	20.0	11.6	5.3

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1955

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	2.1	6.0	9.5	15.7	21.4	24.8	29.1	26.5	22.4	15.5	7.2
2	6.0	2.4	6.5	9.6	16.5	21.1	25.6	28.5	25.5	21.8	15.9	7.0
3	6.3	1.8	7.2	9.1	16.8	22.1	25.9	29.2	25.0	21.2	15.8	7.9
4	6.1	1.3	8.3	9.5	17.4	20.5	27.0	29.6	25.0	21.2	14.6	8.6
5	6.4	1.3	9.0	10.8	18.7	21.1	26.9	29.3	25.2	21.7	13.5	8.2
6	6.6	1.9	8.5	10.5	18.4	22.3	26.2	29.1	25.9	21.7	12.4	7.7
7	5.8	2.8	7.5	10.3	19.4	21.8	****	28.5	24.5	21.7	12.3	7.2
8	5.8	2.7	7.5	9.3	18.0	21.7	24.9	28.4	24.2	21.5	13.0	7.4
9	5.9	3.0	8.2	10.8	17.8	20.4	26.9	27.9	24.3	20.7	12.4	7.3
10	5.6	3.1	8.8	11.8	18.6	20.7	27.2	27.3	23.9	21.1	11.6	7.0
11	5.1	3.8	9.6	12.2	18.8	20.5	27.0	27.5	23.8	20.6	12.2	6.3
12	4.2	1.6	9.5	14.1	19.7	20.7	26.0	26.1	24.1	20.9	12.2	5.8
13	4.3	1.3	9.7	14.0	19.0	20.3	26.2	25.9	23.4	21.2	12.8	5.2
14	3.7	****	10.0	14.3	18.2	20.4	26.0	25.2	22.7	21.0	12.9	5.0
15	3.7	2.6	10.5	13.9	18.0	20.7	26.4	27.1	23.7	20.7	11.6	5.0
16	3.7	3.0	9.5	15.3	18.0	21.4	27.0	27.2	24.1	20.1	13.3	4.5
17	3.9	2.9	9.9	15.1	17.7	22.9	27.3	26.2	24.6	19.3	12.5	3.3
18	3.9	2.6	9.9	14.8	17.6	23.5	27.5	25.9	23.9	18.9	11.9	3.5
19	3.0	3.3	9.3	15.1	18.0	23.1	27.3	26.5	23.4	18.9	11.4	4.0
20	3.0	3.8	9.9	15.7	19.7	23.3	27.9	27.5	23.6	18.1	10.8	3.5
21	2.5	4.5	9.6	15.6	20.3	24.3	28.3	28.4	23.6	17.5	9.7	2.6
22	2.8	4.8	10.6	16.3	20.1	24.7	28.0	28.8	23.0	17.7	10.1	2.2
23	2.8	5.0	9.0	16.0	20.4	25.0	28.0	27.2	22.0	17.5	10.3	2.4
24	2.7	4.1	9.7	16.9	20.8	24.4	27.7	27.0	22.5	17.3	10.6	3.1
25	2.9	4.5	9.4	16.4	21.1	24.8	27.9	27.0	23.0	16.3	9.8	4.3
26	2.7	4.7	9.8	15.9	21.3	24.7	28.4	26.7	21.8	16.1	10.0	3.9
27	2.8	4.9	8.3	15.3	22.2	24.2	28.9	26.2	21.7	16.3	9.6	3.7
28	2.2	5.5	7.3	15.1	23.2	24.3	29.2	26.6	22.0	16.3	9.8	3.1
29	2.2		7.5	15.1	23.1	25.3	28.1	26.4	22.8	16.4	8.9	3.0
30	1.6		7.9	15.6	22.5	25.2	27.8	26.1	22.7	17.0	7.7	2.5
31	1.6		8.6		21.9		28.3	26.0		16.1		2.0
AVG	4.0	3.2	8.8	13.5	19.3	22.6	27.1	27.4	23.8	19.3	11.8	5.0

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1956

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2.0	2.8	6.6	8.3	13.0	20.1	26.5	25.3	27.3	19.1	17.5	8.1
2	2.1	3.3	6.8	9.7	14.5	20.3	27.3	25.2	27.5	19.7	18.1	8.0
3	2.9	3.3	6.9	9.4	14.6	20.3	27.5	25.1	26.2	20.2	17.6	8.0
4	2.5	3.1	6.9	9.1	12.5	20.3	27.9	24.5	26.7	20.3	17.1	8.6
5	2.6	3.3	7.1	11.5	16.0	21.0	27.3	24.2	27.0	19.8	16.6	8.7
6	2.4	3.3	7.5	11.5	16.1	21.4	26.0	24.6	27.2	19.5	16.6	9.0
7	2.4	3.6	8.9	12.3	16.1	21.3	25.9	24.4	26.3	19.3	16.3	9.3
8	2.0	4.6	9.7	9.4	15.8	22.2	26.3	24.6	25.2	19.4	16.1	9.6
9	1.5	4.8	8.0	9.5	16.0	22.5	25.5	25.2	24.2	19.2	15.9	10.1
10	1.1	5.2	9.0	11.7	15.8	22.6	24.9	25.1	23.2	18.5	14.2	8.7
11	1.6	5.2	8.3	9.9	16.6	22.6	25.5	26.0	23.3	18.4	13.7	8.8
12	1.7	5.1	8.5	9.4	17.5	23.3	25.3	25.8	23.2	17.9	12.9	9.3
13	1.9	4.9	8.4	10.4	17.7	23.6	25.2	26.7	23.5	17.7	13.7	9.9
14	1.8	5.8	9.0	10.7	18.3	24.3	25.4	26.2	23.5	17.6	13.2	9.8
15	2.4	6.5	8.1	10.5	18.5	24.3	25.5	26.4	24.3	18.3	13.3	9.5
16	1.6	6.2	7.7	11.6	18.1	24.7	25.8	27.4	24.2	18.0	14.1	9.7
17	1.8	6.3	7.7	10.9	18.4	24.8	25.2	27.0	24.4	17.7	12.9	9.4
18	1.7	6.4	7.2	10.7	18.1	25.0	25.7	27.3	23.8	17.9	12.7	9.6
19	2.0	7.1	6.6	10.6	18.8	23.0	25.4	26.8	23.0	17.9	12.1	9.2
20	1.8	5.8	7.0	10.5	18.5	21.6	25.1	26.5	22.3	17.1	12.1	9.3
21	1.8	6.0	7.3	11.0	18.8	22.5	25.5	25.6	21.5	17.2	12.7	10.2
22	2.1	6.2	7.1	11.3	18.9	24.4	25.6	24.7	21.4	17.5	12.0	9.8
23	1.6	5.5	7.8	11.4	19.1	25.1	26.2	24.7	22.0	17.9	10.5	10.2
24	1.4	5.3	7.1	10.8	18.8	25.4	24.9	24.2	21.5	17.8	9.5	10.0
25	1.6	6.2	6.6	11.6	18.5	25.8	25.5	24.7	21.0	17.3	9.4	9.8
26	1.9	6.5	7.3	11.4	19.7	26.9	26.1	24.7	19.9	16.4	9.5	9.6
27	1.4	7.2	7.5	11.8	19.0	27.1	26.5	25.1	17.9	16.6	9.6	8.6
28	1.8	6.5	7.4	13.3	19.2	26.0	26.4	25.6	18.4	16.5	8.7	8.6
29	1.9		6.7	14.3	19.3	26.3	25.4	25.7	18.2	15.9	8.3	8.7
30	1.3		7.2	14.7	19.2	26.4	25.4	26.3	18.4	16.4	8.6	7.7
31	2.6		7.0		20.0		25.2	26.0		17.2		7.5
AVG	1.9	5.2	7.6	11.0	17.5	23.5	25.9	25.5	23.2	18.1	13.2	9.1

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1957

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	7.3	4.6	6.2	10.3	19.4	21.7	25.3	27.6	24.9	20.1	13.1	9.7
2	6.6	5.0	6.4	10.2	19.4	22.6	25.1	27.7	25.6	20.2	13.1	9.5
3	5.3	4.5	6.6	11.3	18.2	18.2	25.7	28.1	25.9	19.7	13.3	9.1
4	4.7	5.0	6.6	10.9	16.8	16.8	25.6	28.2	25.7	19.0	13.4	9.4
5	4.7	5.3	6.3	11.7	16.4	16.4	26.1	27.2	25.3	18.4	14.1	8.3
6	4.7	5.2	6.2	11.4	16.8	16.8	24.7	26.6	24.5	17.6	13.2	7.4
7	4.7	4.5	6.6	11.1	17.6	17.6	26.1	26.4	25.1	17.6	12.8	8.4
8	4.7	5.4	6.9	11.9	18.0	18.0	26.4	27.1	24.6	17.7	13.1	8.6
9	4.6	5.7	6.2	10.8	18.3	18.3	26.4	26.5	24.6	18.4	12.7	8.6
10	5.4	5.9	6.1	11.3	19.1	19.1	26.0	26.5	25.3	18.3	11.8	7.8
11	4.8	6.2	7.0	12.2	18.6	18.6	25.8	26.8	25.5	18.0	11.2	7.5
12	4.6	5.7	7.5	13.6	19.6	19.6	26.1	27.0	26.2	17.1	10.9	5.4
13	5.0	5.4	8.2	11.8	19.2	19.2	26.5	26.4	26.1	18.1	11.3	4.6
14	4.4	5.4	9.0	11.5	21.1	21.1	26.9	26.0	25.9	16.9	11.7	4.5
15	4.1	4.8	9.1	11.7	21.0	21.0	27.2	25.7	26.3	17.1	12.3	5.2
16	3.6	5.1	9.8	11.8	20.7	20.7	27.0	26.6	26.6	16.9	12.2	5.4
17	3.3	4.8	10.3	13.0	20.7	20.7	26.9	25.9	25.8	16.7	12.7	5.5
18	2.3	5.5	10.2	13.3	21.2	21.2	26.0	25.0	25.1	17.2	12.6	5.8
19	2.2	5.6	9.9	14.2	23.9	20.9	25.9	22.8	24.4	16.9	13.7	6.3
20	2.3	4.7	9.1	15.2	20.8	20.8	26.5	22.6	25.1	16.6	12.9	7.4
21	2.9	5.0	9.1	16.6	20.1	20.1	27.2	23.9	25.3	15.9	12.2	6.8
22	4.4	5.2	9.0	14.7	19.3	19.3	26.9	24.3	25.6	16.1	11.8	7.0
23	4.7	5.5	9.5	16.1	21.1	21.1	26.8	23.8	25.1	15.7	11.6	6.7
24	3.7	5.9	9.3	16.3	22.4	22.4	26.0	23.3	24.4	16.2	11.1	7.4
25	3.4	6.1	9.6	17.3	22.7	22.7	26.1	23.7	24.2	16.1	10.9	6.8
26	3.9	7.2	9.4	18.7	23.0	23.0	26.0	23.5	23.6	15.1	10.6	7.2
27	3.8	7.2	9.4	19.0	21.1	21.3	26.1	24.0	22.5	14.3	10.2	7.2
28	3.8	6.8	9.8	18.9	23.3	23.3	26.2	24.2	23.9	13.5	10.7	6.6
29	5.3		9.8	19.4	22.0	22.0	26.6	24.4	20.5	13.1	11.6	7.3
30	4.7		9.4	20.0	20.9	20.9	26.8	24.6	20.4	12.7	11.5	6.8
31	4.5		10.0		21.3		27.2	25.1		13.2		6.4
AVG	4.3	5.5	8.3	13.9	20.1	20.2	26.3	25.5	24.8	16.8	12.1	7.1

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1958

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	6.7	4.0	3.2	7.9	14.9	22.9	24.7	27.9	25.2	21.3	14.7	9.1
2	6.3	3.4	4.5	7.3	15.3	21.5	24.6	27.2	24.7	19.4	14.5	8.8
3	5.8	3.3	5.1	6.8	15.8	20.1	24.3	26.3	24.5	19.3	13.9	8.6
4	5.2	2.5	4.2	8.7	17.3	20.0	25.6	26.0	24.7	19.0	13.8	9.4
5	4.4	2.5	4.7	8.9	16.8	20.6	25.4	26.3	25.0	19.0	14.2	9.9
6	3.9	3.2	4.5	9.2	15.6	21.0	25.0	27.1	25.3	18.7	14.4	9.4
7	3.5	3.4	5.0	8.9	15.5	21.5	24.1	27.6	24.7	18.0	13.9	8.8
8	2.7	2.8	5.3	7.6	15.5	20.9	24.4	26.7	24.1	18.2	13.6	8.0
9	2.5	2.0	5.4	10.3	15.9	21.2	23.7	26.3	24.1	19.0	13.5	8.2
10	1.9	1.7	4.8	9.5	16.0	21.9	25.3	27.4	23.6	19.5	13.3	7.4
11	2.6	1.8	5.6	8.6	17.2	22.2	24.9	27.6	23.4	19.1	12.5	6.2
12	2.7	2.2	6.0	9.2	18.8	23.6	24.9	28.3	22.8	18.3	12.8	5.0
13	2.2	1.8	5.5	9.6	16.6	23.9	25.5	27.5	22.5	18.0	13.0	5.0
14	2.3	1.5	5.0	10.6	18.2	23.0	25.5	26.3	22.5	17.7	13.4	4.7
15	3.0	1.2	4.9	12.3	18.2	23.6	26.3	26.8	22.5	18.3	13.8	4.5
16	2.9	1.4	4.7	11.9	18.8	22.6	25.4	26.0	23.2	18.5	14.0	3.8
17	2.8	0.3	4.9	11.6	19.7	22.3	25.8	25.7	23.9	18.6	14.5	3.8
18	2.7	-0.2	5.3	12.7	20.5	22.9	26.0	26.1	23.7	18.3	14.9	3.8
19	2.2	-0.4	4.8	13.6	18.4	23.2	25.6	25.8	23.0	17.5	15.2	3.7
20	1.9	-1.1	4.6	14.2	19.3	22.5	25.1	25.9	23.2	17.1	14.7	3.8
21	2.7	0.1	4.5	14.7	20.0	22.2	25.0	26.3	22.3	16.1	14.1	3.5
22	3.3	0.1	4.5	14.6	19.8	21.7	25.8	26.5	22.9	16.0	13.6	3.5
23	2.9	0.5	5.0	12.1	25.1	21.1	25.8	26.9	23.1	16.7	13.6	3.8
24	3.0	1.2	5.4	14.4	19.7	21.9	25.8	26.8	23.2	17.5	13.9	4.1
25	3.2	2.4	6.1	15.0	20.6	22.8	25.8	26.2	23.6	16.9	13.5	4.0
26	3.3	3.0	5.8	15.7	19.2	23.6	26.3	25.3	24.3	16.4	13.3	3.3
27	3.6	3.0	5.8	14.9	20.1	22.9	27.0	24.8	24.1	16.4	12.7	3.1
28	3.5	2.4	6.9	14.8	20.1	23.1	27.5	24.0	22.5	15.6	11.9	3.6
29	3.6		7.1	14.6	18.4	23.6	27.5	24.3	21.8	15.5	11.9	5.2
30	3.8		7.8	15.3	20.7	23.6	28.8	25.1	21.8	15.0	10.7	4.7
31	3.9		7.9		21.1		28.5	25.5		14.9		4.9
AVG	3.4	1.8	5.3	11.5	18.4	22.3	25.7	26.3	23.5	17.7	13.6	5.7

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1959

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	4.9	4.1	6.1	10.8	17.3	23.5	29.2	28.6	28.4	24.8	17.3	7.9
2	5.1	3.7	5.7	10.9	17.6	23.5	28.3	27.9	27.9	24.4	16.6	8.2
3	5.5	2.9	6.1	11.2	19.0	23.4	27.2	27.8	28.4	23.6	15.5	8.3
4	5.5	4.0	6.3	10.5	18.8	23.9	27.2	26.3	28.0	24.4	15.4	8.0
5	3.9	4.4	7.1	11.8	19.2	24.4	26.9	26.1	27.6	24.7	16.2	8.0
6	1.9	4.0	8.3	12.6	19.8	24.4	26.9	25.8	27.3	24.8	16.9	8.2
7	2.1	4.4	7.2	13.2	19.8	24.5	27.3	25.5	27.5	24.7	15.5	7.5
8	2.3	4.6	7.9	13.9	18.9	24.7	27.1	26.0	27.5	24.8	14.6	7.4
9	1.9	4.4	7.7	15.1	22.3	25.7	26.9	26.0	27.6	25.0	14.3	7.5
10	1.8	5.1	7.5	15.4	19.7	26.6	26.2	26.1	27.9	24.8	13.8	7.2
11	1.4	5.2	7.7	15.2	20.0	27.2	26.0	26.6	27.6	25.1	13.6	7.2
12	1.5	5.8	7.9	13.9	20.1	27.3	25.8	26.9	26.3	24.4	13.7	7.9
13	1.6	5.8	7.2	13.2	19.5	26.1	26.1	27.5	26.1	23.6	13.6	8.0
14	2.1	6.4	7.8	12.3	19.0	23.4	26.1	27.8	25.8	23.0	14.0	7.5
15	2.9	6.2	8.3	12.3	19.0	22.7	25.8	28.3	25.5	22.2	13.5	7.4
16	3.2	6.9	8.3	13.5	18.5	23.4	26.0	28.6	25.5	20.9	13.0	7.4
17	1.6	6.6	9.2	14.8	19.1	22.9	26.4	28.0	25.5	20.9	13.0	7.5
18	1.6	6.5	8.0	15.1	18.3	22.2	26.6	27.6	24.0	20.7	11.4	7.6
19	****	5.4	8.1	15.0	19.9	22.3	27.2	28.6	23.2	19.7	10.8	7.2
20	2.8	5.0	9.3	15.9	21.2	23.0	27.5	29.0	23.4	19.1	10.5	6.8
21	4.6	4.7	10.0	16.0	21.5	23.7	26.5	28.9	23.5	19.0	10.2	6.2
22	4.7	5.3	8.6	15.1	21.8	24.3	26.9	28.6	23.5	18.5	10.8	6.2
23	3.3	5.8	9.3	14.3	22.5	24.8	27.6	29.1	24.0	19.3	10.8	5.5
24	3.6	6.0	10.3	14.6	21.8	25.1	27.6	28.5	24.1	19.4	11.2	5.0
25	4.0	5.7	11.2	15.4	22.2	25.8	27.7	29.1	24.6	18.7	11.2	5.1
26	3.6	6.0	10.9	15.9	22.6	25.9	28.4	29.6	25.0	18.2	10.1	5.8
27	3.6	6.1	10.5	16.2	22.6	26.5	28.2	29.3	25.4	17.7	10.8	6.6
28	3.6	6.5	9.7	15.7	23.3	27.2	28.6	29.4	24.8	17.3	11.2	5.8
29	3.8		9.8	16.5	23.4	27.6	28.9	29.1	25.1	16.5	9.8	6.2
30	4.4		9.7	17.2	23.4	28.1	29.0	28.5	25.0	16.4	8.6	5.9
31	4.7		10.2		23.4		28.9	28.3		16.8		****
AVG	3.3	5.3	8.4	14.1	20.5	24.8	27.3	27.9	25.9	21.4	12.9	7.0

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1960

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	5.5	4.4	4.7	8.5	16.1	22.6	25.7	25.3	26.4	21.8	14.4	10.8
2	5.4	4.3	4.1	9.5	16.5	23.0	25.1	26.7	26.4	21.5	14.6	9.4
3	6.4	4.1	2.8	9.7	16.3	22.6	25.9	27.0	26.2	21.5	14.7	8.9
4	5.8	4.1	2.7	10.8	18.2	23.0	25.0	27.3	26.1	20.9	13.7	9.0
5	5.8	4.1	2.2	10.3	17.7	23.9	26.2	27.2	26.3	20.5	13.7	9.4
6	5.5	5.0	2.1	9.4	18.2	24.2	26.2	27.5	27.5	21.0	13.5	9.3
7	5.7	5.0	2.2	10.5	18.6	23.7	25.5	27.2	25.5	21.1	13.0	9.6
8	5.8	4.3	2.5	10.5	18.6	23.5	25.8	26.6	25.7	20.4	11.6	9.3
9	5.7	5.1	1.8	10.7	16.8	22.9	25.8	28.2	25.9	19.8	11.5	8.2
10	5.7	5.8	0.9	10.4	17.3	22.1	25.7	27.5	26.4	20.1	12.2	7.3
11	6.1	7.2	****	10.8	17.2	22.2	25.5	26.9	26.2	20.0	11.3	7.3
12	5.3	6.5	****	10.9	16.9	22.9	25.9	26.2	25.0	20.5	11.1	6.2
13	5.8	5.4	****	12.2	17.1	24.7	26.4	26.6	24.7	20.7	11.1	5.1
14	6.3	4.6	2.5	12.8	16.8	24.1	26.3	27.6	24.3	21.0	11.9	3.9
15	6.8	4.1	3.0	13.3	17.1	24.1	25.7	26.9	24.0	21.1	11.6	3.7
16	6.4	4.4	2.3	14.0	18.4	24.8	25.8	27.2	23.9	21.6	12.3	4.3
17	6.3	4.6	3.0	14.4	19.3	25.3	26.1	26.6	23.0	20.8	13.0	4.1
18	4.2	4.7	2.6	14.0	19.1	24.6	26.1	25.7	24.0	20.8	12.6	4.0
19	6.0	4.1	3.3	14.3	20.0	24.8	26.4	25.8	24.7	20.5	12.3	4.3
20	5.5	4.0	3.6	14.3	20.1	25.5	26.8	25.8	24.9	20.1	11.9	3.7
21	4.7	4.0	3.7	14.7	21.2	25.0	26.6	26.2	24.3	19.2	11.8	4.0
22	5.5	4.1	3.7	15.1	21.7	25.7	26.5	25.8	23.7	18.2	11.9	3.5
23	4.0	4.0	3.6	15.5	21.0	25.2	26.8	26.0	23.3	17.5	12.0	2.6
24	3.5	4.3	3.9	16.0	20.8	25.3	27.2	25.5	23.2	16.9	11.8	2.2
25	3.3	4.1	3.2	15.8	21.8	24.7	27.5	24.7	22.6	16.1	11.5	2.5
26	3.7	4.4	3.2	16.8	22.5	24.7	26.8	24.1	22.3	15.8	11.6	2.9
27	4.3	4.3	5.0	17.5	21.8	26.0	26.5	24.7	21.8	16.0	11.8	3.0
28	4.3	5.3	5.9	16.6	21.2	25.8	26.8	25.5	21.8	15.7	12.2	2.8
29	4.6		6.8	17.2	22.2	25.7	25.5	26.4	21.9	14.8	12.6	2.8
30	4.4		7.8	16.8	23.6	25.4	25.0	26.5	21.9	14.1	11.6	3.2
31	4.3		8.0		22.5		25.7	26.8		14.3		3.2
AVG	5.3	4.6	3.6	13.1	19.3	24.3	26.1	26.4	24.5	19.2	12.4	5.5

