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A note on long-term temperature trends at English lightvessels

by

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Introduction

It has become common practice in recent years to talk glibly about the long-term warming up of the seas around our coasts and to use anomalies as a convenient way of describing those periods of time where the sea surface temperature is abnormal. There is, in a sense, an implied precision about the value of an anomaly which may be largely spurious unless the context is carefully defined, and to do this some simple but fundamental questions must be answered. For example, an anomaly is a departure from the norm: but which norm? and by how much? If it is agreed that we accept the 50-year mean in the 1905-54 ICES Atlas (Ref. 1), for example, can it be assumed that this is biologically, or hydrographically, the most relevant, or would some shorter period mean be more meaningful? If we define the significance of an anomaly in terms of a multiple of the standard deviation of the residual variation about this mean, have we first checked that the random residual is normally distributed? If not, the statistical confidence of the significance is open to question.

As a simple illustration, Figure 1 shows the annual means of sea surface temperature from 1903 to 1964 at the Seven Stones Lightvessel. If we consider the magnitude of the positive anomalies from the overall mean in 1921 (0.86°C) and in 1962 (0.92°C) we conclude that they are of much the same significance, although the 1962 anomaly is slightly greater. However, as anomalies from the linear regression line the 1921 anomaly (1.04) is not only the larger but is two and a half times the anomaly for 1962 (0.44) - hence considerably more significant. In fact, the residual standard deviation about the regression is approximately 0.40°C, and hence a value equal to or exceeding the 1962 anomaly might be expected from purely random causes on about one in three occasions, whereas the chance of equalling or exceeding the 1921 anomaly is almost one in a hundred, or thirty times less likely. Thus, if we are looking for indications of abnormal environmental conditions, the choice of a norm from which to calculate our anomaly may be crucial. How then do we decide which norm to use? It depends of course on the application, or on the hypothesis under test, but my biologist colleagues advise me that fluctuations from relatively short-term means or trends are probably more appropriate than deviations from long period means when dealing with marine animals which have a relatively short life span.

So what I am really asking is how best should we, as fisheries hydrographers, analyse a large mass of long-term trend data at an ocean data station, and although I shall deal in this paper only with surface temperature at two English lightvessels (Figure 2) the principles apply to salinity, or any other parameter collected regularly over a long period in any data field. Clearly, in order to understand the significance of the data and to draw valid quantitative rather than qualitative conclusions, we must be able to describe the data mathematically, i.e. to formulate some simple mathematical model and associate with it a relevant set of tests of statistical significance. Without these tools there is little chance of using large masses of data, such as are contained in the ICES Atlas, for valid prediction or hindcasting of environmental conditions and relating these to biological behaviour patterns.

Southward, 1960 (Ref. 2), among others, has discussed the long-term trends of sea temperature in the Channel at International Station E1 and also at the Seven Stones Lightvessel, and related these to changes in the fauna. He concludes, in his summary, that the sea surface temperature has risen by about 0.5°C over the last 50 years or so, and illustrates it in Figure 3. He implies in his paper (and in this figure) that the SST was fluctuating about a period mean of 11.92°C from 1903-27 and subsequently from 1928-59 about a mean of 12.42°C. Now of course these are the means for the periods before and after 1927, but the conclusion is at the very least open to criticism. Another interpretation is given in my Figure 1, which shows the least squares fitted linear regression, and from this we can conclude that the rise in temperature over the period in question was nearly double Southward's estimate, and has been fluctuating about a continuously rising linear trend.

In my view this conclusion is the more valid, since there is a better fit - a better mathematical description of the data. Ellett from Lowestoft used a similar stepped mean technique (Ref. 3), but his approach was more appropriate since he was essentially testing the hypothesis that there was evidence of significant differences in the long- and short-term means of sea surface temperature and salinity at a number of English lightvessels, and by inference in other data fields of the ICES Atlas. But even in his approach it might have been more rewarding to have used a regression technique, and it was basically the discussion of his paper at Lowestoft which triggered the present approach. However, meanwhile Tomczak, in another paper to this Committee last year (Ref. 4), fitted linear regressions to 144 fields of data from the ICES Atlas, and concluded that the slopes (or what he called the temperature coefficients α) varied from month to month and between fields. Further to his work, the following questions arise:

(a) Is there any regression (or correlation) of temperature on time in each field of data?

(b) Is it fair to represent the trend by a linear regression, i.e. is there evidence of departure from linearity?

(c) Are the slopes of the monthly means significantly different from the annual slope and from each other? Or could they be represented by a common slope within the degree of residual variation expected?

Results

Let us look in a little more detail at the data for the Seven Stones Lightvessel. We saw from Figure 1 that it looked reasonable to represent the data by a linear relationship. We can test whether this is so, of course, to the first order, by calculating the correlation coefficient and testing its significance, but we shall arrive at the same answer by studying the simple analysis of variance table of the regression shown in Table 1. This has the added advantage of giving us immediately a measure of the residual variance.