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1961

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.6	1.5	6.8	10.0	13.6	19.3	24.3	27.7	27.2	22.6	17.2	8.7
2	3.6	0.7	7.1	9.6	13.9	20.1	25.0	27.8	27.9	22.5	17.1	8.8
3	3.4	-0.1	7.3	9.6	14.4	20.6	24.4	27.7	28.0	22.3	17.6	9.1
4	3.3	0.1	8.0	9.4	14.8	20.6	24.4	27.3	28.0	21.1	18.2	8.8
5	3.3	****	8.6	9.3	15.5	21.4	24.7	26.6	28.4	20.4	18.2	9.7
6	3.3	0.8	8.7	10.0	14.8	21.6	23.6	26.8	29.0	20.5	18.0	9.4
7	3.3	0.7	9.4	10.1	15.5	22.7	24.1	27.5	29.0	21.3	17.5	8.9
8	3.5	0.8	9.2	9.9	16.9	23.1	25.1	27.2	28.3	21.1	16.6	8.6
9	3.5	1.0	8.0	10.1	17.7	23.2	24.4	28.2	28.3	21.1	15.5	8.0
10	2.7	1.2	8.4	10.0	17.9	22.7	23.7	27.5	28.3	21.6	14.7	7.5
11	2.6	2.0	7.6	10.0	18.6	24.6	24.8	27.3	27.9	21.8	14.1	7.9
12	3.2	1.9	8.4	10.1	18.9	25.1	25.1	26.9	28.0	21.1	14.0	8.0
13	3.0	2.5	9.3	9.8	19.6	25.5	25.7	26.4	27.9	21.1	14.7	7.6
14	3.5	3.0	9.1	10.9	20.0	24.7	25.5	26.2	27.2	20.8	14.8	6.9
15	3.8	3.3	9.0	11.2	20.7	23.7	25.9	26.2	25.7	19.3	15.0	7.2
16	4.0	3.3	8.7	11.3	20.5	22.3	25.0	26.4	24.4	18.9	14.7	6.5
17	4.4	3.4	8.2	10.8	20.3	22.7	24.8	26.3	22.9	18.6	14.7	6.8
18	4.6	4.4	8.0	10.8	20.1	23.3	25.0	26.1	22.5	19.0	13.9	6.8
19	4.3	5.5	8.4	11.4	20.3	23.0	26.0	25.2	21.9	19.3	13.3	6.6
20	3.6	4.3	9.0	11.8	20.0	23.9	24.9	24.6	22.5	18.9	13.3	6.9
21	2.9	5.4	8.8	11.9	19.7	23.3	25.3	24.7	22.9	18.6	11.9	6.6
22	2.7	5.5	8.0	12.6	20.1	22.9	26.4	25.0	22.7	17.6	11.5	6.1
23	2.2	5.5	8.5	14.0	20.2	24.0	27.2	25.8	23.2	17.1	11.1	6.4
24	2.4	6.6	8.4	14.0	19.7	23.6	28.0	26.4	23.9	17.2	11.4	6.1
25	1.9	7.1	8.6	13.6	20.0	23.2	28.0	26.5	23.8	17.2	11.0	5.4
26	0.7	5.8	9.3	14.7	19.7	22.7	27.9	26.6	24.3	16.9	10.7	5.4
27	0.5	7.4	10.0	14.9	20.0	22.2	28.3	26.7	23.7	16.3	10.7	5.0
28	0.3	6.4	10.9	14.7	17.1	21.8	28.6	27.6	23.7	16.0	10.4	5.4
29	0.5		11.9	13.3	17.6	22.2	28.1	27.6	23.0	16.0	10.0	5.0
30	0.5		11.9	13.0	18.0	22.8	28.0	27.7	22.9	16.6	9.1	4.8
31	1.0		10.7		18.3		28.0	27.3		16.6		4.2
AVG	2.8	3.3	8.9	11.4	18.2	22.8	25.8	26.7	25.6	19.3	14.0	7.1

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1962

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	4.4	3.3	5.7	10.8	18.7	23.4	23.4	26.4	26.2	20.2	13.3	10.0
2	4.4	2.9	4.7	10.1	17.9	23.0	25.1	26.5	26.1	20.2	13.2	9.8
3	4.1	3.5	5.0	9.8	17.7	22.1	23.8	25.8	24.6	20.0	12.9	7.9
4	4.8	4.0	5.1	10.6	17.2	22.3	22.9	26.1	24.8	19.8	12.6	9.4
5	5.4	4.1	4.6	10.9	18.6	21.9	22.3	26.5	25.0	20.5	11.9	9.7
6	6.1	4.1	4.3	11.9	18.3	22.1	23.3	26.1	24.7	20.8	****	9.1
7	6.0	3.6	3.9	12.6	18.6	22.8	25.0	25.7	23.7	20.5	****	8.2
8	4.0	3.6	3.7	11.3	19.2	23.3	26.1	26.7	23.3	20.8	****	7.7
9	4.7	3.3	4.0	12.6	18.3	23.7	25.6	27.1	23.6	20.7	****	8.0
10	4.4	3.2	4.1	12.6	18.6	24.3	25.8	26.2	25.0	20.8	****	6.8
11	3.4	2.8	4.6	12.9	18.0	23.6	25.7	25.4	24.4	21.0	****	6.0
12	2.9	5.0	5.7	11.1	18.6	22.1	25.7	25.4	24.3	21.1	****	6.0
13	2.2	2.4	5.3	11.7	17.9	22.2	25.7	25.1	24.7	20.8	****	4.6
14	1.8	2.6	5.4	11.6	20.0	21.6	26.0	25.5	25.0	****	****	3.6
15	3.3	3.0	5.4	11.1	20.1	22.2	26.2	25.7	24.1	20.8	****	3.3
16	3.3	2.8	6.2	11.3	20.8	23.1	26.2	26.1	23.7	21.0	****	3.3
17	3.5	3.2	5.8	10.7	20.4	23.7	25.4	25.7	24.7	21.0	****	3.5
18	2.9	3.7	6.1	10.7	20.8	24.4	25.8	26.1	23.7	19.4	****	3.7
19	2.9	2.9	6.2	11.2	22.3	25.1	24.4	25.4	23.7	19.7	10.1	3.7
20	2.9	4.0	8.1	11.4	21.9	24.0	26.2	25.3	23.0	19.9	9.6	4.3
21	3.0	4.1	7.7	11.7	22.2	23.6	25.7	26.2	21.3	19.1	****	3.5
22	3.9	4.7	5.7	12.8	22.8	24.4	26.4	25.7	21.0	19.1	****	3.3
23	4.6	4.7	7.6	12.6	23.0	24.8	25.8	25.4	20.7	18.6	8.1	3.5
24	4.0	5.0	7.7	13.8	23.0	24.8	26.1	25.2	20.3	18.2	9.0	3.5
25	4.1	5.0	10.8	14.0	22.8	24.7	25.8	25.5	****	****	****	3.2
26	5.0	4.0	8.3	15.5	22.9	25.0	26.0	26.1	20.4	****	9.3	3.2
27	4.9	6.1	8.3	16.4	22.2	25.1	25.8	25.7	20.1	14.7	9.1	3.0
28	4.3	6.1	9.2	16.9	21.1	24.4	25.9	25.2	20.1	15.1	9.1	3.2
29	3.9		9.7	17.9	20.8	23.9	25.4	24.8	19.7	****	9.4	2.9
30	4.0		10.7	17.7	21.7	23.0	25.8	25.2	19.4	****	9.7	2.3
31	2.7		11.2		23.0		25.8	25.9		14.3		0.9
AVG	3.9	3.9	6.5	12.5	20.3	23.4	25.3	25.8	23.1	19.5	10.5	5.2

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1963

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	1.2	2.2	12.2	14.8	21.2	26.6	27.9	25.5	20.0	15.8	10.4
2	1.1	1.6	2.4	12.6	14.7	20.7	26.8	27.1	25.7	20.1	15.0	9.9
3	0.9	1.6	3.0	13.7	16.2	19.4	25.9	26.9	25.7	20.0	13.8	10.2
4	1.1	0.9	4.0	12.5	16.4	21.2	25.4	26.6	25.1	19.9	13.6	11.0
5	1.3	1.8	3.8	11.9	16.9	22.6	25.3	26.4	24.1	19.4	14.1	9.1
6	1.2	2.5	3.9	12.5	16.1	22.5	25.8	27.1	23.7	19.6	14.6	9.4
7	1.6	3.1	4.3	12.7	16.7	22.5	26.0	26.9	24.1	19.6	14.3	8.7
8	1.9	2.6	5.5	13.6	17.1	22.6	26.5	26.5	24.1	19.7	14.1	8.7
9	2.1	2.2	5.9	12.2	18.2	22.5	25.4	27.0	23.9	19.4	14.1	8.6
10	2.7	2.7	6.1	11.6	18.5	23.0	25.0	26.6	24.0	19.3	14.3	8.2
11	3.7	2.8	6.2	12.9	17.7	22.5	24.8	26.4	24.9	19.3	14.3	7.6
12	4.1	2.9	6.3	11.5	17.2	22.5	25.3	26.8	25.0	19.1	14.3	7.1
13	4.0	2.8	7.2	11.5	17.1	22.3	25.4	26.1	23.5	18.8	13.6	7.5
14	3.0	2.6	7.3	11.6	17.1	22.5	24.7	25.8	22.6	18.7	12.7	7.1
15	2.9	2.5	7.9	12.2	18.2	22.7	25.0	25.9	21.9	18.7	12.5	6.3
16	2.9	1.9	7.6	13.2	17.9	22.6	25.8	25.6	21.2	19.0	12.5	5.5
17	3.0	1.8	8.1	13.0	17.7	23.0	26.3	25.9	21.0	18.9	13.0	4.4
18	3.1	1.8	9.6	13.0	18.3	22.8	26.1	26.4	21.2	19.0	12.6	5.1
19	3.7	2.5	9.0	14.4	19.2	23.4	27.2	25.5	22.2	19.3	13.0	4.8
20	4.3	2.9	8.6	13.3	19.1	24.0	26.2	26.1	22.3	18.5	12.5	3.3
21	4.2	2.6	6.6	15.2	19.0	23.0	26.4	26.3	21.9	18.9	12.7	3.0
22	3.2	2.1	7.1	16.3	20.0	23.7	26.5	25.9	21.5	18.3	12.7	2.4
23	4.0	2.4	7.2	15.5	19.1	23.4	26.8	26.9	20.5	18.5	13.2	2.1
24	2.7	1.9	7.9	14.4	19.2	24.3	26.8	27.2	20.0	18.6	12.6	2.5
25	2.4	3.0	9.3	14.5	19.3	24.2	27.2	26.5	20.1	18.6	11.8	2.5
26	1.8	2.1	9.7	15.0	19.3	25.0	27.8	26.0	20.2	18.7	11.6	2.5
27	2.5	1.6	9.7	16.3	19.3	25.1	28.2	25.8	20.7	19.1	12.5	2.7
28	1.3	1.7	10.3	15.5	19.8	25.2	27.8	25.7	20.4	18.6	12.9	3.2
29	1.4		11.2	14.7	20.0	25.8	26.9	25.5	20.4	17.8	12.9	3.2
30	1.4		11.4	15.2	20.1	25.8	27.3	25.5	20.0	16.7	11.4	2.9
31	1.6		12.0		20.8		27.6	26.0		16.0		2.3
AVG	2.5	2.2	7.1	13.5	18.1	23.1	26.3	26.4	22.6	18.9	13.3	5.9

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1964

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2.5	4.0	3.7	7.7	****	****	****	25.1	25.4	****	15.1	8.9
2	2.7	3.7	4.8	7.2	****	****	****	25.1	25.2	****	15.1	9.4
3	3.0	3.5	5.4	8.6	****	****	****	26.0	25.2	****	14.7	9.2
4	3.7	3.3	6.0	9.0	****	****	****	25.2	25.0	****	14.7	10.5
5	3.3	****	6.6	8.6	****	****	****	24.9	25.5	19.7	14.7	10.4
6	3.9	****	****	8.1	****	****	****	25.0	25.5	19.3	14.6	10.0
7	4.1	****	7.6	9.0	****	****	****	25.4	25.1	18.7	14.1	9.7
8	4.1	4.6	7.8	9.6	****	****	****	24.9	25.0	17.2	14.1	9.4
9	4.7	4.4	8.5	10.8	****	****	****	25.8	25.3	16.4	14.5	8.5
10	4.6	4.3	9.0	****	****	****	****	24.6	25.7	****	14.4	8.9
11	4.0	4.7	8.0	****	****	****	****	25.4	26.0	****	14.4	8.5
12	3.3	5.0	8.3	****	****	****	****	25.8	25.2	****	14.6	8.6
13	3.0	4.3	8.3	****	****	****	****	25.2	23.3	16.8	14.5	9.6
14	2.2	3.7	8.0	****	****	****	****	24.6	22.5	16.9	14.7	9.3
15	1.4	3.6	8.3	****	****	****	25.7	24.1	22.5	16.8	14.4	8.8
16	1.2	3.8	8.0	****	****	****	26.1	23.3	22.7	16.5	14.7	7.6
17	1.4	4.2	7.7	****	****	****	26.3	24.0	22.7	16.5	14.8	8.0
18	1.3	3.6	7.9	****	****	****	25.7	24.4	22.9	17.1	14.8	8.3
19	1.8	4.0	7.5	****	****	****	25.5	24.4	23.3	17.0	14.8	6.2
20	1.9	4.0	7.9	****	****	****	25.9	24.4	22.9	16.2	14.7	6.8
21	2.2	3.7	8.0	****	****	****	26.1	25.0	21.8	15.7	14.0	6.9
22	3.0	3.9	8.0	****	****	****	25.2	25.5	21.6	15.2	12.9	6.9
23	3.0	3.7	8.0	****	****	****	26.5	25.7	21.9	14.7	12.6	6.6
24	3.6	3.2	****	****	****	****	25.7	26.4	21.8	14.6	12.5	7.0
25	4.4	3.3	10.3	****	****	****	25.0	26.2	21.5	****	12.4	7.6
26	3.9	4.5	8.8	****	****	****	25.5	25.5	21.1	15.0	12.5	9.3
27	3.6	4.4	9.1	****	****	****	25.6	25.4	****	15.2	12.8	9.2
28	****	4.3	9.1	****	****	****	25.7	25.5	****	15.1	12.5	7.9
29	****		8.3	****	****	****	25.8	25.8	****	14.9	13.2	7.5
30	3.5		8.4	****	****	****	26.4	25.8	****	15.0	11.4	7.7
31	3.5		8.8		****		25.3	25.5		15.1		7.6
AVG	3.1	4.0	7.8	8.7	****	****	25.8	25.2	23.7	16.3	14.0	8.4

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1965

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	7.1	2.6	5.0	9.4	15.5	21.6	24.0	24.7	24.8	21.8	13.7	9.7
2	7.3	1.9	5.0	7.4	15.4	22.6	24.1	25.0	23.8	21.6	13.5	8.6
3	6.9	1.5	4.9	8.5	14.7	20.8	23.6	25.1	23.6	21.5	13.3	8.3
4	6.1	1.6	5.0	9.0	16.8	20.9	24.7	25.1	24.3	21.0	13.3	8.7
5	6.2	2.1	4.4	9.7	17.5	21.8	24.3	26.1	23.2	19.7	13.0	8.2
6	6.2	2.9	5.1	9.3	17.2	21.8	24.8	26.1	23.7	18.9	13.6	8.3
7	6.2	3.8	5.1	9.4	17.3	22.6	25.2	26.1	23.4	18.0	13.7	7.7
8	6.8	4.4	5.8	9.6	16.9	22.8	24.6	26.4	24.3	18.4	13.8	7.5
9	7.1	3.9	5.7	9.6	16.9	21.9	25.6	26.0	24.1	18.7	13.9	7.6
10	6.6	4.3	5.2	10.8	17.5	23.2	25.4	26.1	24.0	18.3	13.0	7.5
11	6.5	4.6	5.2	10.2	19.0	23.6	25.1	26.1	23.8	18.4	12.9	7.7
12	6.2	5.1	5.8	11.1	18.9	22.6	24.7	26.7	23.6	18.2	13.0	7.9
13	6.1	5.4	5.9	10.2	19.0	22.6	25.4	26.4	24.4	18.3	13.0	8.5
14	6.1	4.4	6.2	11.1	19.0	22.3	26.3	26.5	24.3	18.3	13.0	8.4
15	4.8	4.0	6.5	10.7	18.8	20.5	25.7	26.5	24.3	18.6	12.6	8.6
16	4.3	4.1	6.3	11.2	19.4	19.7	26.4	26.6	24.3	18.6	12.9	8.4
17	3.8	4.4	6.6	12.2	18.4	19.8	26.5	26.6	24.6	18.2	12.3	8.2
18	2.9	4.4	7.1	12.5	19.3	20.3	26.2	27.1	25.0	17.5	11.1	8.0
19	3.0	4.0	6.2	12.2	19.9	20.4	26.1	26.7	25.5	17.8	11.2	7.9
20	2.5	3.3	5.5	14.1	20.8	21.1	25.5	25.8	25.8	18.2	11.5	7.5
21	3.0	3.7	5.7	13.3	21.5	21.5	25.8	26.4	26.2	17.8	****	7.1
22	2.9	4.0	6.5	12.1	21.7	21.4	25.4	26.2	26.4	17.9	11.4	7.1
23	3.7	3.6	7.2	11.5	22.6	21.8	25.2	26.0	25.8	17.9	11.1	6.9
24	3.6	4.4	7.1	12.6	20.9	****	25.9	26.0	25.5	17.8	10.5	6.9
25	3.2	3.3	6.9	13.0	21.4	21.6	26.7	25.5	24.9	16.8	10.7	7.3
26	4.0	3.4	8.2	12.5	21.5	21.8	25.9	26.1	24.3	15.9	10.8	7.1
27	4.4	4.8	8.0	12.6	22.1	22.5	25.5	26.5	23.7	15.7	11.0	6.2
28	3.8	5.3	8.6	12.9	21.8	23.1	25.2	26.1	22.6	15.4	10.4	6.0
29	4.0		9.2	13.2	21.3	23.4	24.4	24.7	22.7	14.6	10.5	6.1
30	3.6		9.3	13.5	20.7	23.8	24.7	24.7	22.6	14.1	10.4	6.5
31	3.0		9.4		20.7		24.8	24.4		14.0		7.1
AVG	4.9	3.8	6.4	11.2	19.2	21.9	25.3	25.9	24.3	18.0	12.2	7.7

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1966

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	7.4	****	4.7	8.6	15.0	19.0	26.0	25.5	26.1	19.7	14.7	9.1
2	7.9	-0.7	5.8	8.5	14.6	19.1	26.5	24.7	26.0	18.7	15.3	8.8
3	8.0	-0.1	6.0	9.4	15.4	19.7	25.8	24.1	26.4	19.0	14.2	8.6
4	7.5	-0.8	6.7	9.6	14.7	20.2	26.7	23.5	25.7	19.1	13.4	7.2
5	7.3	-0.7	7.2	9.4	15.2	21.1	26.9	23.6	26.1	19.0	13.0	7.2
6	7.5	-0.1	6.2	9.4	15.8	21.5	26.7	24.1	25.5	18.3	13.0	7.3
7	7.5	0.4	5.5	9.0	16.9	21.7	26.2	23.6	25.1	18.2	12.7	7.0
8	6.6	****	5.9	10.0	16.9	21.5	25.6	24.7	24.0	18.0	12.7	8.0
9	5.0	****	6.4	10.1	16.1	21.6	26.8	24.7	23.8	18.0	13.5	8.6
10	5.7	1.5	6.7	9.7	15.8	21.9	26.2	24.7	23.3	18.9	13.8	9.4
11	5.7	2.2	6.7	10.0	16.3	20.4	26.2	24.6	24.0	18.6	14.8	8.8
12	5.0	2.2	7.2	11.2	15.8	19.4	27.2	24.2	23.3	17.9	13.8	8.0
13	5.0	3.7	7.3	10.5	16.5	20.2	28.0	24.4	22.2	18.0	13.0	8.0
14	5.2	2.0	7.1	10.1	16.5	20.3	28.2	24.3	22.2	18.6	12.7	7.5
15	4.7	2.5	7.7	10.8	16.4	21.6	27.2	24.7	22.6	18.9	12.7	6.9
16	4.5	2.3	7.6	11.7	16.7	21.6	26.5	25.4	22.1	18.7	11.9	6.6
17	4.3	4.0	7.3	11.9	17.5	20.8	26.2	24.0	21.7	17.9	11.9	6.6
18	3.8	4.4	8.0	12.1	18.0	21.0	26.6	25.5	21.5	17.2	12.1	6.9
19	3.3	4.4	8.2	12.6	18.4	21.1	25.7	26.1	21.4	17.2	12.1	6.9
20	3.0	4.3	8.2	13.5	19.4	21.5	26.0	26.1	20.7	16.6	11.4	6.6
21	3.1	4.1	9.0	14.1	20.1	22.6	25.3	26.4	21.0	16.4	11.1	6.5
22	2.7	4.1	9.6	14.2	19.0	22.2	25.4	26.8	21.5	15.8	10.5	6.4
23	3.0	4.3	10.0	14.7	19.7	22.7	25.3	26.9	21.6	17.1	10.5	6.2
24	3.0	3.9	10.1	15.3	20.3	23.3	25.1	26.1	21.4	17.2	10.4	5.0
25	2.7	3.8	9.1	14.7	19.7	23.2	25.8	25.7	20.8	16.9	10.5	4.3
26	2.2	3.8	9.1	14.7	19.7	24.3	26.5	25.5	20.3	16.1	11.0	3.9
27	2.0	4.1	9.0	14.7	20.2	24.5	27.2	25.9	20.1	15.7	11.1	3.8
28	1.3	4.9	8.7	13.7	20.2	24.4	26.5	26.1	20.3	15.5	10.8	3.3
29	0.4		8.8	14.1	20.4	24.3	26.1	26.6	20.3	15.5	10.1	3.7
30	-0.4		9.0	14.9	20.3	25.4	25.2	26.4	20.7	15.0	9.4	3.6
31	-1.4		8.6		19.1		24.7	26.4		14.0		3.6
AVG	4.3	2.6	7.7	11.8	17.6	21.7	26.3	25.2	22.7	17.5	12.3	6.6

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1967

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.6	5.8	2.7	10.1	14.4	16.8	24.1	25.9	24.4	19.7	15.3	7.7
2	4.3	6.4	2.5	11.0	14.7	17.7	24.7	26.8	23.6	20.0	15.3	7.0
3	4.7	5.5	4.2	11.1	14.4	18.9	24.4	26.7	23.6	20.3	15.7	7.3
4	4.1	6.1	4.7	11.1	14.7	20.0	24.6	26.5	23.3	20.5	15.7	7.2
5	4.0	6.1	5.3	10.5	15.7	20.7	23.6	25.2	24.2	20.5	14.7	7.2
6	3.8	6.1	5.8	11.4	15.5	21.1	23.9	25.5	23.7	20.7	14.0	7.1
7	4.1	5.3	5.5	11.9	15.0	21.5	23.0	25.5	24.0	19.7	13.5	7.2
8	5.0	4.6	6.4	11.8	14.4	21.9	23.9	26.1	24.3	19.0	12.5	7.7
9	5.2	4.0	6.8	11.7	13.8	23.8	24.7	25.9	24.1	19.8	11.6	7.7
10	5.1	3.8	7.4	11.4	14.1	22.2	25.0	25.3	23.6	19.7	11.9	7.8
11	4.7	4.1	7.8	12.2	14.6	23.3	25.2	24.7	22.6	19.1	11.9	7.9
12	4.3	4.1	8.2	11.7	15.5	23.6	25.4	23.8	21.7	18.6	12.2	8.5
13	4.5	4.1	8.3	11.7	15.1	24.2	24.7	23.3	21.6	18.3	12.2	8.3
14	4.7	4.3	8.6	12.5	15.1	23.3	24.1	23.9	21.4	18.2	11.9	8.3
15	4.7	5.0	9.1	12.6	15.8	23.3	24.0	****	21.4	18.2	11.2	8.3
16	5.0	5.5	7.6	13.9	15.8	23.9	24.3	****	20.8	18.5	9.2	7.6
17	4.4	5.0	7.6	14.4	16.7	23.8	25.2	****	20.7	18.7	8.5	7.2
18	4.7	4.7	7.5	13.3	17.0	23.9	25.1	****	21.4	18.2	9.3	7.2
19	3.6	4.7	6.6	13.6	17.8	23.0	25.2	25.8	21.9	17.1	9.1	8.0
20	3.7	4.3	6.4	13.1	17.5	22.7	25.5	25.1	22.2	17.2	9.2	8.3
21	4.0	4.7	6.4	13.3	17.1	23.3	25.5	25.0	22.1	16.7	9.1	7.8
22	4.7	4.7	6.6	13.9	16.5	23.9	25.8	25.0	21.6	16.6	9.2	8.3
23	5.3	4.7	6.6	13.3	16.7	23.6	26.4	24.4	21.0	16.6	9.1	7.4
24	6.1	4.4	6.6	12.9	15.5	24.7	26.7	24.1	20.1	17.0	8.5	6.4
25	6.2	3.0	7.2	13.3	15.0	24.4	26.1	25.3	20.1	16.6	9.2	5.8
26	6.7	2.1	8.3	12.5	16.1	24.1	25.8	25.8	20.1	16.3	9.3	7.7
27	7.2	2.7	8.2	12.1	16.4	23.9	26.4	25.8	20.0	16.1	9.6	5.8
28	5.8	3.0	8.4	11.9	17.2	23.9	25.9	25.1	20.5	16.0	8.5	5.6
29	5.1		8.3	12.7	18.9	23.6	25.8	25.7	21.1	15.5	8.0	5.8
30	5.3		9.2	13.0	17.7	23.6	25.0	25.2	20.1	15.4	7.6	5.8
31	5.2		10.0		17.6		25.5	25.3		15.3		5.1
AVG	4.8	4.6	6.9	12.3	15.9	22.6	25.0	25.3	22.0	18.1	11.1	7.3

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1968

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	5.3	3.7	2.3	10.5	****	****	25.5	26.4	23.3	22.9	15.2	9.6
2	4.8	3.8	2.8	10.8	****	****	26.1	26.9	23.9	23.0	15.8	10.0
3	4.7	3.8	2.6	10.5	****	****	25.9	26.7	24.2	22.9	15.8	10.0
4	4.6	3.6	2.1	11.9	****	20.0	25.3	26.4	24.4	22.2	15.4	10.1
5	4.0	3.8	3.3	13.0	****	21.3	25.4	26.5	24.8	20.9	15.5	9.0
6	3.0	4.8	3.6	13.6	****	22.1	25.5	27.9	24.1	20.7	15.3	8.3
7	3.5	4.2	3.9	13.7	****	22.8	25.7	27.2	24.6	20.9	15.3	8.0
8	3.0	3.9	4.3	12.5	****	23.3	25.8	27.5	24.1	20.7	15.3	7.5
9	1.7	3.8	4.8	13.4	****	23.6	25.1	28.3	24.1	20.0	14.4	7.0
10	1.9	3.5	5.8	13.0	****	23.3	25.1	27.7	23.6	19.3	13.6	6.4
11	1.6	2.6	****	12.5	****	23.8	25.1	26.9	23.8	19.5	12.7	5.6
12	1.4	3.4	****	11.4	****	23.9	24.8	25.8	23.0	19.6	11.8	5.0
13	1.0	2.6	****	11.9	****	23.5	25.5	25.8	23.1	19.7	11.2	4.8
14	1.5	2.5	****	12.0	****	22.7	25.8	26.3	23.4	19.7	10.6	5.4
15	1.7	2.2	****	12.3	****	23.4	26.2	25.5	23.3	19.1	10.5	4.6
16	1.7	2.8	****	****	****	23.9	26.7	26.9	23.2	20.7	10.8	4.0
17	1.6	3.0	****	****	****	23.9	27.2	27.5	23.3	21.2	11.1	3.9
18	1.7	2.5	****	****	****	23.3	27.5	27.6	22.6	21.8	11.6	3.7
19	1.9	2.2	7.1	****	****	23.0	****	27.7	22.7	21.4	11.4	4.2
20	2.2	2.7	8.0	****	****	23.4	****	27.9	22.9	20.3	10.2	4.5
21	2.6	2.7	8.8	****	****	23.9	26.4	27.3	22.7	19.5	9.7	4.3
22	3.1	2.2	9.6	****	****	24.0	26.9	27.8	22.3	19.7	9.6	4.0
23	3.2	2.4	9.9	****	****	24.7	26.9	28.0	****	19.5	10.0	4.2
24	2.6	2.1	9.4	****	****	25.6	27.4	28.9	****	19.7	10.0	3.9
25	2.0	2.2	8.5	****	****	25.5	26.8	28.0	****	19.1	9.7	3.6
26	1.8	2.7	9.2	****	****	24.2	25.8	27.2	****	17.9	9.6	3.1
27	2.2	3.2	10.2	****	****	25.2	25.3	26.3	23.0	16.8	9.7	3.2
28	2.2	3.5	10.0	****	****	23.7	25.5	25.1	22.7	16.5	10.2	4.4
29	3.0		10.5	****	****	24.0	26.0	24.4	22.6	16.3	10.7	4.3
30	3.6		11.1	****	****	24.6	25.9	24.1	22.7	15.2	10.1	4.1
31	3.3		11.4		****		26.4	24.3		15.1		4.1
AVG	2.7	3.1	6.9	12.2	****	23.6	26.0	26.8	23.4	19.7	12.1	5.6

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1969

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.8	4.6	3.1	9.7	14.7	21.6	26.9	26.4	26.0	20.6	14.4	8.8
2	3.0	4.5	2.5	10.3	15.5	23.1	26.8	26.1	25.9	20.8	14.5	8.2
3	3.0	3.7	2.7	10.6	16.0	22.4	26.6	25.8	25.9	21.2	15.2	7.5
4	2.9	3.9	3.3	10.4	16.8	22.6	26.9	25.7	26.1	21.0	15.0	7.4
5	2.3	3.8	3.7	10.9	17.3	22.7	26.4	25.9	26.2	20.1	14.1	6.6
6	2.2	3.9	3.6	10.3	18.0	22.8	27.5	26.4	25.7	20.1	13.0	6.1
7	2.4	4.0	3.4	11.9	18.7	23.2	28.0	26.4	26.0	20.0	13.1	5.8
8	2.3	3.7	4.3	12.2	18.3	23.9	26.7	26.4	25.4	20.1	12.8	****
9	2.6	3.0	3.8	12.8	18.3	23.2	25.9	26.3	15.0	20.2	12.5	****
10	2.7	3.3	3.5	12.6	17.2	23.1	25.3	25.4	24.1	20.2	12.3	****
11	2.5	3.8	3.5	12.8	17.2	23.3	25.8	25.8	23.6	20.1	12.1	****
12	2.2	****	3.5	13.6	16.4	24.4	26.4	25.8	23.8	20.1	11.9	****
13	2.2	****	3.6	13.6	17.2	25.3	25.8	25.5	23.9	20.3	11.6	****
14	2.1	****	3.6	13.8	17.3	24.7	26.4	25.8	23.7	20.5	11.6	****
15	1.7	****	3.8	14.2	18.3	24.9	26.9	26.5	23.9	19.9	****	****
16	2.3	****	4.8	14.1	18.8	****	26.9	26.7	24.3	19.1	****	6.1
17	2.2	3.8	4.1	15.0	19.7	****	26.7	26.5	24.1	18.8	****	5.2
18	2.7	2.6	6.4	15.5	19.2	****	27.3	26.3	23.6	18.3	****	5.1
19	3.3	2.5	5.5	15.5	19.4	****	27.9	26.1	22.8	17.7	****	5.0
20	3.1	2.4	6.2	13.9	20.2	****	27.8	25.4	21.4	18.3	****	4.7
21	3.3	2.7	6.4	14.5	19.6	24.0	26.8	24.7	21.1	18.8	****	4.7
22	3.2	2.7	6.5	14.1	19.9	23.8	27.5	25.0	21.2	18.3	****	4.4
23	3.3	2.5	7.0	13.5	20.4	24.3	27.2	25.3	21.1	17.2	****	4.3
24	3.8	3.0	8.3	13.3	20.3	24.4	26.2	25.4	20.9	15.8	****	4.4
25	4.0	3.0	8.0	13.7	20.2	24.1	26.1	25.9	20.8	15.2	****	4.1
26	3.6	3.0	7.5	15.1	20.3	24.7	26.4	26.2	21.4	15.3	****	4.0
27	3.5	2.7	7.5	15.3	20.5	25.4	26.2	25.4	21.9	16.0	9.3	3.6
28	3.3	3.4	8.3	15.2	20.6	26.3	26.9	25.2	21.0	15.3	9.5	2.7
29	2.4		8.6	15.5	20.5	26.2	26.1	25.2	20.8	14.4	9.2	3.3
30	3.3		9.4	15.1	21.3	27.1	26.7	25.8	20.8	13.9	9.1	3.6
31	4.3		9.1		22.5		26.6	25.8		14.3		3.7
AVG	2.9	3.3	5.3	13.3	18.7	24.1	26.7	25.8	23.1	18.4	12.3	5.2

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1970

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	3.7	3.0	4.8	8.3	16.8	22.3	25.1	27.2	26.5	21.5	15.8	10.1
2	3.6	3.9	5.0	9.4	17.7	22.7	24.6	26.9	25.8	21.7	16.3	10.3
3	3.6	3.9	5.3	9.2	16.6	23.0	25.3	27.2	25.6	22.2	16.5	10.3
4	3.6	2.2	5.2	10.0	15.4	22.5	25.8	26.6	25.8	21.6	15.5	10.4
5	2.7	1.2	5.3	10.0	16.6	22.9	24.9	26.5	25.8	21.1	15.0	9.7
6	3.0	2.5	5.5	9.4	15.2	21.9	24.6	26.6	****	20.9	14.7	9.4
7	3.0	3.0	5.8	9.1	14.7	21.8	25.3	26.5	****	20.8	****	8.9
8	2.2	2.8	6.1	9.8	16.0	23.0	25.4	26.5	****	21.2	****	7.7
9	1.1	3.3	6.4	10.5	17.0	23.3	25.2	26.1	24.5	21.5	****	7.4
10	****	3.3	6.5	10.5	16.6	23.3	25.0	25.2	24.7	22.0	14.9	7.9
11	****	3.0	7.1	11.0	16.2	23.9	24.7	24.7	24.9	22.1	14.9	8.2
12	0.8	3.0	6.8	11.3	16.9	24.5	24.7	25.2	24.2	22.2	15.1	8.5
13	5.8	3.3	6.4	11.8	18.6	25.0	25.4	25.9	24.4	22.2	14.9	8.6
14	5.8	3.0	6.4	11.4	19.4	23.5	25.6	25.4	24.7	22.4	14.7	8.0
15	0.5	3.2	6.0	10.7	20.5	23.0	25.1	27.0	25.0	22.2	14.5	7.5
16	****	3.0	6.1	11.7	20.0	23.7	24.8	27.5	25.2	21.2	14.0	7.0
17	1.0	3.3	6.0	11.9	19.6	24.0	26.6	27.2	25.3	19.4	13.3	7.6
18	1.3	3.6	5.9	12.7	18.3	24.9	25.9	27.3	25.0	18.3	12.7	7.5
19	1.2	3.6	5.8	12.5	18.6	25.5	26.1	26.9	****	18.5	12.9	7.6
20	0.8	3.6	5.9	12.9	19.1	25.0	25.8	27.0	****	17.7	12.9	7.9
21	0.0	3.5	6.5	13.6	20.5	25.0	24.7	26.7	****	17.7	13.0	7.6
22	-0.9	3.9	6.4	14.4	21.4	24.7	24.1	26.7	25.7	18.1	12.2	7.7
23	-0.8	4.6	6.5	14.0	21.7	24.7	24.1	26.4	25.8	18.6	12.4	7.9
24	-0.6	5.0	6.8	14.5	****	24.7	24.7	26.4	26.2	18.7	10.7	8.0
25	-0.2	5.0	7.7	14.5	****	24.4	25.5	26.4	26.4	18.5	10.2	7.4
26	****	3.8	8.6	14.9	22.1	24.7	25.8	26.1	26.6	18.6	9.1	7.3
27	1.5	3.6	8.7	14.4	22.1	24.6	26.8	26.2	25.8	17.6	9.2	5.9
28	1.9	4.6	10.0	15.0	21.5	24.0	27.1	26.4	****	16.4	10.0	****
29	2.1		9.7	15.4	21.0	24.4	27.0	26.8	****	15.7	10.0	****
30	3.2		8.2	15.8	21.0	24.1	26.7	27.2	24.6	15.6	10.3	****
31	2.6		7.9		21.6		27.3	27.2		15.8		****
AVG	1.9	3.4	6.6	12.0	18.7	23.8	25.5	26.5	25.4	19.7	13.2	8.2

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1971

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	****	3.0	8.8	9.1	16.3	20.6	27.4	27.0	26.5	22.9	21.5	8.8
2	****	2.5	8.3	10.3	15.6	20.7	25.3	28.6	26.4	22.9	21.6	8.3
3	****	1.6	8.6	10.2	15.5	21.5	26.5	28.3	26.5	22.8	21.1	7.7
4	6.0	2.1	7.8	11.5	15.2	22.8	26.1	28.6	26.8	22.8	19.4	7.2
5	6.7	2.5	7.0	12.4	15.9	22.9	27.2	27.3	26.6	23.1	19.0	6.6
6	6.2	3.3	7.9	10.9	16.4	23.1	26.7	27.0	****	22.8	18.7	6.6
7	5.5	3.5	7.7	10.3	16.3	24.3	26.5	26.3	****	22.2	18.6	8.3
8	5.3	4.1	7.4	10.0	16.9	23.8	27.2	26.5	27.3	21.9	16.8	8.0
9	4.8	3.9	7.0	11.5	17.6	23.3	27.7	28.0	27.1	21.2	16.2	9.0
10	4.6	3.0	7.4	11.1	18.3	23.8	27.4	26.2	27.2	21.2	15.5	9.8
11	4.7	3.0	7.6	12.2	18.7	23.8	26.9	26.9	27.3	****	15.4	****
12	5.1	3.8	8.3	14.5	19.3	23.4	26.5	27.2	27.4	****	13.6	****
13	4.7	4.4	9.4	13.9	19.4	23.5	26.5	26.6	26.9	20.9	14.1	****
14	4.9	3.6	9.4	13.3	19.0	23.9	26.5	26.1	26.3	20.2	15.0	****
15	4.9	2.5	11.3	13.0	19.0	23.8	26.9	27.1	26.3	21.1	****	****
16	4.5	4.6	10.5	13.0	18.8	22.6	26.6	27.6	26.4	21.9	15.5	****
17	4.0	4.7	10.1	13.8	18.7	22.3	26.9	26.9	26.6	21.5	15.3	****
18	4.0	5.3	9.8	13.7	19.8	22.8	27.7	26.4	26.4	21.0	15.0	****
19	3.7	6.2	9.3	14.8	20.8	23.9	27.5	26.5	26.3	20.8	15.2	****
20	2.8	5.4	9.2	15.0	22.0	24.5	26.6	26.9	26.8	19.6	15.6	8.3
21	4.6	7.3	9.6	14.8	21.4	25.1	26.2	27.2	25.9	19.6	14.8	8.6
22	3.2	7.3	9.5	14.0	20.4	25.6	25.9	27.6	25.0	19.7	13.8	8.0
23	4.1	6.6	9.0	13.7	20.5	24.8	26.1	27.4	24.6	20.0	12.2	6.9
24	3.9	6.3	8.3	14.5	21.4	25.6	26.8	27.2	24.8	20.0	11.3	7.5
25	4.4	6.5	8.3	14.1	21.0	26.3	26.5	26.2	24.0	20.5	11.1	7.7
26	5.2	6.9	7.2	14.7	21.4	25.5	26.8	****	23.8	20.1	11.0	7.7
27	3.5	8.3	7.2	14.7	21.8	26.3	26.5	****	24.2	20.3	10.1	8.6
28	2.5	8.0	8.3	15.2	19.7	27.2	27.0	****	24.0	20.1	10.4	8.6
29	2.1		8.1	15.9	19.9	27.6	26.6	****	23.7	20.4	10.3	8.3
30	3.0		7.9	15.9	19.3	27.6	26.3	27.0	23.1	20.5	10.6	8.6
31	3.6		8.0		19.5		26.2	26.9		20.4		8.6
AVG	4.4	4.6	8.5	13.1	18.9	24.1	26.7	27.1	25.9	21.1	15.1	8.1

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1972

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	8.0	5.2	6.9	9.4	16.9	18.6	22.8	****	****	21.7	14.9	9.0
2	8.3	5.0	6.9	9.1	17.2	18.9	23.9	****	****	22.5	15.4	8.7
3	8.3	5.3	8.9	8.8	17.2	20.2	24.2	****	****	21.9	16.1	9.1
4	8.0	4.5	8.3	9.4	16.4	20.5	23.9	****	****	22.0	16.1	8.7
5	8.0	3.8	4.7	10.3	16.7	21.1	23.6	****	****	21.8	15.8	9.8
6	7.7	3.6	6.7	10.8	17.2	21.4	22.5	****	****	21.5	15.3	10.4
7	7.2	4.7	6.7	10.8	17.8	21.4	22.5	****	****	21.5	15.0	9.7
8	6.9	3.8	6.9	9.4	17.2	21.4	23.0	****	****	20.4	****	9.3
9	6.6	2.7	6.6	9.1	16.7	21.1	23.3	****	****	20.3	****	9.7
10	7.7	3.3	6.4	9.1	16.1	20.5	****	****	****	19.6	14.6	10.3
11	8.0	3.3	6.7	10.0	16.4	19.2	****	****	****	19.5	14.4	10.4
12	8.3	3.3	7.2	10.2	16.9	20.3	****	****	****	19.8	14.3	9.8
13	9.1	4.1	8.3	10.5	17.5	19.7	****	****	****	19.9	14.4	10.0
14	8.9	4.1	7.7	11.1	17.2	20.5	****	****	****	19.8	14.6	9.8
15	7.5	5.2	7.5	11.6	17.5	21.1	****	****	****	19.7	14.1	9.6
16	6.7	5.8	8.9	12.7	18.0	21.6	****	****	****	18.8	13.0	8.7
17	4.4	5.5	8.6	12.8	18.6	21.7	****	****	****	18.8	12.4	7.3
18	3.6	5.0	8.3	13.6	19.7	22.5	****	****	****	17.9	12.1	6.5
19	4.7	4.7	7.2	13.6	19.4	23.6	****	****	****	17.0	11.9	6.6
20	5.2	4.1	9.7	15.0	18.6	23.6	****	****	****	16.2	12.1	6.9
21	5.8	3.8	9.7	14.7	18.8	23.0	****	****	****	15.2	11.6	6.8
22	5.5	4.4	10.0	14.1	19.1	21.6	****	****	****	15.4	11.3	6.9
23	5.5	4.4	9.4	14.7	18.6	20.5	****	****	****	15.7	10.9	7.1
24	5.8	4.7	9.1	14.7	18.6	20.8	****	****	****	15.8	9.9	7.2
25	6.6	5.0	8.3	14.4	18.0	21.4	****	****	****	15.7	9.4	7.3
26	6.4	5.0	8.6	14.7	16.9	21.7	****	****	****	15.3	9.9	7.4
27	6.1	5.2	8.6	14.1	16.9	22.2	****	****	****	15.1	9.6	7.2
28	5.3	4.7	9.1	14.4	18.6	23.0	****	****	****	15.4	9.5	7.1
29	5.5		9.1	15.5	19.2	22.8	****	****	****	15.5	9.4	7.0
30	5.8		8.8	16.1	20.0	22.2	****	****	****	15.3	9.1	6.9
31	5.8		8.9		20.2		****	****		15.3		7.6
AVG	6.7	4.4	8.0	12.2	17.9	21.3	23.3	****	****	18.4	12.8	8.4

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1973

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	8.0	5.8	6.2	12.0	16.0	21.6	25.8	27.6	28.9	23.3	17.2	12.2
2	8.0	6.6	6.6	10.7	17.1	22.6	26.2	27.4	28.5	23.0	16.5	12.0
3	7.6	6.0	6.6	10.6	17.2	22.8	26.5	27.3	28.5	23.5	16.6	11.8
4	7.9	5.9	7.0	11.1	16.9	22.9	27.0	27.2	28.7	23.9	16.3	12.3
5	8.0	7.2	7.0	10.5	16.2	23.3	27.1	27.8	28.4	23.8	15.3	13.2
6	7.6	7.1	6.8	11.0	16.3	24.1	26.9	28.1	28.2	22.9	14.4	12.9
7	6.8	6.7	7.2	11.2	17.5	23.4	27.5	28.4	28.3	22.8	13.9	12.2
8	5.4	6.9	7.3	10.9	17.6	23.9	27.5	28.8	28.8	22.4	14.3	11.9
9	4.9	6.4	7.4	11.4	17.8	24.0	28.0	29.2	27.8	22.4	13.7	10.8
10	4.2	5.3	7.6	11.3	****	24.1	27.9	30.0	26.9	22.5	12.4	10.8
11	4.3	4.6	7.9	11.0	19.5	23.9	27.4	28.8	26.5	22.3	11.9	9.3
12	4.4	4.3	8.4	10.3	20.7	23.4	26.7	27.8	26.5	21.8	12.0	9.4
13	3.6	4.0	9.3	10.4	20.7	23.7	26.6	27.6	26.1	21.7	11.7	9.4
14	3.4	4.1	9.7	10.4	19.6	24.8	26.4	27.0	25.6	21.8	11.8	9.3
15	3.7	4.8	10.3	11.1	17.3	25.6	26.1	26.7	25.4	21.4	12.3	8.8
16	4.1	4.0	11.0	12.2	18.5	24.2	25.9	27.2	25.2	21.0	12.3	8.5
17	4.4	3.5	10.8	12.4	19.0	23.3	25.8	27.7	25.2	21.5	11.4	6.9
18	4.6	3.3	9.7	13.0	18.0	23.1	26.2	27.2	25.2	19.9	11.1	6.6
19	5.0	3.5	9.2	13.8	18.0	23.0	26.7	26.6	24.8	19.2	11.9	6.4
20	5.0	4.3	9.1	14.8	18.1	24.0	26.3	26.8	24.8	18.9	11.8	7.1
21	4.8	4.1	9.1	15.3	17.5	24.3	25.9	26.4	24.5	18.9	11.9	7.9
22	5.5	4.1	****	14.9	18.2	25.8	25.8	26.0	24.4	18.7	12.5	5.5
23	5.6	4.5	8.6	15.1	18.1	23.9	26.3	25.8	25.2	18.6	12.6	5.3
24	5.8	4.6	****	15.8	18.3	25.0	26.3	26.6	25.1	18.6	12.9	5.5
25	5.8	5.5	****	16.5	18.3	25.4	26.5	26.3	24.9	18.5	13.8	5.8
26	5.5	5.5	9.6	16.3	17.8	25.7	26.4	26.8	24.5	18.6	13.3	7.0
27	5.2	5.0	9.4	15.8	18.0	25.8	26.7	27.1	24.6	18.5	14.0	7.7
28	5.5	5.6	9.8	13.7	19.4	25.9	26.7	27.3	24.8	18.3	14.1	7.3
29	5.8		10.2	14.6	19.7	25.3	27.1	25.5	24.9	18.1	13.4	7.3
30	5.0		10.4	15.3	20.9	25.3	27.1	28.4	24.4	17.3	12.2	7.3
31	5.3		10.8		21.1		27.5	28.5		17.2		7.6
AVG	5.5	5.1	8.7	12.8	18.3	24.1	26.7	27.4	26.2	20.7	13.3	8.9

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1974

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	8.0	9.3	7.5	10.6	17.5	21.7	23.6	28.0	28.0	21.1	17.0	8.9
2	7.0	9.6	7.8	11.5	17.4	21.5	24.8	27.4	27.5	20.4	17.4	9.3
3	7.0	9.8	8.6	12.8	17.5	22.1	25.4	27.3	27.7	18.5	17.3	9.7
4	7.0	9.0	9.2	13.5	18.1	22.3	25.5	26.4	26.8	18.2	17.3	9.3
5	6.4	7.5	9.9	13.7	17.3	22.3	25.2	26.7	25.7	18.0	17.5	8.6
6	6.3	6.2	10.0	13.0	16.8	23.1	24.6	25.7	24.8	18.1	17.3	8.2
7	6.8	7.6	10.7	13.3	16.8	22.4	25.8	24.7	24.2	18.6	16.3	8.5
8	6.9	6.9	11.5	12.9	16.3	22.4	26.0	25.2	23.9	18.3	15.0	9.0
9	7.0	5.8	11.3	12.7	17.3	23.7	26.3	25.2	24.0	17.8	15.0	9.3
10	7.2	5.8	11.1	12.3	17.5	24.6	26.6	25.2	24.5	18.0	15.2	8.0
11	8.4	6.3	10.5	13.0	17.9	24.2	26.0	24.8	24.9	18.1	14.8	7.8
12	8.3	6.1	9.7	13.3	18.3	24.6	25.8	25.9	25.3	18.3	14.7	8.2
13	6.7	6.9	9.6	13.6	18.4	23.9	25.9	26.4	26.0	18.5	14.6	8.4
14	6.2	7.3	9.4	14.8	19.7	24.1	25.9	27.2	25.3	18.7	13.9	8.4
15	6.5	7.5	9.3	12.7	19.9	24.5	26.9	26.6	24.6	18.9	13.9	8.4
16	6.7	6.1	9.5	14.5	20.1	24.5	27.0	26.7	24.6	18.9	13.1	8.5
17	7.5	6.5	8.9	15.8	20.8	24.6	26.6	26.8	24.8	18.8	13.1	8.5
18	7.4	6.4	9.4	14.5	22.0	24.8	26.8	27.0	24.7	18.3	12.9	8.4
19	7.9	6.0	10.0	14.4	21.6	25.2	26.4	26.6	24.8	17.6	12.6	7.9
20	8.1	7.3	10.0	15.3	21.2	25.3	26.4	26.4	25.3	16.2	12.7	8.0
21	8.7	8.2	10.3	15.4	21.3	24.8	26.3	26.4	25.2	14.2	12.8	8.1
22	8.4	10.0	10.1	15.4	20.8	25.3	26.0	26.5	24.1	14.3	12.6	8.2
23	8.6	8.6	9.6	15.4	21.4	25.0	25.9	26.9	23.1	14.3	12.1	7.7
24	8.4	8.7	9.8	14.6	21.6	24.4	25.6	27.3	21.3	15.0	12.0	8.3
25	8.1	7.5	9.0	14.4	21.7	23.9	25.6	27.1	21.3	15.1	11.8	9.0
26	8.0	6.1	8.8	14.5	21.1	23.4	25.5	27.4	21.4	15.4	12.0	8.6
27	9.4	6.5	9.3	15.2	20.3	22.8	25.8	27.1	21.1	15.8	11.3	8.1
28	10.0	7.0	10.7	15.9	20.3	23.3	26.4	27.9	21.9	15.4	10.4	8.3
29	10.1		10.6	17.4	20.1	24.9	****	27.7	22.7	15.8	9.9	8.5
30	10.3		10.1	17.8	21.2	24.1	****	27.5	****	16.1	9.8	9.1
31	9.4		10.0		21.7		27.5	27.8		16.8		9.3
AVG	7.8	7.4	9.8	14.1	19.5	23.8	25.9	26.6	24.5	17.3	13.9	8.5

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1975

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	9.2	11.4	8.1	10.6	14.5	22.9	25.8	28.4	25.4	22.9	16.7	11.9
2	8.6	11.2	7.9	11.4	14.8	23.0	25.7	28.9	25.5	22.2	17.0	****
3	7.8	8.8	6.6	11.5	15.8	24.1	26.0	29.2	25.4	20.9	17.1	****
4	8.2	6.3	5.7	9.8	16.0	24.3	26.0	29.3	25.7	20.1	17.3	****
5	8.0	6.8	6.2	9.3	15.6	24.7	25.9	29.4	26.1	20.5	17.4	****
6	8.0	6.6	6.9	9.2	16.6	23.8	26.2	28.9	26.3	21.4	17.3	10.3
7	8.1	6.5	7.4	8.5	16.7	22.8	25.8	27.5	26.2	21.3	17.3	9.7
8	7.9	6.6	7.0	8.5	17.8	23.0	26.3	27.2	25.8	21.1	17.5	9.7
9	8.3	6.6	6.5	9.7	18.0	23.3	26.6	27.3	25.8	20.7	17.5	9.2
10	8.4	6.3	6.0	10.1	18.2	23.5	27.0	27.4	25.3	20.5	17.9	8.9
11	9.5	6.4	6.1	9.8	18.5	22.9	26.5	27.7	25.3	20.7	17.8	8.5
12	9.9	6.8	6.1	9.8	19.1	22.6	25.8	27.7	24.9	20.6	17.1	8.1
13	9.3	6.4	6.8	9.7	18.3	23.3	25.5	27.7	24.4	20.0	16.5	8.8
14	8.8	6.2	6.9	10.2	19.0	24.3	25.5	27.9	23.4	20.6	15.8	8.5
15	7.6	6.5	6.8	10.0	19.9	25.1	25.2	27.8	22.7	21.0	15.8	9.0
16	7.1	6.7	7.3	10.0	20.1	25.0	25.1	27.8	22.4	21.0	14.5	9.2
17	6.7	6.8	7.5	10.6	19.7	25.7	25.8	28.0	22.6	20.7	13.8	8.8
18	6.7	6.9	7.8	11.2	20.0	26.8	26.3	28.8	22.0	20.5	13.9	8.8
19	7.3	7.2	8.3	11.4	20.2	26.0	26.1	28.6	22.2	20.3	14.1	7.2
20	7.2	7.3	8.4	12.3	21.4	26.0	26.8	29.2	23.1	19.9	14.2	6.4
21	6.6	7.7	9.6	12.9	21.4	26.4	27.0	28.8	23.0	19.4	13.9	6.6
22	6.3	7.9	9.7	13.4	22.7	26.0	27.1	28.3	22.4	19.5	13.9	6.2
23	6.3	8.7	10.2	14.0	23.1	26.0	25.1	28.1	22.5	20.0	13.3	6.3
24	6.9	10.0	10.9	14.3	23.1	26.2	28.1	27.9	22.7	20.0	12.5	5.0
25	7.7	8.6	10.9	15.4	23.3	26.5	27.1	28.2	23.4	20.1	12.3	4.8
26	7.4	8.1	10.4	15.5	22.9	26.4	27.0	28.6	23.4	20.0	12.0	4.4
27	7.0	7.9	9.5	15.3	23.4	26.5	27.1	28.3	23.3	19.5	11.5	4.6
28	7.4	7.5	9.9	15.1	23.8	25.8	27.0	28.3	22.5	19.3	11.8	4.8
29	9.1		10.0	14.9	23.8	25.8	27.0	28.1	22.6	19.3	11.6	4.8
30	10.5		10.4	14.7	24.0	****	27.5	28.0	22.9	18.9	11.4	4.5
31	11.3		10.5		24.0		27.8	27.2		17.1		4.4
AVG	8.0	7.5	8.1	11.6	19.9	24.8	26.4	28.2	24.0	20.3	15.0	7.4

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1976

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	4.9	4.5	10.7	12.4	16.0	22.0	25.4	26.5	24.4	22.6	12.1	7.0
2	4.9	4.0	11.0	11.9	17.1	21.8	25.7	26.9	24.1	22.5	12.0	6.9
3	4.7	3.3	11.3	11.1	16.8	21.0	25.3	26.6	23.6	22.5	11.6	6.5
4	4.6	4.2	11.4	12.0	16.8	19.6	25.2	25.7	23.9	22.8	10.9	5.5
5	3.6	4.5	12.2	12.6	16.8	19.1	25.5	24.8	24.2	22.6	11.3	5.5
6	3.8	4.3	12.5	13.4	17.3	19.2	25.7	25.2	24.1	****	11.6	5.6
7	4.4	4.1	12.3	13.5	17.5	19.8	25.5	25.1	23.7	****	11.0	6.1
8	4.4	3.5	11.5	13.4	17.0	21.0	25.8	25.9	24.0	****	10.9	6.3
9	3.5	4.0	10.9	12.3	17.4	21.6	25.5	25.3	23.5	****	9.4	5.5
10	3.5	4.1	10.1	12.3	17.0	22.7	26.8	24.9	22.5	****	8.5	4.9
11	2.9	4.4	10.2	12.2	16.7	22.3	26.0	24.5	21.9	****	8.6	5.2
12	4.0	5.0	9.5	12.1	16.8	22.5	26.3	25.2	22.3	19.1	8.6	5.7
13	3.7	5.0	10.6	12.5	17.1	21.9	26.1	25.8	23.0	18.6	8.1	5.8
14	3.6	6.0	10.2	13.6	18.0	22.0	25.8	25.9	23.0	18.5	7.4	5.3
15	3.0	5.8	10.4	13.9	19.4	22.6	26.4	26.0	22.8	17.8	7.5	5.1
16	2.8	6.9	10.2	14.0	19.9	23.1	26.8	25.9	23.1	18.2	7.8	5.1
17	2.6	7.7	9.4	15.0	20.4	22.7	26.3	25.9	23.8	17.2	7.5	5.2
18	2.4	8.3	9.6	15.9	19.4	23.6	26.5	25.5	23.8	16.1	7.6	5.1
19	2.2	8.5	9.3	16.9	18.3	24.0	26.1	25.3	23.9	15.3	7.9	5.1
20	2.2	8.2	10.0	17.2	18.4	24.4	25.9	25.2	23.5	15.4	8.4	5.3
21	2.8	8.9	10.9	17.5	19.5	22.9	26.2	24.7	23.4	15.2	8.3	5.2
22	2.5	9.1	11.2	18.6	19.5	24.2	26.6	24.5	22.9	15.2	8.1	4.1
23	2.1	8.4	11.2	17.5	19.8	24.7	26.5	25.1	22.6	15.2	7.8	3.5
24	2.4	8.5	11.7	18.8	18.9	24.8	26.4	25.9	22.5	15.2	7.5	3.6
25	2.8	9.0	11.5	17.8	19.1	24.4	26.3	26.5	22.8	15.0	7.3	3.1
26	4.1	9.5	12.3	16.4	19.1	25.1	26.4	26.8	22.9	14.7	7.1	3.1
27	4.8	9.6	12.9	15.2	18.8	26.1	25.7	26.9	23.0	13.6	7.8	3.4
28	3.7	9.7	12.8	14.8	19.0	26.2	26.9	26.4	23.3	12.5	8.1	3.4
29	4.1		13.0	15.3	19.8	26.0	26.8	26.3	23.0	11.7	8.1	3.4
30	3.8		12.9	15.6	20.6	25.6	27.0	26.9	22.7	11.7	7.8	3.4
31	4.1		12.6		21.7		26.9	25.6		11.6		3.4
AVG	3.5	6.4	11.2	14.5	18.4	22.9	26.1	25.7	23.3	16.8	8.9	4.9

DAILY AVERAGE WATER TEMPERATURE AT VIMS PIER IN 1977

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1	2.7	-0.8	6.7	12.7	17.4	22.9	26.8	27.8	28.9	24.3	14.3	10.4
2	2.6	-0.3	6.8	13.3	17.6	23.5	26.8	27.6	29.8	24.3	14.9	10.5
3	2.2	-0.5	7.0	13.8	19.0	23.4	26.8	28.3	30.2	22.2	15.8	9.9
4	2.3	0.3	7.7	13.9	19.6	23.5	26.8	28.3	30.4	21.0	16.4	10.0
5	1.9	0.6	7.9	13.6	19.8	23.8	27.3	28.3	30.4	21.3	16.9	9.9
6	1.6	-0.1	7.8	12.8	20.5	23.6	28.1	28.2	28.8	21.7	17.1	10.2
7	1.4	-0.5	7.9	12.8	21.2	22.3	28.6	28.2	27.7	20.5	17.0	8.9
8	1.4	****	8.0	13.0	21.5	21.2	29.0	28.3	27.0	19.1	16.9	7.1
9	1.1	-0.1	8.0	12.6	18.9	21.0	29.6	28.4	25.2	19.6	17.5	7.5
10	1.1	0.8	8.6	12.9	17.7	21.0	29.5	28.8	26.1	18.8	17.2	6.9
11	0.9	1.0	9.5	14.0	17.8	20.8	28.6	29.0	26.0	18.8	15.8	6.5
12	****	1.3	10.4	15.6	17.2	22.3	28.7	28.2	25.8	19.1	13.9	5.8
13	****	1.9	11.4	17.4	17.7	22.8	28.9	28.7	25.5	18.2	13.0	5.7
14	****	2.4	10.8	16.1	19.1	23.2	29.6	28.2	25.4	17.2	12.8	6.2
15	****	2.6	10.8	17.7	19.4	23.2	29.7	28.2	25.0	16.3	12.7	6.7
16	****	2.4	11.9	18.2	19.7	23.6	30.0	28.3	25.1	16.0	13.2	6.5
17	****	2.4	12.0	17.3	20.4	24.0	30.0	28.0	26.0	14.0	13.5	6.8
18	-0.4	2.3	12.3	17.3	21.8	24.3	29.6	28.0	26.0	14.6	13.1	6.8
19	-0.7	2.2	11.9	19.3	22.5	24.8	29.9	27.3	26.4	14.7	12.8	6.6
20	-0.7	2.2	11.9	18.1	22.7	25.3	29.4	26.4	26.1	14.5	12.6	6.9
21	-0.9	2.2	11.8	18.4	23.1	25.5	29.9	26.4	25.6	14.7	12.5	6.9
22	-1.1	2.6	11.8	18.4	23.7	25.3	29.2	26.6	25.5	15.4	12.9	6.7
23	-1.0	3.5	11.1	18.3	23.3	25.1	28.7	26.9	25.3	15.2	12.7	6.4
24	-1.0	3.8	10.2	18.6	23.0	25.1	28.0	27.1	25.6	15.2	12.8	6.6
25	-1.0	3.9	10.1	16.9	22.8	25.0	27.5	26.8	25.8	15.5	12.5	7.2
26	-0.6	4.6	10.0	17.0	22.9	25.3	26.9	26.5	25.8	15.3	11.4	6.4
27	-0.2	6.3	10.1	16.9	23.7	25.9	26.9	26.8	25.1	15.4	10.0	5.6
28	0.3	6.2	10.6	16.9	23.7	27.3	26.0	26.5	24.3	15.7	10.0	5.2
29	-0.3		10.5	17.0	24.9	26.3	27.0	26.5	24.6	15.4	10.1	4.6
30	-0.3		11.1	17.2	23.8	26.8	27.3	27.5	24.1	15.1	9.9	4.7
31	-0.2		10.9		22.7		27.8	28.3		14.5		4.7
AVG	0.4	2.0	9.9	15.9	20.9	23.9	28.4	27.7	26.4	17.5	13.7	7.1

MONTHLY AVERAGE WATER TEMPERATURE AT VIMS PIER

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1954	4.3	5.4	8.2	14.6	18.6	23.5	25.6	25.7	24.7	20.0	11.6	5.3
1955	4.0	3.2	8.8	13.5	19.3	22.6	27.1	27.4	23.8	19.3	11.8	5.0
1956	1.9	5.2	7.6	11.0	17.5	23.5	25.9	25.5	23.2	18.1	13.2	9.1
1957	4.3	5.5	8.3	13.9	20.1	20.2	26.3	25.5	24.8	16.8	12.1	7.1
1958	3.4	1.8	5.3	11.5	18.4	22.3	25.7	26.3	23.5	17.7	13.6	5.7
1959	3.3	5.3	8.4	14.1	20.5	24.8	27.3	27.9	25.9	21.4	12.9	7.0
1960	5.3	4.6	3.6	13.1	19.3	24.3	26.1	26.4	24.5	19.2	12.4	5.5
1961	2.8	3.3	8.9	11.4	18.2	22.8	25.8	26.7	25.6	19.3	14.0	7.1
1962	3.9	3.9	6.5	12.5	20.3	23.4	25.3	25.8	23.1	19.5	10.5	5.2
1963	2.5	2.2	7.1	13.5	18.1	23.1	26.3	26.4	22.6	18.9	13.3	5.9
1964	3.1	4.0	7.8	8.7 ?	18.5	22.0	25.8	25.2	23.7	16.3	14.0	8.4
1965	4.9	3.8	6.4	11.2	19.2	21.9	25.3	25.9	24.3	18.0	12.2	7.7
1966	4.3	2.6	7.7	11.8	17.6	21.7	26.3	25.2	22.7	17.5	12.3	6.6
1967	4.8	4.6	6.9	12.3	15.9	22.6	25.0	25.3	22.0	18.1	11.1	7.3
1968	2.7	3.1	6.9	12.2	17.1	23.6	26.0	26.8	23.4	19.7	12.1	5.6
1969	2.9	3.3	5.3	13.3	18.7	24.1	26.7	25.8	23.1	18.4	12.3	5.2
1970	1.9	3.4	6.6	12.0	18.7	23.8	25.5	26.5	25.4	19.7	13.2	8.2
1971	4.4	4.6	8.5	13.1	18.9	24.1	26.7	27.1	25.9	21.1	15.1	8.1
1972	6.7	4.4	8.0	12.2	17.9	21.3	23.3 ?	24.1	24.0	18.4	12.8	8.4
1973	5.5	5.1	8.7	12.8	18.3	24.1	26.7	27.4	26.2	20.7	13.3	8.9
1974	7.8	7.4	9.8	14.1	19.5	23.8	25.9	26.6	24.5	17.3	13.9	8.5
1975	8.0	7.5	8.1	11.6	19.9	24.8	26.4	28.2	24.0	20.3	15.0	7.4
1976	3.5	6.4	11.2	14.5	18.4	22.9	26.1	25.7	23.3	16.8	8.9	4.9
1977	0.4	2.0	9.9	15.9	20.9	23.9	28.4	27.7	26.4	17.5	13.7	7.1

Appendix B. Long term water temperature statistics for each calendar day of the year at Gloucester Point.

LONG TERM WATER TEMPERATURE STATISTICS FOR JAN AT GLOUCESTER POINT

DAY	DAY	24YEAR	STD	COEFF	MOVING AVG		EXTREMES			
MON	YR	AVERAGE	DEV	VARI	7DAYS	10DAYS	HIGH	YR	LOW	YR
1	1	5.43	2.04	0.38	5.25	5.19	9.20	1975	2.00	1956
2	2	5.21	2.08	0.40	5.17	5.12	8.60	1975	1.10	1963
3	3	5.13	1.98	0.39	5.07	5.04	8.30	1972	0.90	1963
4	4	5.05	1.87	0.37	4.99	4.93	8.20	1975	1.10	1963
5	5	4.83	1.98	0.41	4.85	4.84	8.00	1972	1.30	1963
6	6	4.67	2.06	0.44	4.71	4.74	8.00	1975	1.20	1963
7	7	4.63	1.91	0.41	4.59	4.63	8.10	1975	1.40	1977
8	8	4.42	1.86	0.42	4.49	4.54	7.90	1975	1.40	1977
9	9	4.21	2.01	0.48	4.41	4.45	8.30	1975	1.10	1970
10	10	4.35	2.06	0.47	4.35	4.36	8.40	1975	1.10	1956
11	11	4.33	2.24	0.52	4.28	4.27	9.50	1975	0.90	1977
12	12	4.25	2.24	0.53	4.20	4.18	9.90	1975	0.80	1970
13	13	4.26	2.14	0.50	4.16	4.07	9.30	1975	1.00	1968
14	14	4.13	2.09	0.51	4.05	3.97	8.90	1972	1.50	1968
15	15	3.86	1.86	0.48	3.89	3.88	7.60	1975	0.50	1970
16	16	3.91	1.63	0.42	3.76	3.79	7.10	1975	1.20	1964
17	17	3.58	1.65	0.46	3.63	3.71	7.50	1974	1.00	1970
18	18	3.22	1.69	0.52	3.55	3.64	7.40	1974	-0.40	1977
19	19	3.39	1.87	0.55	3.50	3.57	7.90	1974	-0.70	1977
20	20	3.32	1.89	0.57	3.45	3.53	8.10	1974	-0.70	1977
21	21	3.54	1.95	0.55	3.44	3.51	8.70	1974	-0.90	1977
22	22	3.55	1.98	0.56	3.49	3.52	8.40	1974	-1.10	1977
23	23	3.54	2.01	0.57	3.56	3.55	8.60	1974	-1.00	1977
24	24	3.50	2.05	0.58	3.63	3.58	8.40	1974	-1.00	1977
25	25	3.61	2.13	0.59	3.63	3.62	8.10	1974	-1.00	1977
26	26	3.85	2.05	0.53	3.65	3.65	8.00	1974	-0.60	1977
27	27	3.83	2.14	0.56	3.68	3.69	9.40	1974	-0.20	1977
28	28	3.55	2.20	0.62	3.72	3.73	10.00	1974	0.30	1961
29	29	3.66	2.45	0.67	3.78	3.75	10.10	1974	-0.30	1977
30	30	3.75	2.58	0.69	3.79	3.74	10.50	1975	-0.40	1966
31	31	3.77	2.61	0.69	3.75	3.72	11.30	1975	-1.40	1966

LONG TERM WATFR TEMPERATURE STATISTICS FOR FEB AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	32	4.08	2.45	0.60	3.73	3.70	11.40	1975	-0.80	1977
2	33	3.90	2.63	0.68	3.73	3.71	11.20	1975	-0.70	1966
3	34	3.53	2.41	0.68	3.72	3.75	9.80	1974	-0.50	1977
4	35	3.41	2.21	0.65	3.73	3.77	9.00	1974	-0.80	1966
5	36	3.64	2.09	0.58	3.73	3.78	7.50	1974	-0.70	1966
6	37	3.69	1.89	0.51	3.72	3.77	7.10	1973	-0.10	1966
7	38	3.83	1.84	0.48	3.75	3.78	7.60	1974	-0.50	1977
8	39	4.13	1.42	0.34	3.84	3.81	6.90	1973	0.80	1961
9	40	3.79	1.58	0.42	3.90	3.86	6.60	1975	-0.10	1977
10	41	3.77	1.50	0.40	3.94	3.92	6.30	1975	0.80	1977
11	42	4.00	1.58	0.39	3.97	3.97	7.20	1960	1.00	1977
12	43	4.09	1.57	0.39	3.97	4.03	6.80	1975	1.30	1977
13	44	3.96	1.51	0.38	4.04	4.08	6.90	1974	1.30	1955
14	45	4.04	1.55	0.38	4.13	4.12	7.30	1974	1.50	1958
15	46	4.13	1.65	0.40	4.19	4.18	7.50	1974	1.20	1958
16	47	4.32	1.69	0.39	4.24	4.24	6.90	1959	1.40	1958
17	48	4.39	1.75	0.40	4.29	4.31	7.70	1976	0.30	1958
18	49	4.40	1.92	0.44	4.38	4.39	8.30	1976	-0.20	1958
19	50	4.44	1.97	0.44	4.47	4.48	8.50	1976	-0.40	1958
20	51	4.33	1.93	0.45	4.55	4.57	8.20	1976	-1.10	1958
21	52	4.62	2.04	0.44	4.63	4.65	8.90	1976	0.10	1958
22	53	4.81	2.21	0.46	4.72	4.73	10.00	1974	0.10	1958
23	54	4.85	1.97	0.41	4.80	4.84	8.70	1975	0.50	1958
24	55	4.99	2.09	0.42	4.95	4.96	10.00	1975	1.20	1958
25	56	5.03	1.89	0.38	5.09	5.10	9.00	1976	2.20	1968
26	57	4.98	1.88	0.38	5.22	5.25	9.50	1976	2.10	1963
27	58	5.40	2.02	0.37	5.36	5.40	9.60	1976	1.60	1963
28	59	5.55	1.89	0.34	5.52	5.54	9.70	1976	1.70	1963

LONG TERM WATER TEMPERATURE STATISTICS FOR MAR AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	60	5.72	2.15	0.38	5.68	5.68	10.70	1976	2.20	1963
2	61	5.83	2.07	0.36	5.87	5.84	11.00	1976	2.40	1963
3	62	6.10	2.11	0.35	6.03	6.02	11.30	1976	2.60	1968
4	63	6.20	2.11	0.34	6.18	6.18	11.40	1976	2.10	1968
5	64	6.27	2.22	0.35	6.35	6.31	12.20	1976	2.20	1960
6	65	6.51	2.30	0.35	6.49	6.46	12.50	1976	2.10	1960
7	66	6.64	2.30	0.35	6.59	6.63	12.30	1976	2.20	1960
8	67	6.90	2.14	0.31	6.75	6.80	11.50	1974	2.50	1960
9	68	6.78	2.03	0.30	6.94	6.97	11.30	1974	1.80	1960
10	69	6.85	2.18	0.32	7.14	7.12	11.10	1974	0.90	1960
11	70	7.32	1.70	0.23	7.28	7.27	10.50	1974	3.50	1969
12	71	7.58	1.57	0.21	7.42	7.40	10.40	1977	3.50	1969
13	72	7.88	1.82	0.23	7.58	7.52	11.40	1977	3.60	1969
14	73	7.65	2.08	0.27	7.72	7.62	10.80	1977	2.50	1960
15	74	7.88	2.17	0.28	7.82	7.73	11.30	1971	3.00	1960
16	75	7.90	2.18	0.28	7.85	7.84	11.90	1977	2.30	1960
17	76	7.86	2.12	0.27	7.88	7.91	12.00	1977	3.00	1960
18	77	8.02	1.97	0.25	7.96	7.96	12.30	1977	2.60	1960
19	78	7.75	1.88	0.24	8.00	8.03	11.90	1977	3.30	1960
20	79	8.08	1.88	0.23	8.06	8.11	11.90	1977	3.60	1960
21	80	8.20	1.96	0.24	8.15	8.19	11.80	1977	3.70	1960
22	81	8.17	2.06	0.25	8.25	8.29	11.80	1977	3.70	1960
23	82	8.33	1.78	0.21	8.39	8.40	11.20	1976	3.60	1960
24	83	8.50	1.81	0.21	8.50	8.54	11.70	1976	3.90	1960
25	84	8.71	1.86	0.21	8.65	8.70	11.50	1976	3.20	1960
26	85	8.75	1.74	0.20	8.83	8.86	12.30	1976	3.20	1960
27	86	8.85	1.58	0.18	9.02	9.03	12.90	1976	5.00	1960
28	87	9.25	1.46	0.16	9.19	9.21	12.80	1976	5.90	1960
29	88	9.42	1.55	0.16	9.38	9.39	13.00	1976	6.70	1956
30	89	9.63	1.47	0.15	9.57	9.57	12.90	1976	7.20	1956
31	90	9.73	1.43	0.15	9.78	9.77	12.60	1976	7.00	1956

LONG TERM WATER TEMPERATURE STATISTICS FOR APR AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	EXTREMES LOW	YR
1	91	10.00	1.39	0.14	9.97	9.98	12.70	1977	7.70	1964
2	92	10.13	1.51	0.15	10.18	10.18	13.30	1977	7.20	1964
3	93	10.34	1.59	0.15	10.36	10.36	13.80	1977	6.80	1958
4	94	10.55	1.40	0.13	10.57	10.52	13.90	1977	8.70	1958
5	95	10.90	1.42	0.13	10.71	10.70	13.70	1974	8.60	1964
6	96	10.93	1.49	0.14	10.89	10.87	13.60	1968	8.10	1964
7	97	11.19	1.63	0.15	11.06	11.04	13.70	1968	8.50	1975
8	98	10.97	1.71	0.16	11.22	11.21	13.90	1959	7.60	1958
9	99	11.37	1.43	0.13	11.36	11.38	15.10	1959	9.10	1972
10	100	11.50	1.42	0.12	11.51	11.53	15.40	1959	9.10	1972
11	101	11.67	1.56	0.13	11.65	11.71	15.20	1959	8.60	1958
12	102	11.87	1.73	0.15	11.85	11.92	15.60	1977	9.20	1958
13	103	11.99	1.82	0.15	12.08	12.14	17.40	1977	9.60	1958
14	104	12.19	1.58	0.13	12.34	12.39	16.10	1977	10.10	1966
15	105	12.35	1.67	0.14	12.58	12.65	17.70	1977	10.00	1975
16	106	13.01	1.78	0.14	12.87	12.94	18.20	1977	10.00	1975
17	107	13.28	1.83	0.14	13.20	13.23	17.30	1977	10.60	1975
18	108	13.38	1.69	0.13	13.55	13.51	17.30	1977	10.70	1956
19	109	13.89	1.96	0.14	13.89	13.78	19.30	1977	10.60	1956
20	110	14.30	1.87	0.13	14.12	14.05	18.10	1977	10.50	1956
21	111	14.66	1.84	0.13	14.36	14.30	18.40	1977	11.00	1956
22	112	14.73	1.84	0.12	14.60	14.52	18.60	1976	11.30	1956
23	113	14.60	1.84	0.13	14.81	14.72	18.30	1977	11.40	1956
24	114	14.99	1.94	0.13	14.96	14.89	18.80	1976	10.80	1956
25	115	15.04	1.65	0.11	15.04	15.05	18.60	1954	11.60	1956
26	116	15.34	1.74	0.11	15.16	15.20	19.00	1954	11.40	1956
27	117	15.36	1.84	0.12	15.33	15.36	19.40	1954	11.80	1956
28	118	15.20	1.61	0.11	15.49	15.54	18.90	1957	11.90	1967
29	119	15.56	1.66	0.11	15.68	15.72	19.40	1957	12.70	1967
30	120	15.84	1.66	0.10	15.86	15.91	20.00	1957	13.00	1961

LONG TERM WATER TEMPERATURE STATISTICS FOR MAY AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	121	16.06	1.65	0.10	16.05	16.09	19.40	1957	13.00	1956
2	122	16.42	1.62	0.10	16.31	16.28	20.20	1954	13.90	1961
3	123	16.60	1.52	0.09	16.52	16.49	20.10	1954	14.40	1961
4	124	16.65	1.64	0.10	16.74	16.70	19.60	1977	12.50	1956
5	125	17.03	1.23	0.07	16.93	16.88	19.80	1977	15.20	1966
6	126	17.05	1.42	0.08	17.09	17.04	20.50	1977	14.80	1961
7	127	17.37	1.57	0.09	17.22	17.20	21.20	1977	14.70	1970
8	128	17.41	1.44	0.08	17.36	17.35	21.50	1977	14.40	1967
9	129	17.52	1.52	0.09	17.50	17.50	22.30	1959	13.80	1967
10	130	17.50	1.40	0.08	17.64	17.67	20.00	1954	14.10	1967
11	131	17.66	1.24	0.07	17.78	17.83	20.00	1959	14.60	1967
12	132	18.01	1.41	0.08	17.94	18.01	20.70	1973	15.50	1967
13	133	18.00	1.27	0.07	18.13	18.18	20.70	1973	15.10	1967
14	134	18.34	1.46	0.08	18.36	18.39	21.10	1957	15.10	1967
15	135	18.57	1.50	0.08	18.59	18.62	21.00	1957	15.50	1954
16	136	18.82	1.34	0.07	18.83	18.86	20.80	1962	15.80	1967
17	137	19.09	1.18	0.06	19.10	19.09	20.80	1974	16.70	1967
18	138	19.27	1.38	0.07	19.35	19.34	22.00	1974	17.00	1967
19	139	19.71	1.63	0.08	19.59	19.57	23.90	1957	17.80	1967
20	140	19.90	1.43	0.07	19.85	19.76	22.70	1977	17.50	1967
21	141	20.08	1.55	0.08	20.03	19.94	23.10	1977	17.10	1967
22	142	20.23	1.71	0.08	20.19	20.10	23.70	1977	16.50	1967
23	143	20.70	1.99	0.10	20.31	20.24	25.10	1958	16.70	1967
24	144	20.33	1.84	0.09	20.41	20.37	23.10	1975	15.50	1967
25	145	20.39	2.00	0.10	20.49	20.48	23.30	1975	15.00	1967
26	146	20.53	1.96	0.10	20.58	20.59	23.00	1957	16.10	1967
27	147	20.58	1.92	0.09	20.62	20.71	23.70	1977	16.40	1967
28	148	20.69	1.90	0.09	20.75	20.81	23.80	1975	17.10	1961
29	149	20.83	1.80	0.09	20.89	20.91	24.90	1977	17.60	1961
30	150	21.01	1.67	0.08	21.05	21.02	24.00	1975	17.70	1967
31	151	21.22	1.58	0.07	21.17	21.14	24.00	1975	17.60	1967

LONG TERM WATER TEMPERATURE STATISTICS FOR JUN AT GLOUCESTER POINT

DAY	DAY	24YEAR	STD	COEFF	MOVING AVG		EXTREMES			
MON	YR	AVERAGE	DEV	VARI	7DAYS	10DAYS	HIGH	YR	LOW	YR
1	152	21.40	1.68	0.08	21.28	21.28	23.50	1959	16.80	1967
2	153	21.60	1.57	0.07	21.42	21.43	23.50	1959	17.70	1967
3	154	21.44	1.58	0.07	21.58	21.58	24.10	1975	18.20	1957
4	155	21.45	1.71	0.08	21.71	21.74	24.30	1975	16.80	1957
5	156	21.85	1.76	0.08	21.86	21.90	24.70	1975	16.40	1957
6	157	22.07	1.64	0.07	22.00	22.04	24.40	1959	16.80	1957
7	158	22.18	1.42	0.06	22.18	22.17	24.50	1959	17.60	1957
8	159	22.41	1.38	0.06	22.36	22.33	24.70	1959	18.00	1957
9	160	22.57	1.50	0.07	22.53	22.49	25.70	1959	18.30	1957
10	161	22.75	1.52	0.07	22.68	22.63	26.60	1959	19.10	1957
11	162	22.72	1.84	0.08	22.80	22.75	27.20	1959	18.60	1957
12	163	23.00	1.78	0.08	22.91	22.85	27.30	1959	19.40	1966
13	164	23.11	1.83	0.08	22.98	22.94	26.10	1959	19.20	1957
14	165	23.01	1.42	0.06	23.03	23.03	24.80	1973	20.30	1966
15	166	23.19	1.48	0.06	23.12	23.11	25.70	1954	20.50	1965
16	167	23.06	1.38	0.06	23.17	23.20	25.00	1975	19.70	1965
17	168	23.11	1.44	0.06	23.24	23.29	25.70	1975	19.80	1965
18	169	23.37	1.44	0.06	23.33	23.38	26.80	1975	20.30	1965
19	170	23.36	1.47	0.06	23.43	23.48	26.00	1975	20.40	1965
20	171	23.58	1.42	0.06	23.56	23.61	26.00	1975	20.80	1957
21	172	23.65	1.36	0.06	23.74	23.74	26.40	1975	20.10	1957
22	173	23.90	1.64	0.07	23.87	23.89	26.00	1975	19.30	1957
23	174	23.94	1.47	0.06	24.03	24.03	26.00	1975	20.50	1972
24	175	24.37	1.26	0.05	24.19	24.17	26.20	1975	20.80	1972
25	176	24.32	1.32	0.05	24.35	24.30	26.50	1975	21.40	1972
26	177	24.48	1.29	0.05	24.47	24.45	26.90	1956	21.70	1972
27	178	24.68	1.61	0.07	24.59	24.63	27.10	1956	21.30	1957
28	179	24.73	1.53	0.06	24.74	24.80	27.30	1977	21.80	1961
29	180	24.78	1.55	0.06	24.93	24.95	27.60	1959	22.00	1957
30	181	24.79	1.76	0.07	25.09	25.08	28.10	1959	20.90	1957

LONG TERM WATER TEMPERATURE STATISTICS FOR JUL AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	182	25.42	1.41	0.06	25.24	25.20	29.20	1959	22.80	1972
2	183	25.66	1.06	0.04	25.38	25.31	28.30	1959	23.90	1972
3	184	25.60	1.04	0.04	25.48	25.41	27.50	1956	23.60	1965
4	185	25.70	1.15	0.04	25.61	25.53	27.90	1956	22.90	1962
5	186	25.68	1.31	0.05	25.67	25.64	27.30	1956	22.30	1962
6	187	25.53	1.36	0.05	25.71	25.72	28.10	1977	22.50	1972
7	188	25.69	1.42	0.06	25.76	25.75	28.60	1977	22.50	1972
8	189	25.86	1.24	0.05	25.78	25.77	29.00	1977	23.00	1972
9	190	25.89	1.38	0.05	25.79	25.81	29.60	1977	23.30	1972
10	191	25.98	1.26	0.05	25.85	25.85	29.50	1977	23.70	1961
11	192	25.81	0.99	0.04	25.91	25.90	28.60	1977	24.30	1954
12	193	25.77	0.99	0.04	25.95	25.97	28.70	1977	23.90	1954
13	194	25.97	0.96	0.04	25.99	26.03	28.90	1977	24.40	1954
14	195	26.10	1.09	0.04	26.04	26.08	29.60	1977	24.10	1967
15	196	26.11	1.11	0.04	26.12	26.12	29.70	1977	24.00	1967
16	197	26.18	1.12	0.04	26.20	26.16	30.00	1977	24.30	1967
17	198	26.32	1.03	0.04	26.26	26.21	30.00	1977	24.80	1961
18	199	26.40	1.00	0.04	26.28	26.26	29.60	1977	25.00	1954
19	200	26.35	1.14	0.04	26.31	26.29	29.90	1977	24.40	1962
20	201	26.35	1.04	0.04	26.34	26.33	29.40	1977	24.90	1961
21	202	26.26	1.10	0.04	26.36	26.37	29.90	1977	24.70	1970
22	203	26.32	1.03	0.04	26.37	26.40	29.20	1977	24.10	1970
23	204	26.37	1.00	0.04	26.40	26.44	28.70	1977	24.10	1970
24	205	26.46	1.00	0.04	26.44	26.47	28.10	1975	24.70	1970
25	206	26.47	0.84	0.03	26.52	26.50	28.00	1961	25.00	1964
26	207	26.55	0.84	0.03	26.56	26.55	28.40	1955	25.50	1964
27	208	26.68	0.94	0.04	26.61	26.61	28.90	1955	25.30	1968
28	209	26.81	0.99	0.04	26.66	26.67	29.20	1955	25.20	1965
29	210	26.60	1.02	0.04	26.73	26.72	28.90	1959	24.40	1965
30	211	26.69	1.17	0.04	26.78	26.75	29.00	1959	24.70	1965
31	212	26.84	1.21	0.05	26.81	26.75	28.90	1959	24.70	1966

LONG TERM WATER TEMPERATURE STATISTICS FOR AUG AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	213	26.91	1.20	0.04	26.79	26.75	29.10	1955	24.70	1965
2	214	26.95	1.11	0.04	26.78	26.72	28.90	1975	24.70	1966
3	215	26.90	1.26	0.05	26.76	26.69	29.20	1955	24.10	1966
4	216	26.65	1.44	0.05	26.69	26.69	29.60	1955	23.50	1966
5	217	26.49	1.39	0.05	26.64	26.67	29.40	1975	23.60	1966
6	218	26.58	1.28	0.05	26.60	26.62	29.10	1955	24.10	1966
7	219	26.35	1.28	0.05	26.53	26.55	28.50	1955	23.60	1966
8	220	26.53	1.08	0.04	26.49	26.48	28.80	1973	24.60	1956
9	221	26.70	1.25	0.05	26.45	26.42	29.20	1973	24.70	1966
10	222	26.42	1.34	0.05	26.39	26.39	30.00	1973	24.60	1964
11	223	26.33	1.28	0.05	26.36	26.38	29.00	1977	24.50	1976
12	224	26.22	1.19	0.05	26.34	26.39	28.30	1958	23.80	1967
13	225	26.18	1.18	0.05	26.33	26.40	28.70	1977	23.30	1967
14	226	26.12	1.11	0.04	26.34	26.37	28.20	1977	23.90	1967
15	227	26.38	1.05	0.04	26.36	26.33	28.30	1959	24.10	1964
16	228	26.66	1.12	0.04	26.35	26.31	28.60	1959	23.30	1964
17	229	26.46	1.08	0.04	26.35	26.31	28.00	1959	24.00	1964
18	230	26.47	1.06	0.04	26.37	26.31	28.80	1975	24.40	1964
19	231	26.18	1.25	0.05	26.35	26.33	28.60	1959	22.80	1957
20	232	26.17	1.41	0.05	26.29	26.33	29.20	1975	22.60	1957
21	233	26.26	1.27	0.05	26.26	26.30	28.90	1959	23.90	1957
22	234	26.23	1.27	0.05	26.24	26.27	28.80	1955	24.30	1957
23	235	26.24	1.26	0.05	26.24	26.24	29.10	1959	23.80	1957
24	236	26.30	1.32	0.05	26.25	26.22	28.90	1968	23.30	1957
25	237	26.27	1.15	0.04	26.24	26.23	29.10	1959	23.70	1957
26	238	26.24	1.30	0.05	26.22	26.24	29.60	1959	23.50	1957
27	239	26.19	1.15	0.04	26.23	26.24	29.30	1959	24.00	1957
28	240	26.19	1.28	0.05	26.23	26.22	29.40	1959	24.00	1958
29	241	26.09	1.24	0.05	26.22	26.19	29.10	1959	24.30	1958
30	242	26.33	1.23	0.05	26.19	26.15	28.50	1959	24.10	1968
31	243	26.32	1.18	0.04	26.14	26.12	28.50	1973	24.30	1968

LONG TERM WATER TEMPERATURE STATISTICS FOR SEP AT GLOUCESTER POINT

DAY	DAY	24YEAR	STD	COEFF	MOVING AVG		EXTREMES			
MON	YR	AVERAGE	DEV	VARI	7DAYS	10DAYS	HIGH	YR	LOW	YR
1	244	26.16	1.43	0.05	26.11	26.09	28.90	1973	23.30	1968
2	245	26.02	1.55	0.06	26.09	26.04	29.80	1977	23.60	1967
3	246	25.90	1.69	0.07	26.05	25.97	30.20	1977	23.60	1965
4	247	25.93	1.62	0.06	25.90	25.85	30.40	1977	23.30	1967
5	248	25.95	1.59	0.06	25.78	25.70	30.40	1977	23.20	1965
6	249	25.81	1.64	0.06	25.60	25.58	29.00	1961	23.70	1963
7	250	25.51	1.58	0.06	25.47	25.44	29.00	1961	23.40	1965
8	251	25.37	1.58	0.06	25.33	25.30	28.80	1973	23.30	1962
9	252	24.70	2.53	0.10	25.14	25.13	28.30	1961	15.00	1969
10	253	25.03	1.57	0.06	24.94	24.95	28.30	1961	22.50	1976
11	254	24.91	1.55	0.06	24.74	24.76	27.90	1961	21.90	1976
12	255	24.63	1.57	0.06	24.55	24.59	28.00	1961	21.70	1967
13	256	24.40	1.55	0.06	24.44	24.43	27.90	1961	21.60	1967
14	257	24.15	1.48	0.06	24.29	24.30	27.20	1961	21.40	1967
15	258	24.01	1.35	0.06	24.13	24.18	26.30	1957	21.40	1967
16	259	23.93	1.44	0.06	23.98	24.03	26.60	1957	20.80	1967
17	260	23.99	1.52	0.06	23.87	23.88	26.60	1971	20.70	1967
18	261	23.77	1.40	0.06	23.76	23.74	26.40	1971	21.20	1963
19	262	23.63	1.37	0.06	23.64	23.61	26.40	1977	21.40	1966
20	263	23.64	1.53	0.06	23.52	23.50	26.80	1971	20.70	1966
21	264	23.35	1.61	0.07	23.37	23.39	26.20	1965	21.00	1966
22	265	23.20	1.59	0.07	23.26	23.26	26.40	1965	21.00	1962
23	266	23.07	1.63	0.07	23.13	23.11	25.80	1965	20.50	1963
24	267	22.92	1.83	0.08	22.97	22.97	26.20	1970	20.00	1963
25	268	22.98	1.81	0.08	22.82	22.82	26.40	1970	20.10	1963
26	269	22.73	1.93	0.09	22.68	22.67	26.60	1970	19.90	1956
27	270	22.56	1.97	0.09	22.55	22.51	25.80	1970	17.90	1956
28	271	22.30	1.67	0.07	22.39	22.35	24.80	1959	18.40	1956
29	272	22.20	1.74	0.08	22.20	22.17	25.10	1959	18.20	1956
30	273	22.17	1.80	0.08	22.00	21.98	25.00	1959	18.40	1956

LONG TERM WATER TEMPERATURE STATISTICS FOR OCT AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	274	21.81	1.56	0.07	21.79	21.77	24.80	1959	19.10	1956
2	275	21.61	1.56	0.07	21.59	21.56	24.40	1959	18.70	1966
3	276	21.35	1.50	0.07	21.37	21.34	23.90	1954	18.50	1974
4	277	21.11	1.62	0.08	21.12	21.12	24.40	1959	18.20	1974
5	278	20.87	1.75	0.08	20.87	20.92	24.70	1959	18.00	1974
6	279	20.68	1.81	0.09	20.65	20.73	24.80	1959	17.60	1957
7	280	20.40	1.73	0.08	20.49	20.56	24.70	1959	17.60	1957
8	281	20.10	1.73	0.09	20.34	20.40	24.80	1959	17.20	1964
9	282	20.05	1.71	0.09	20.21	20.24	25.00	1959	16.40	1964
10	283	20.21	1.62	0.08	20.07	20.09	24.80	1959	18.00	1974
11	284	20.10	1.71	0.09	19.96	19.95	25.10	1959	18.00	1957
12	285	19.90	1.74	0.09	19.86	19.81	24.40	1959	17.10	1957
13	286	19.73	1.71	0.09	19.75	19.66	23.60	1959	16.80	1964
14	287	19.60	1.82	0.09	19.57	19.50	23.00	1959	16.90	1957
15	288	19.41	1.60	0.08	19.35	19.30	22.20	1959	16.30	1977
16	289	19.30	1.61	0.08	19.13	19.05	21.90	1971	16.00	1977
17	290	18.94	1.81	0.10	18.87	18.79	21.50	1971	14.00	1977
18	291	18.60	1.65	0.09	18.56	18.54	21.80	1968	14.60	1977
19	292	18.35	1.63	0.09	18.26	18.31	21.40	1968	14.70	1977
20	293	17.87	1.55	0.09	17.99	18.09	20.30	1968	14.50	1977
21	294	17.45	1.65	0.09	17.76	17.85	19.60	1971	14.20	1974
22	295	17.33	1.55	0.09	17.56	17.60	19.70	1968	14.30	1974
23	296	17.36	1.60	0.09	17.33	17.35	20.00	1971	14.30	1974
24	297	17.37	1.56	0.09	17.13	17.11	20.00	1971	14.60	1964
25	298	17.17	1.55	0.09	16.95	16.88	20.50	1971	15.00	1976
26	299	16.75	1.57	0.09	16.75	16.66	20.10	1971	14.70	1976
27	300	16.50	1.60	0.10	16.50	16.47	20.30	1971	13.60	1976
28	301	16.18	1.64	0.10	16.23	16.29	20.10	1971	12.50	1976
29	302	15.90	1.79	0.11	15.98	16.09	20.40	1971	11.70	1976
30	303	15.64	1.82	0.12	15.81	15.89	20.50	1971	11.70	1976
31	304	15.45	1.70	0.11	15.65	15.69	20.40	1971	11.60	1976

LONG TERM WATER TEMPERATURE STATISTICS FOR NOV AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	EXTREMES LOW	YR
1	305	15.46	1.88	0.12	15.49	15.52	21.50	1971	12.10	1976
2	306	15.53	1.92	0.12	15.35	15.35	21.60	1971	12.00	1976
3	307	15.37	2.00	0.13	15.24	15.18	21.10	1971	11.60	1976
4	308	15.06	1.97	0.13	15.10	15.01	19.40	1971	10.90	1976
5	309	14.93	1.95	0.13	14.91	14.82	19.00	1971	11.30	1976
6	310	14.86	1.95	0.13	14.68	14.62	18.70	1971	11.60	1976
7	311	14.49	1.98	0.14	14.42	14.39	18.60	1971	11.00	1976
8	312	14.15	1.83	0.13	14.17	14.15	17.50	1975	10.90	1976
9	313	13.88	1.97	0.14	13.90	13.92	17.50	1975	9.40	1976
10	314	13.57	1.99	0.15	13.63	13.70	17.90	1975	8.50	1976
11	315	13.33	1.92	0.14	13.40	13.48	17.80	1975	8.60	1976
12	316	13.04	1.72	0.13	13.19	13.28	17.10	1975	8.60	1976
13	317	12.94	1.74	0.13	13.03	13.09	16.50	1975	8.10	1976
14	318	12.88	1.79	0.14	12.89	12.92	15.80	1975	7.40	1976
15	319	12.70	1.78	0.14	12.75	12.77	15.80	1975	7.50	1976
16	320	12.73	1.78	0.14	12.64	12.63	15.50	1971	7.80	1976
17	321	12.58	1.81	0.14	12.52	12.43	15.30	1971	7.50	1976
18	322	12.37	1.68	0.14	12.39	12.34	15.00	1971	7.60	1976
19	323	12.29	1.75	0.14	12.24	12.16	15.20	1958	7.90	1976
20	324	12.10	1.76	0.15	12.04	11.98	15.60	1971	8.40	1976
21	325	11.93	1.69	0.14	11.81	11.79	14.80	1971	8.30	1976
22	326	11.69	1.47	0.13	11.61	11.59	13.90	1975	8.10	1976
23	327	11.29	1.52	0.13	11.38	11.40	13.60	1958	7.80	1976
24	328	11.03	1.50	0.14	11.16	11.21	13.90	1958	7.50	1976
25	329	10.93	1.48	0.13	10.96	11.01	13.80	1973	7.30	1976
26	330	10.68	1.42	0.13	10.78	10.76	13.30	1958	7.10	1976
27	331	10.57	1.41	0.13	10.58	10.49	14.00	1973	7.80	1976
28	332	10.55	1.42	0.13	10.33	10.23	14.10	1973	8.10	1976
29	333	10.41	1.52	0.15	10.05	10.00	13.40	1973	8.00	1967
30	334	9.87	1.29	0.13	9.78	9.79	12.20	1973	7.60	1967

LONG TERM WATER TEMPERATURE STATISTICS FOR DEC AT GLOUCESTER POINT

DAY MON	DAY YR	24YEAR AVERAGE	STD DEV	COEFF VARI	MOVING AVG 7DAYS	MOVING AVG 10DAYS	EXTREMES HIGH	YR	LOW	YR
1	335	9.29	1.27	0.14	9.54	9.57	12.20	1973	7.00	1976
2	336	8.97	1.17	0.13	9.28	9.36	12.00	1973	6.90	1976
3	337	8.80	1.15	0.13	9.02	9.13	11.80	1973	6.50	1976
4	338	8.91	1.45	0.16	8.80	8.90	12.30	1973	5.50	1976
5	339	8.73	1.56	0.18	8.65	8.69	13.20	1973	5.50	1976
6	340	8.60	1.61	0.19	8.53	8.49	12.90	1973	5.60	1976
7	341	8.30	1.50	0.18	8.40	8.31	12.20	1973	4.80	1954
8	342	8.24	1.32	0.16	8.19	8.15	11.90	1973	5.20	1954
9	343	8.16	1.25	0.15	7.98	7.96	10.80	1973	5.40	1954
10	344	7.87	1.39	0.18	7.77	7.77	10.80	1973	4.90	1976
11	345	7.45	1.36	0.18	7.57	7.57	10.40	1972	4.80	1954
12	346	7.21	1.58	0.22	7.37	7.36	9.80	1972	4.40	1954
13	347	7.18	1.91	0.27	7.13	7.15	10.00	1972	4.50	1954
14	348	6.91	1.95	0.28	6.89	6.95	9.80	1956	3.60	1962
15	349	6.80	1.92	0.28	6.73	6.77	9.60	1972	3.30	1962
16	350	6.49	1.83	0.28	6.57	6.62	9.70	1956	3.30	1962
17	351	6.22	1.82	0.29	6.43	6.47	9.40	1956	3.30	1955
18	352	6.27	1.76	0.28	6.31	6.32	9.60	1956	3.50	1955
19	353	6.12	1.52	0.25	6.16	6.16	9.20	1956	3.70	1958
20	354	6.20	1.71	0.28	6.02	6.03	9.30	1956	3.30	1963
21	355	6.06	1.93	0.32	5.92	5.92	10.20	1956	2.60	1955
22	356	5.75	2.02	0.35	5.81	5.84	9.80	1956	2.20	1955
23	357	5.52	2.04	0.37	5.74	5.74	10.20	1956	2.10	1963
24	358	5.52	2.00	0.36	5.62	5.66	10.00	1956	2.20	1960
25	359	5.52	2.02	0.37	5.51	5.58	9.80	1956	2.50	1960
26	360	5.60	2.19	0.39	5.46	5.49	9.60	1956	2.50	1963
27	361	5.39	2.06	0.38	5.43	5.43	9.20	1964	2.70	1963
28	362	5.27	1.94	0.37	5.39	5.40	8.60	1956	2.70	1969
29	363	5.39	1.89	0.35	5.37	5.37	8.70	1956	2.80	1960
30	364	5.33	1.95	0.37	5.32	5.32	9.10	1974	2.30	1962
31	365	5.20	2.23	0.43	5.28	5.26	9.30	1974	0.90	1962

Appendix C: The Box-Jenkins Technique

C-1. The fundamental operators used in the Box-Jenkins method

C-1-1. The deterministic and stochastic models

One might consider that a model or formulation called the deterministic model, can be fitted exactly to the behavior of a phenomenon. For example, we can calculate the route of a ship navigated in known direction with known velocity. However, it is hard, almost impossible, to predict future behavior precisely because there exist unknown factors which can affect the final result, such as variable wind velocity and current direction can move a boat off course. Therefore, it is assumed that no behavior can be predicted exactly, but that it is possible to look for the probability limits within which it would be. This kind of process is said to be a stochastic process. Some physical phenomena can be decomposed into two portions. The first component is described by a true response function which is easy to calculate for any instant of time. The second portion is the stochastic process which can be approached only by statistical theory.

C-1-2. Stationary and non-stationary processes

If a stochastic process is in statistical equilibrium about a constant mean level over long periods, this is called a stationary process. On the contrary, a stochastic process in an uncontrolled situation or one which has different mean level with time changes (such as stock prices frequently exhibit) exhibits non-stationary behavior.

C-1-3. Backward, forward and backward difference operators

Three operators are introduced to simplify the relation between data. The first is the backward operator, B, which is defined by $BZ_t = Z_{t-1}$. The current value multiplied by a factor B is equal to the previous value. Hence $B^2Z_t = BZ_{t-1} = Z_{t-2}$ and furthermore $B^nZ_t = Z_{t-n}$. The second operator, the inverse order for past operator ($F = B^{-1}$), is the forward operator which is given by $FZ_t = Z_{t+1}$; therefore $F^nZ_t = Z_{t+n}$. The present value times the nth power of F is to be estimated by the value n intervals in the future. The third operator is the backward difference operator "∇" which can be written in terms of B; $\nabla Z_t = Z_t - Z_{t-1} = (1-B)\ Z_t$ (the first difference); $\nabla^2 Z_t = (1-B)(Z_t - Z_{t-1}) = Z_t - 2Z_{t-1} + Z_{t-2} = (1-B)^2 Z_t$ (the second difference); hence $\nabla^n Z_t = (1-B)^n Z_t$ (the nth difference). In this study, it will be seen that the backward difference operator is a useful tool to distinguish a non-stationary process from a stationary process.

C-1-4. The ARMA process and the ARIMA process

Shocks are random drawings from a fixed distribution, usually assumed normal and having a mean of zero and variance δ_a^2. Such a sequence of random variables a_t, a_{t-1}, a_{t-2}, ... is called a white noise process. (Box & Jenkins, 1970, p. 88). One concept of white noise is that the next value for this process may not be predicted even though one knows all of the previous values. One tries to have the residual autocorrelation function of a time series exhibit a random process as closely as possible; in this way the model will be selected.

Each shock, $\tilde{z}_t$ (where $\tilde{z}_t$ is the deviation from the mean or some other origin) can be estimated by the present shock plus the weighted sum of either all previous random shocks or all previous deviations.

They are
$$\tilde{z}_t = a_t + \underline{\overline{\psi}}_1 a_{t-1} + \underline{\overline{\psi}}_2 a_{t-2} + \cdots$$
$$= a_t + \sum_{j=1}^{\infty} \underline{\overline{\psi}}_j a_{t-j} \qquad \text{(C-1)}$$
$$\tilde{z}_t = a_t + \pi_1 \tilde{z}_{t-1} + \pi_2 \tilde{z}_{t-2}$$
$$= a_t + \sum_{j=1}^{\infty} \pi_j \tilde{z}_{t-j} \qquad \text{(C-2)}$$

From equation C-1, if a set of weighted values is given, the current disturbance $\tilde{z}_t$ can be expressed by the sum of previous shocks plus the present shock. This process is said to be a moving average model.

Hence, the first order of moving average process is defined by

$$\tilde{z}_t = a_t - \theta a_{t-1} = (1-\theta B)\ a_t \qquad (C-3)$$

The moving average model of order 2 is given by

$$\tilde{z}_t = (1- \theta_1 B - \theta_2 B^2)\ a_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} \qquad (C-4)$$

and the moving average model of order q is given by

$$\tilde{z}_t = a_t - \theta_1 a_{t-1} - \theta_2 a_{t-2} - \ldots . \theta_q a_{t-q}$$

$$= (1 - \theta_1 B - \theta_2 B^2 - \ldots . - \theta_q B^q)\ a_t \qquad (C-5)$$

equation C-5 may be written as

$$\tilde{z}_t = \theta_q\ (B)\ a_t$$

$\theta_q(B)$ is called the moving average operator with order q. Similarly, equation C-2 also can be taken with the number of weighted values depending on the practical situation. This process is called the autoregressive model of order p. $\phi_p(B)$ is the autoregressive operator with order p. The first order of autoregressive model is obtained by $\tilde{z}_t = \phi \tilde{z}_{t-1} + a_t$.

$$(1 - \phi B)\ \tilde{z}_t = a_t \qquad (C-7)$$

The pth order of the autoregressive model is given by

$$(1 - \phi_1 B - \phi_2 B^2 - \ldots . - \phi_p B^p)\ \tilde{z}_t = a_t \qquad (C-7)$$

$$\phi_p(B) = (1 - \phi_1 B - \ldots . - \phi_p B^p)$$

$$\therefore\ \phi_p(B)\ \tilde{z}_t = a_t \qquad (C-8)$$

It sometimes will be necessary to include both autoregressive and moving average terms in the model.

Thus, $$\tilde{z}_t = \phi_1 \tilde{z}_{t-1} + \phi_2 \tilde{z}_{t-2} + \dots + \phi_p \tilde{z}_{t-p} + a_t - \theta_1 a_{t-1} - \dots - \theta_q a_{t-q}$$

$$\phi_p(B)\ \tilde{z}_t = \theta_q(B)\ a_t \qquad \text{(C-9)}$$

is called the mixed autoregressive-moving average process of order (p,q) which is sometimes abbreviated to ARMA (p,q). However, for non-stationary processes, the ARMA model is not capable of covering the entire series. The complementary method to be added is the difference operator "∇" which is required to acquire stationarity. (Box & Jenkins, 1970 chapter 4 & 6). Normally, it has a priority over the autoregressive and moving average processes. Accordingly, the ARMA model is modified as follows:

$$\phi_p(B)\ (1-B)^d\ \tilde{z}_t = \theta_q(B)\ a_t$$

or $$\phi_p(B)\ \nabla^d\ \tilde{z}_t = \theta_q(B)\ a_t \qquad \text{(C-10)}$$

C-2. Model identification

C-2-1. The ACF and PACF and their behavior as indicators of ARMIA processes

To identify the model which should be built up, one must determine the type of model which might be used and obtain an initial estimate of the model parameters. In practice, it is not necessary to know exactly which type has the greatest probability of describing a given time series because there are different ways to investigate model types. Eventually those different ways produce a set of very similar coefficients after the model is checked. It should be mentioned that in preference to a model which has small residual variance but a high order, we would choose a lower order model with a somewhat larger residual variance. For instance, if the difference of residual variance between (1,0,1) and (2,0,0) models is one percent, the simpler (1,0,1) model is preferred. This criterion is an important factor in making the final selection from several similar models.

The techniques which are used to identify the type of model utilize the autocorrelation function (ACF) and partial autocorrelation function (PACF). Before being described by the ARIMA process, a time series should be modified to remove the non-stationary situation, thus becoming a stationary stochastic process. Those two techniques can provide information which indicates which series include non-stationary process. The characteristic of the ACF for non-stationary series which is most apparent is that moderate values continue and are not damped relative to the first few values of the function. An alternative method is to construct the first one or two differences of the original time series and then examine the corresponding ACF until an obvious stationary process is shown (i.e. the ACF dies out quickly). Therefore, if the estimated ACF does not die out quickly, this will be a signal for a non-stationary stochastic process. Box & Jenkins (1970) mentioned that generally it is sufficient to inspect the stationary process for the 0th, 1st or 2nd order of the difference operators used.

The partial autocorrelation function (PACF) is a minor tool to assist in examining series. For the ARMA model system the ACF and PACF have symmetric solutions to illustrate the same series. For example, the ACF for the first order autoregressive model can be described as an exponential decay with increasing lag value and the ACF for the first order moving average model will tail off after the first value. (i.e. the PACF for the first order autoregressive model will tail off after the first value and the PACF for the first order moving average model can be explained as an exponential decay with increasing lag value).

If the ACF is expressed by the same formulation as previously

$$\left(\gamma_K = \sum_{t=1}^{N-K} (Z_t - \bar{Z})(Z_{t+K} - \bar{Z}) \Big/ \sum_{t=1}^{N} (Z_t - \bar{Z})^2\right)$$

then the PACF is defined as

$$\gamma_j = \phi_{K1}\gamma_{j-1} + \phi_{K2}\gamma_{j-2} + \phi_{K3}\gamma_{j-3} + \cdots + \phi_{K(K-1)}\gamma_{j-K+1} + \phi_{KK}\gamma_{j-K} \qquad \text{(C-11-A)}$$

here $K=1,2,\ldots$ $\qquad j=1,\ldots K$

γ_j is autocorrelation coefficients

ϕ_{KK} is the partial autocorrelation coefficients

ϕ_{Kj} is the jth coefficient in an autoregressive process of order K

The PACF can be expressed directly as:

$$\phi_{\ell\ell} = \begin{cases} \gamma_1 & \ell=1 \\ \dfrac{\gamma_\ell - \sum_{j=1}^{\ell-1} \phi_{\ell-1,j}\gamma_{\ell-j}}{1 - \sum_{j=1}^{\ell-1} \phi_{\ell-1,j}\,\gamma_j} & \ell=2,K \end{cases} \qquad \text{(C-11-B)}$$

where $\phi_{\ell j} = \phi_{\ell-1,j} - \phi_{\ell\ell}\phi_{\ell-1,\ell-j} \quad j=1,2,\ldots,\ell-1$

Some common characteristics for the basic ARIMA model types and forms of the ACF distributions are represented in Table C-1. The (1,d,0) model means the current disturbance Z_t equals a fixed proportion ϕ_1 of the previous disturbance Z_{t-1} plus the present shock a_t. The autocorrelation function decays exponentially to zero when ϕ_1 is positive, but decays exponentially to zero and oscillates in sign when ϕ_1 is negative. Yet the (o,d,1) model indicates the current disturbance Z_t equals the present shock a_t subtracted from a fixed proportion θ_1 of the previous shock a_{t-1}. The ACF for this process has a cutoff after lag 1. In other words, except for the one neighboring value, no relationship exists for the first order moving average process. Other models might be composed of these two basic types. The most important terms for the (2,d,0) model are the two previous

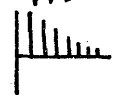
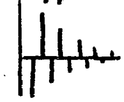
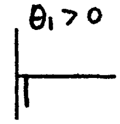
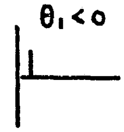
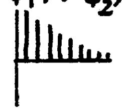
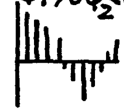
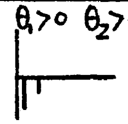
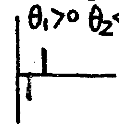
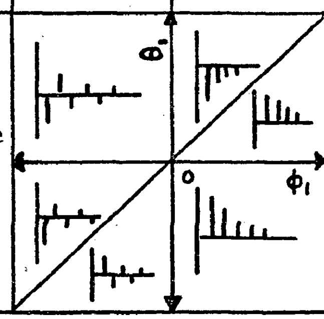
order	behavior	the style of dis.		range
(1.d.1)	decays exponentially	$\phi_1 > 0$ 	$\phi_1 < 0$ 	$-1<\phi_1<1$
(o,d,1)	only the first a.c.f. non-zero	$\theta_1 > 0$ 	$\theta_1 < 0$ 	$-1<\theta_1<1$
(2,d,0)	mixture of expo- -nential or damped sine curve	$\phi_1>0$ $\phi_2>0$ 	$\phi_1>0$ $\phi_2<0$ 	$-1<\phi_2<1$ $\phi_2+\phi_1<1$ $\phi_2-\phi_1<1$
(0,d,2)	only the first a.c.f. non-zero	$\theta_1>0$ $\theta_2>0$ 	$\theta_1>0$ $\theta_2<0$ 	$-1<\theta_2<1$ $\theta_2+\theta_1<0$ $\theta_2-\theta_1<0$
(1,d,1)	decays exponen- -tially from the first lag			$-1<\phi_1<1$ $-1<\theta_1<1$

Table C-1. The teeoretical behavior of the autocorrelation functions for some low order ARIMA processes.

neighbor values etc. In addition, it is easy to see the neighboring relation between disturbances for an autoregressive process is stronger than for a moving average process at the same order.

It is useful to know the nature of the ACF for both simple and mixed models, so that this knowledge will aid in interpreting real situations. It is necessary to emphasize that the behavior is for theoretical situations; these distributions normally will not coincide absolutely with real data. Box & Jenkins (1970) showed that after the theoretical ACF has damped out, for real time series moderatively large estimated autocorrelation coefficients can occur and some ripples and trends are expected to occur too. It also is suggested that closely related models need to be included and identified at the same time because the result of such comparisons is more accurate.

C-2-2. Computed ACF's for Z, ∇Z, and $\nabla^2 Z$

The estimated autocorrelations of Z, ∇Z and $\nabla^2 Z$ for water temperature residuals after removing the most significant harmonic for the yearly cycle and record mean are shown graphically in Figures C-1 and C-2. From Figure C-1, it is observed that the values for the first 80 autocorrelations die out with an exponential decay; then follows what looks like a sine wave with diminishing amplitude. The mean level is at approximately 0.05 unit. This stochastic process may

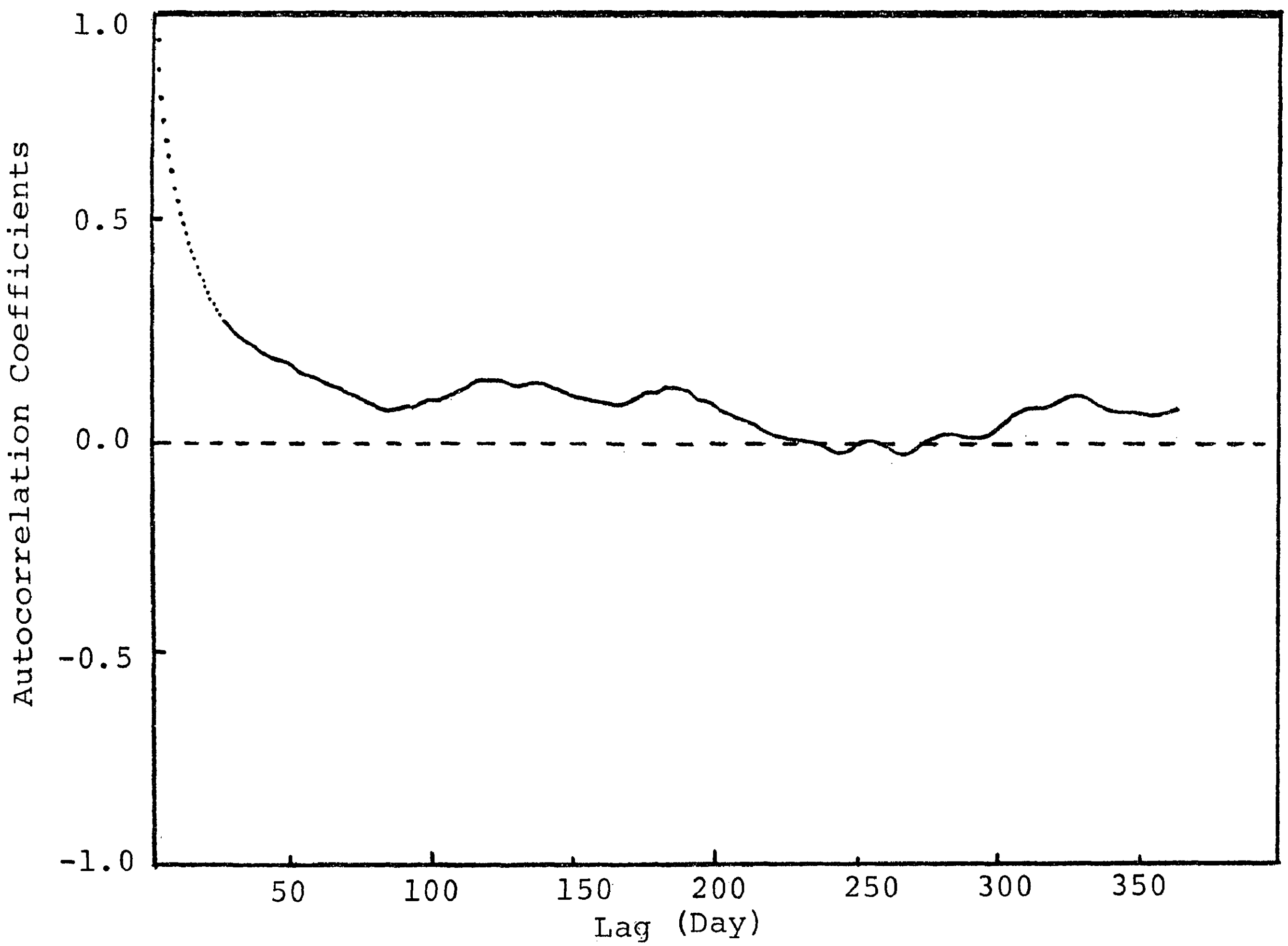


Figure C-1. The autocorrelation function of R_t; $R_t = y_t - \alpha_0 - \alpha_1 \sin(wt + \alpha_2)$.

be fitted by a mixture of exponentials and damped sine curves, as has been revealed by Box & Jenkins' work. Some imaginary roots might be included in this process, in which case they contribute a sine term solution to the ACF for the characteristic equation $\phi_p(B) = 0$ and the resulting ACF will follow a damped sine curve. Of course, the real root portion for this characteristic equation could be indicated as a damped exponential.

It should be remembered that the estimated ACF will differ somewhat from the theoretical values. Considering this idea, the series can be fitted by the (1,0,0) model or the (1,0,1) model which only slightly changes the relative coefficients of the (2,0,0) model. For Figure C-2, the first difference operator is used to modify the series and the new ACF value computed again. Surprisingly, no values greater than 0.05 function units occur after the first 4 lags. The new series already approaches "white noise". The first 4 values of ACF are not enough to construct a model. If we check the second difference series of the ACF, it is described well by a (0,2,1) model because the first value is approximately equal to 0.5, and subsequent variations are all less than 0.04 and around the zero line. It should be noted that the higher order of the difference series can make those shocks disappear. But a (0,2,1) model will be investigated to determine its adequacy.

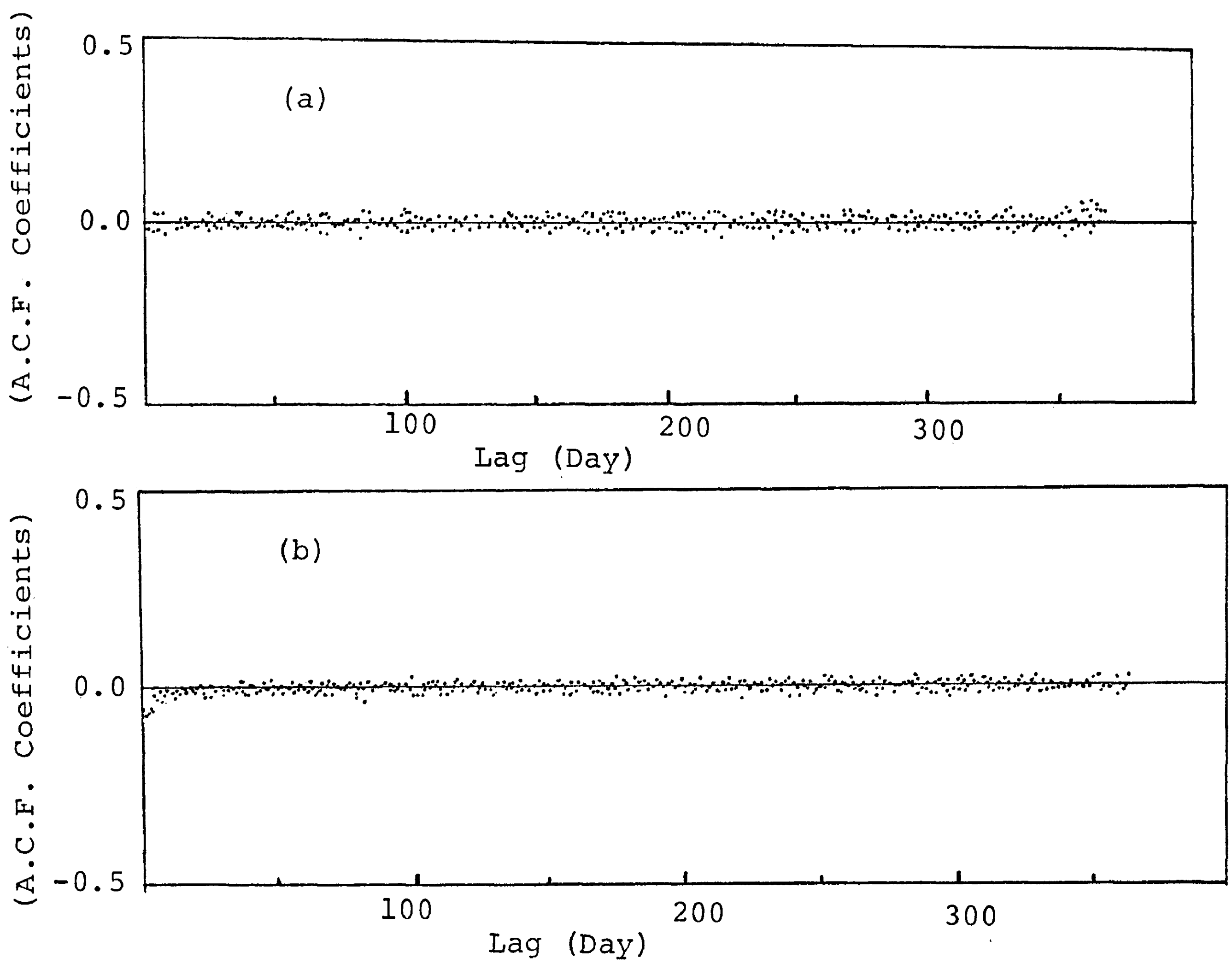


Figure C-2. The autocorrelation function of (a) ∇R_t; $R_t = y_t - \alpha_0 - \alpha_1 \sin(wt + \alpha_2)$ (b) $\nabla^2 R_t$; $R_t = y_t - \alpha_0 - \alpha_1 \sin(wt + \alpha_2)$.

The PACF is computed to confirm the nature of this series. In Figure C-3, one notes that the first function value is large, but none of the second to fifth values is over 0.04 function units. That is strong evidence that the first order autoregressive model is appropriate. In summary, the water temperature series can be represented by the (1,0,0), (2,0,0), (1,0,1), or the (0,2,1) model.

C-3. Model estimation

C-3-1. Estimating parameters for the autoregressive model

The autoregressive model belongs to a linear process, thus the least square estimate method is available. The general form of the autoregressive model is:

$$\tilde{Z}_t = \phi_1 \tilde{Z}_{t-1} + \phi_2 \tilde{Z}_{t-2} + \cdots \phi_p \tilde{Z}_{t-p} + a_t \quad \text{(order=p)}$$

The least square method is expected to reduce the magnitude of the sum of squares between the observed and estimated values as small as possible.

$$\therefore S(\phi_1, \ldots, \phi_p) = \sum_{t=p+1}^{n} (\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1} \cdots$$
$$- \phi_p Z_{t-1})^2 = \text{minimum} \qquad \text{(C-15)}$$

With differentiations of the sum of squares, a set of linear equations can be obtained with respect to $\phi_1, \ldots \phi_p$; each equation is set equal to zero.

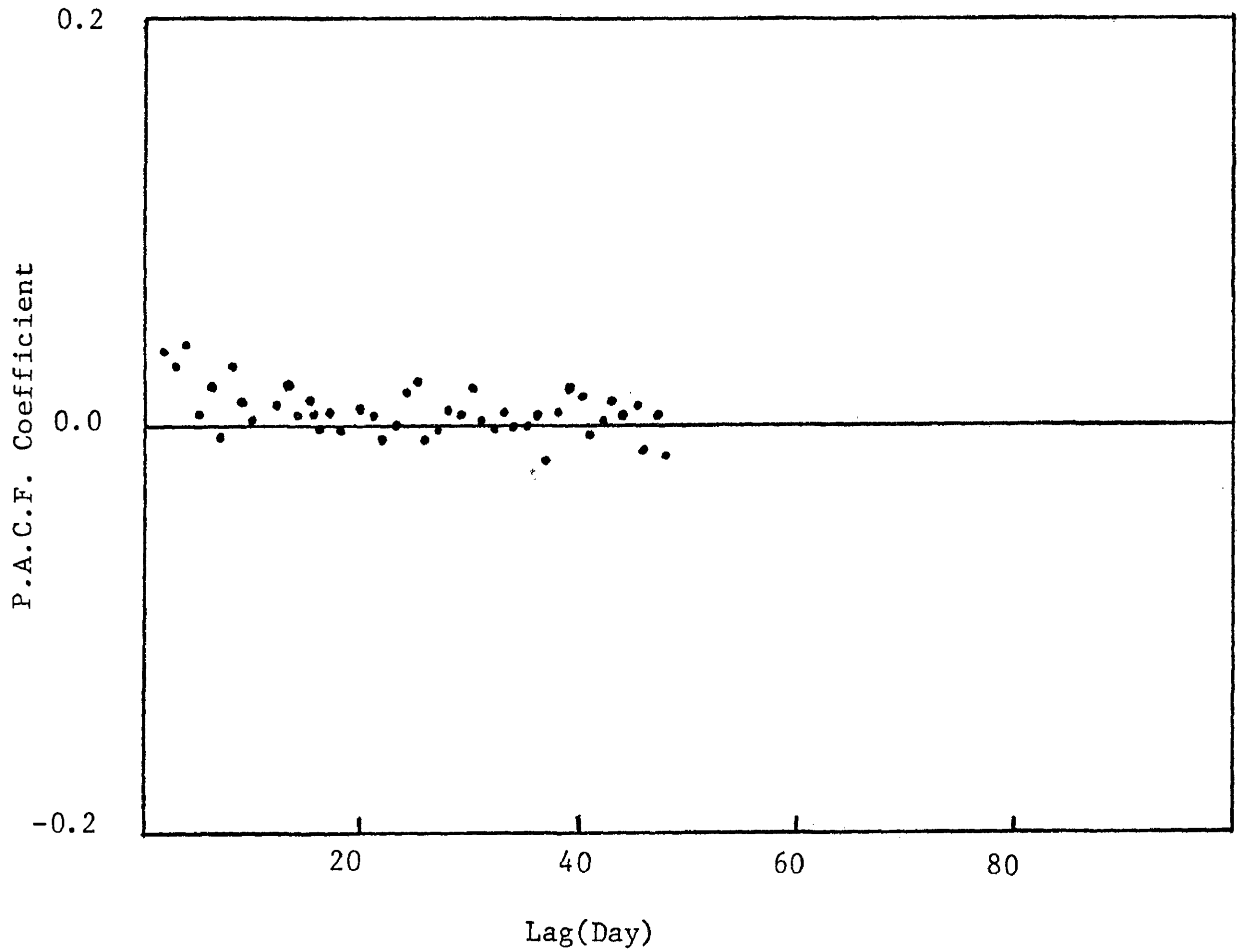


Figure C-3. Indicates the second-fifty partial autocorrelation function of R_t; $R_t=\alpha_0-\alpha_1.\sin(wt+\alpha_2)$. The first partial autocorrelation coefficient equal to 0.91874. It can't be shown in this figure.

If the order is 1, equation C-15 becomes

$$S(\phi_1) = \sum_{t=2}^{n} (\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1})^2 = \text{minimum}$$

and

$$\frac{\partial S}{\partial \phi_1} = -2 \sum_{t=2}^{n} \tilde{Z}_{t-1}(\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1}) = 0$$

$$\therefore \phi_1 = \sum_{t=2}^{n} \tilde{Z}_{t-1} \cdot \tilde{Z}_t \Big/ \sum_{t=2}^{n} \tilde{Z}_{t-1} \cdot \tilde{Z}_{t-1}$$

Thus, the autoregressive model of order 1 is fitted to the water temperature variation model. Its coefficient is 0.91875.

For (2,0,0) model, the sum of squares is

$$S(\phi_1,\phi_2) = \sum_{t=3}^{n} (\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1} - \phi_2 \tilde{Z}_{t-2})^2 = \text{minimum}$$

$$\frac{\partial S}{\partial \phi_1} = -2 \sum_{t=3}^{n} \tilde{Z}_{t-1} (\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1} - \phi_2 \tilde{Z}_{t-2}) = 0$$

$$\frac{\partial S}{\partial \phi_2} = -2 \sum_{t=3}^{n} \tilde{Z}_{t-2} (\tilde{Z}_t - \phi_1 \tilde{Z}_{t-1} - \phi_2 \tilde{Z}_{t-2}) = 0$$

The above equations can be arranged in a matrix form:

$$\begin{pmatrix} \sum_{t=3}^{n} \tilde{Z}_{t-1} \cdot \tilde{Z}_{t-1} & \sum_{t=3}^{n} \tilde{Z}_{t-1} \cdot \tilde{Z}_{t-2} \\ \sum_{t=3}^{n} \tilde{Z}_{t-1} \cdot \tilde{Z}_{t-2} & \sum_{t=3}^{n} \tilde{Z}_{t-2} \cdot \tilde{Z}_{t-2} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \sum_{t=3}^{n} \tilde{Z}_t \cdot \tilde{Z}_{t-1} \\ \sum_{t=3}^{n} \tilde{Z}_t \cdot \tilde{Z}_{t-2} \end{pmatrix}$$

Then ϕ_1 and ϕ_2 can be determined by multiplying the inverse matrix of the 2x2 matrix on the left side by the matrix on the right side. The result is

$\phi_1 = 0.91039$ $\phi_2 = 0.00919$

If only one parameter needs to be estimated, one can alter the original equation to another form, then insert the assumed value to find the region which has the minimum square value of residuals. When this inserted value of accuracy increases, the result is approached.

For instance, for the first order of autoregressive model:

$$\tilde{Z}_t = \phi\tilde{Z}_{t-1} + a_t$$

$$\sum_{i=2}^{n} a_j^2 = \sum_{t=2}^{n} (\tilde{Z}_t - \phi\tilde{Z}_{t-1})^2$$

values can be chosen to determine under which value the summation of shocks square is minimum. In Figure C-4, ϕ is about 0.919 when the computed region is between 0.91 to 0.93.

C-3-2. Estimating parameters for the moving average model

Since it is hard to express the sum of squares in explicit form, the moving average process also needs to have the type of equation changed. For example, the first order moving average model is expressed as:

$$\tilde{Z}_t = \theta_q(B) \cdot a_t \qquad (q=1)$$

$$\therefore \tilde{Z}_t = a_t - \theta a_{t-1}$$

Since the expected value of the residuals a_t is equal to zero, therefore a_0 can be assumed zero.

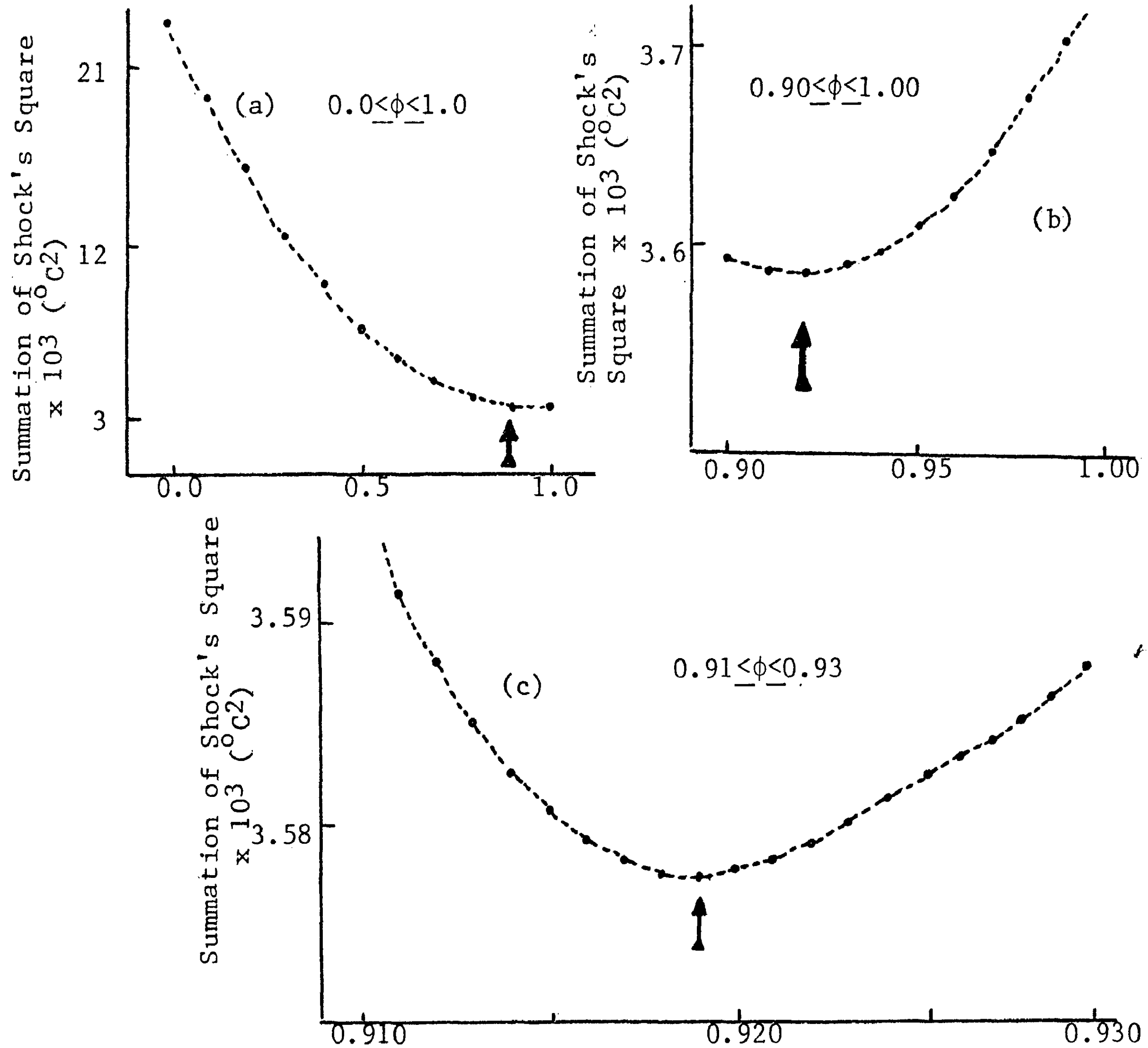


Figure c-4. Shows that three stages to be estimated ϕ from (a) to (c) when the computed region is chosen between 0.91 to o.93. The summation of shocks square has a minimum value at ϕ =0.919.

$a_0 = 0 \qquad a_1 = \tilde{Z}_1$

$a_2 = \tilde{Z}_2 + \theta a_1 \; \ldots .$

$a_n = \tilde{Z}_n + \theta a_{n-1}$

$$S(\theta) = \sum_{t=1}^{n} (a_t)^2$$

The sum of squares, can be obtained for different values of θ. For a higher order moving average process, this approach can be followed but the final value will depend on two or more corresponding values.

C-3-3. Estimating parameters for mixed models

The equations for the autoregressive-moving average model also need to be transformed (Carlson 1970). The first order mixed model is:

$$\tilde{Z}_t = \phi_1 \tilde{Z}_{t-1} + a_t - \theta_1 a_{t-1}$$

If a value of θ_1 is assumed, then the data $Z_1, \ldots, Z_t$ may be converted to a new data set t_1, t_2, ..., t_n

$t_1 = \tilde{Z}_1$

$t_2 = \tilde{Z}_2$

$t_n = \tilde{Z}_n + \theta_1 t_{n-1}$

This set of t_n can be described as an autoregressive model

$$t_t = \phi t_{t-1} + a_t \qquad \text{(C-16)}$$

From equation C-16, parameter ϕ can be estimated as previously mentioned for autoregressive model which normally uses the least square method. The results are $\phi_1 = 0.919$ and $\phi_2 = -0.008$. The sum of squares computed from a pair of ϕ_1 and θ_1 values can be shown on the (ϕ_1, θ_1) plane.

If the contours of constant sum of squares are sketched, the lowest center can be observed as in Figure C-5. The observed values are approximately equal to $\phi_1 = 0.9$ and $\theta = 0.00$. The parameters for the four possible models are summarized in Table C-2.

C-4. Checking the adequacy of the models

Four models have been identified, and the parameters which are used to fit that model also have been estimated. Coefficients for some of the models are highly similar to each other, such as the parameters for the (1,0,0) models, since $\theta = 0.00$. This seems to tell us that both these models can express the same behavior if both are under the standard error which is permissible for the estimated autocorrelation function. However, for each model tested, the most important step is to determine whether this model is adequate. If it is not adequate, how can this model be altered to present the true behavior. Thus, the checking process not only will move us toward a complete model but also will give us more confidence in the model chosen.

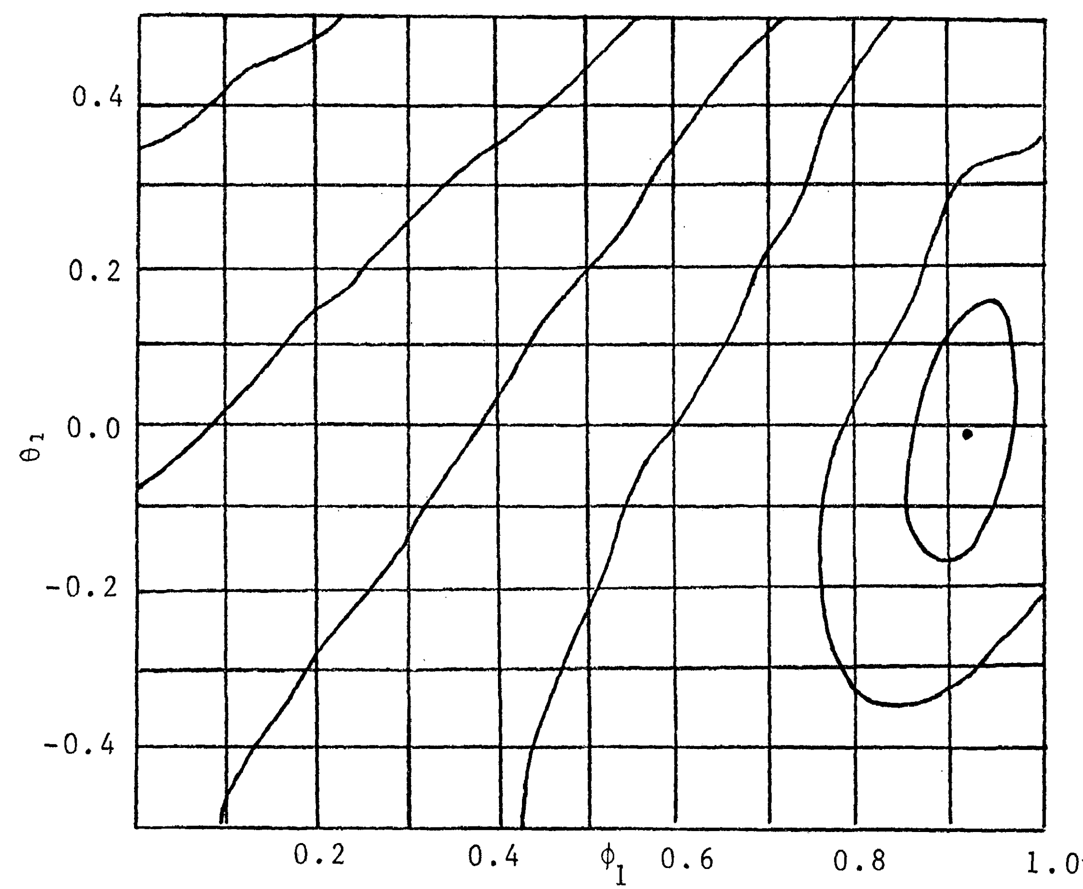


Figure C-5. Indicates the lowest value of $S(\phi_1,\theta_1)$ is shown at ϕ_1=0.91, θ_1=0.00 for (1,0,1) model. The contour shows the same amount of summation of shocks square for a pair ϕ_1 and θ_1 are chosen. This result explains the coefficient ϕ_1=0.91 and the coefficient θ_1=0.

Table C-2. The final estimates for each possible model.

ARIMA Process	Parameter Values	The Type of Model
(1,0,0)	$\phi_1 = 0.91875$	$\tilde{z}_t - 0.91875\,\tilde{z}_{t-1} = a_t$
(2,0,0)	$\phi_1 = 0.91019$ $\phi_2 = 0.00919$	$\tilde{z}_t - 0.91019\tilde{z}_{t-1} - 0.00919\,\tilde{z}_{t-2} = a_t$
(1,0,1)	$\phi_1 = 0.9199$ $\theta_1 = -0.008$	$\tilde{z}_t - 0.9199\tilde{z}_{t-1} = a_t + 0008a_{t-1}$
(0,2,1)	$\theta_1 = 0.99$	$\nabla^2\tilde{z}_t = a_t - 0.99a_{t-1}$

C-4-1. The ACF for residual series

The most common method used to check an assumed model is to observe the distribution of the residuals using the statistical behavior. The probability distribution may produce a straight line such as was used in Chapter II. The ACF again can play this important role for checking the residual series. As we know, the theoretical autocorrelation function is distributed around zero values for each lag after a model is fitted completely. But due to slight differences, the estimated ACF may be distributed approximately normally about zero with variance n^{-1} based on Baretetts' approximation. That means if the estimated ACF is within the upper or lower bounds with a standard error of $n^{-1/2}$ (one standard deviation) one can still regard this process as "white noise" behavior. However, at low lags a reduction of variance can occur and the residual ACF can be highly correlated. Those relations disappear quickly at high lags (Box & Jenkins, 1970). Therefore, one can use $n^{-1/2}$ as the standard error to examine the distribution at low lags. According to the above assumption, the standard error is about 0.0213 for the 95 percent (two standard deviation) confidence limit. In Figure C-6 the individually computed and fitted models are shown. Apparently, except for the first couple values at low lags, the estimated ACF have only about one tenth the values outside the bound. This result is associated with the length of series and the choice as to whether a lag value is regarded as moderate or high.

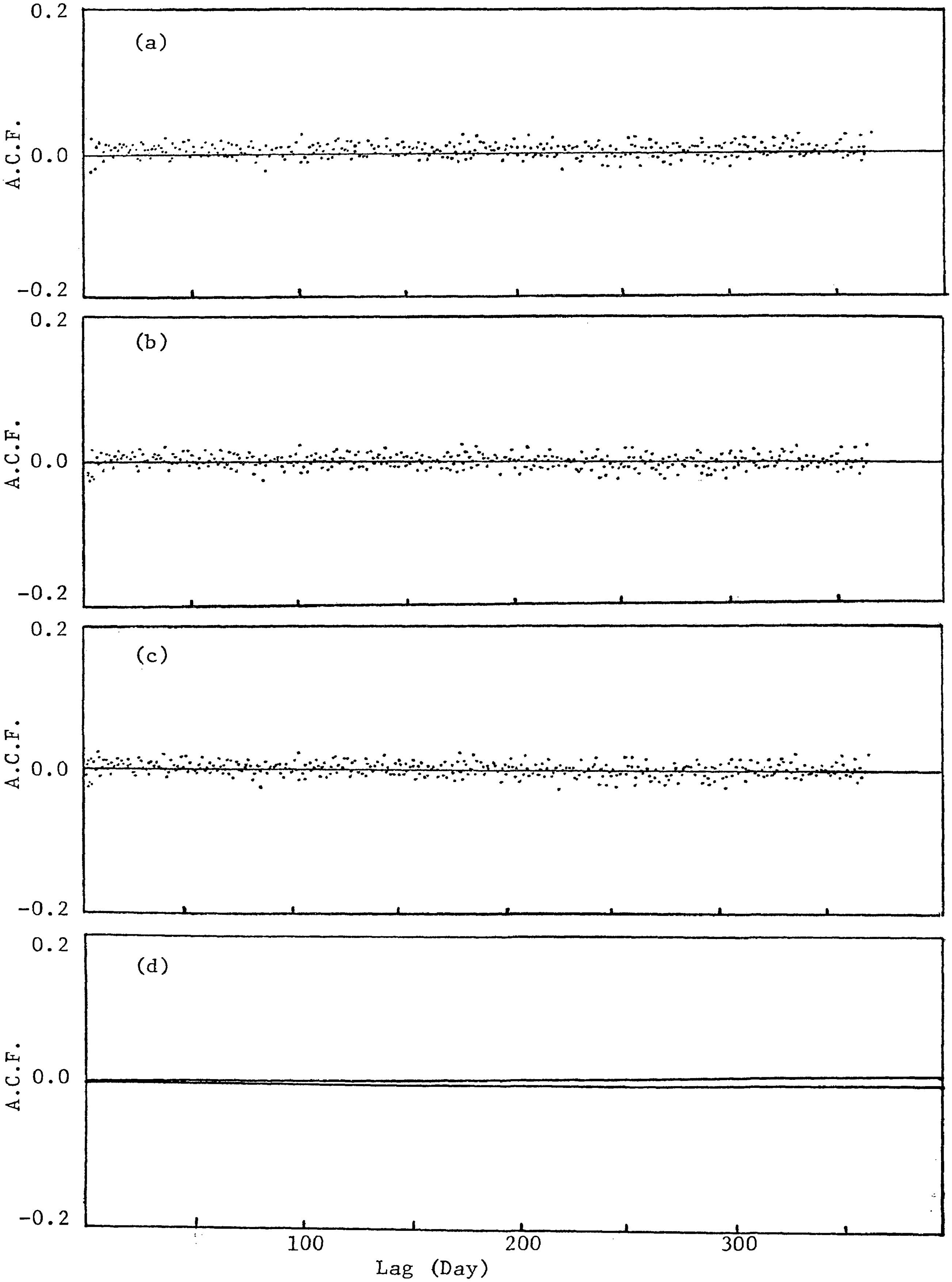


Figure C-6. The autocorrelation function for each residual series when the model fits for the (a) (1,0,0) model, (b) (1,0.1) model, (c) 2,0,0) model, and (d) the (0,2,1) model.

C-4-2. Q* value and the residual variance checking

Usually, the $Q=N \sum_{i=1}^{n} r_i^2$ which is calculated by summing the residual ACF multiplied by the number, N = n-d. If the fitted model is acceptable, then this value, say Q, is approximately distributed as Chi-square distribution with degree of freedom (k-p-q), the maximum calculated lag value subtracted from the order of the autoregressive process plus the order of the moving average, and will fall between the corresponding confidence limits for the Chi-square distribution. Normally the 95 percent limit is to be expected as the standard if this model is appropriate. From Table C-3 the Q value is equal to 475.32 while the 5 percent point for X^2 with 364 degrees of freedom is 407.207. The question to be considered is whether this sample is so large that the maximum lag number, 365, is too low. Therefore, we extend the lag values to 1095, and then calculate the sum of residual ACF squared. It was found that even though the value tripled, the Q value still cannot prove that this model is adequate, because the Q value tripled too. In Table C-3 are listed the Q values for each fitted model. Unfortunately, none of them is less than the 90 percent limit value. It is worthwhile to observe whether

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*Q value testing is the method which can check whether a model is adequate or not from the residual ACF of distribution.

Table C-3. The Q value (Chi-squares) for each residual series and the ARIMA process is fitted.

Model Style	r_i^2	Q	$Q_{0.90}$	n=N-d	Degree of Freedom
(1,0,0)	0.0542	475.32	409.21	8760	364
(1,0,1)	0.05411	474.00	408.15	8760	363
(2,0,0)	0.05350	468.66	408.15	8760	363
(0,2,1)	0.10061	881.14	409.21	8758	364

the moving Q value converges or not. A (0,2,1) model residual ACF, which increases constantly, is shown in Figure C-6d. This phenomenon indicates that high correlations probably will appear for large lags. However, especially low correlation values occur at low lags.

Now, we must pay attention to one of the most important processes of this study, which is to find a model that minimizes the sum of squares and produces a minimum total variance. The variance of the original data is 70.14 c^2. The ratio of the sum of squares of the residual for each model to the initial sum of squares is a good indicator of the best model. Table C-4 presents some of the statistical results to aid in the final decision. The (1,0,0), (1,0,1) and (2,0,0) models still have very similar solutions. The percentage of total variance is reduced to less than 0.06. The best choice is the (1,0,0) process which has the most simplicity and lowest order. The final question to be considered is how to modify the model when it is inadequate. Box & Jenkins (1970) suggested that making another ARIMA model from the residual series, then combining this model with the original model.

For example, suppose that b_t is the residual from the model C-17 and this model appears to be nonrandom.

$$\phi_b(B)\nabla^{d_b}\tilde{z}_t = \theta_b(B)\ B_t \qquad \text{(C-17)}$$

Table C-4. The residual analysis for each possible model.

Model Style	Sum of Residuals	Total Squares of Residuals	Percentage of Total Variance	The ratio of s_r/s_o
annual cycle and mean removed	-151.15	23023.25	4.52	-----
(1,0,0)	-12.41	3588.71	0.58	0.15587
(1,0,1)	-12.12	3589.38	0.58	0.15590
(2,0,0)	-12.67	3588.13	0.58	0.15585
(0,2,1)	-99.64	3826.68	0.67	0.16621

*s_r = the summation of squares for the residual series (model is fitted)

s_o = the summation of squares for water temperature series after annual cycle and mean record are removed.

Using the ACF of b_t, it can be used to build a model for which the residual is random.

$$\phi_a(B)\nabla^{d_a} b_t = \theta_a(B)\ a_t \qquad \text{(C-18)}$$

Substituting C-18 into C-17, we have a new model:

$$\phi_b(B) \cdot \phi_a(B)\nabla^{d_b}\nabla^{d_a}\ \tilde{z}_t = \theta_b(B)\cdot \theta_a(B)\ a_t \qquad \text{(C-19)}$$

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