Table 1 Seven Stones annual means regression

Source	Sum of squares	D of F	Mean square	Exp. value mean square
Regression	$b^2\Sigma(x-\bar{x})^2 = 5.75$	1	5.75	$\sigma^2+B\Sigma(x-\bar{x})^2$
Residual	$\Sigma(y-\bar{y}-b(x-\bar{x}))^2 = 8.61$	53	0.162	σ^2
Total	$\Sigma(y-\bar{y})^2 = 14.36$	54		

If we let y and x represent temperature and the year (less 1960) we have the usual linear regression model

$$y = \bar{y} + b(x-\bar{x}),$$

where b is the slope, and, in this case,

$$y = 12.26 + 0.017\ (x - 32.29).$$

Testing the mean square against the residual, we have

$$F_{1,53} = 35.5,$$

which is significant at 0.001 level and shows that we may certainly assume that there is a first order linear relationship. Now, of course, we should have checked the normality of the random residual, but since the scatter is clearly symmetrical we could check that it is reasonable to assume a normal distribution by estimating various confidence limits from the residual standard deviation $\sigma = \sqrt{0.162} = 0.40$ approximately, and checking the number of observations which should fall within these limits. Ninety-five per cent confidence limits have been drawn on Figure 1 and we could expect not more than 1 in 20 or 2-3 points to be outside them, which agrees quite well.

If we now consider the annual means at the Varne Lightvessel, as illustrated in Figure 3, and plot the linear regression line which is calculated as

$$y = 11.41 + 0.018\ (x - 33.35)$$

we are immediately in doubt as to whether the low points at 1915, 1916, 1917 and 1918 may reasonably be reckoned as within the assumed normal distributions of the residual about the regression, although from the analysis of variance in Table 2, the regression is seen to be significant at the 5 per cent level, since $F_{1,46} = 5.35$.

Table 2 Varne annual means regression

Source	Sum of squares	D of F	Mean square
Regression	5.08	1	5.08
Residual	43.59	46	0.948
Total	48.67	47	

If the low points are omitted and an amended regression calculated, together with the associated 95 per cent confidence limits, we see that the low points cannot be considered to be from the same population as the remainder and are not therefore properly represented by the regression. This does not of itself justify their rejection as valid data, but certainly it is only the remainder that can be properly represented by a linear regression, the equation of which is amended to

$$y = 11.66 + 0.006\ (x - 34.89),$$

and we now estimate from Table 3 that $F_{1,42} = 1.37$, which is not significant at the 20 per cent level, i.e. we have not sufficient evidence from these data to support the view that there has been a statistically significant rise in the annual means of surface temperature over the period.

Table 3 Varne amended annual means regression

Source	Sum of squares	D of F	Mean square
Regression	0.47	1	0.47
Residual	14.42	42	0.343
Total	14.89	43	

Let us now consider the regressions of the monthly means. As shown in Table 4, the slopes vary considerably from 0.024 to 0.009 at Seven Stones and from 0.027 to -0.010 at Varne, the highest being in general in the autumn months, showing that the average rate of increase in temperature has been greater at this time of year at both locations over the 60-year period.

Table 4 Regression slopes of monthly means at Seven Stones and Varne Lightvessels

Month	Seven Stones			Varne		
	Slope	S.D.	Significance level (%)	Slope	S.D.	Significance level (%)
January	0.017	0.004	1	0.007	0.010	NS
February	0.016	0.005	1	0.003	0.012	NS
March	0.017	0.005	1	-0.010	0.010	NS
April	0.019	0.005	1	-0.001	0.009	NS
May	0.016	0.006	1	0.000	0.007	NS
June	0.021	0.006	1	0.019	0.009	5
July	0.016	0.007	5	0.019	0.009	5
August	0.009	0.007	NS	0.020	0.008	2
September	0.021	0.007	1	0.026	0.008	1
October	0.022	0.005	1	0.027	0.008	1
November	0.024	0.004	1	0.027	0.009	1
December	0.021	0.004	1	0.013	0.008	NS

Also included in Table 4 are the standard deviations of the regression slopes σ_i and the significance level of the regression, from which we can deduce that the slopes are not significantly different from zero in August at Seven Stones and from December to May inclusive at Varne. Since the slopes are scattered about zero from December to May at Varne, there is no reason to suppose that there has been any long-term warming in these months over the period. Whether there are significant differences between the monthly slopes can be tested by calculating the weighted average residual variance for the months to be tested, and hence the variance σ_{12}^2 of the difference of the regression slopes b_1 and b_2. The significance may then be tested by Student's t test

$$t = \frac{b_1 - b_2}{\sigma_{12}}$$

with $n_1 + n_2$ degrees of freedom. None of the pairs of months at Seven Stones (excluding August) turn out to have significantly different slopes at this level of confidence. Similarly, the differences between the monthly slopes at Varne from June-November are not sufficiently large to be statistically significant at the 95 per cent level.

The next step is to consider whether it is reasonable to represent the trend by a linear regression. In order to test for departure from linearity, we must include in the simple model above a departure term $B_t (t = 1,\text{---}K)$ at each of the K arrays of y, so the model becomes

$$y_{ti} = \bar{y}_{..} + \beta(x_t - \bar{x}) + B_t + Z_{ti} \qquad i = 1\text{---}n_t$$

where β is the expected value of the regression coefficient b and Z_{ti} is the random residual which we are assuming to be independent, normally distributed and of constant standard deviation along the regression line. It is clear that some replication $(i = 1\text{---}n_t)$ is necessary in the t'th array of y in order to separate the variance due to departure from linearity and the random residual. If the suffixes of B_t and Z_{ti} were identical, these variances could not be distinguished. We can overcome the replication requirement by grouping the means. Normally 3-year groups have been used but these become 2- or 4-year groups at either end of a gap in the data, such as the 1914-18 war period. An example of the analysis of variance tables is shown for the April monthly means at Seven Stones in Table 5, since this is one of the more interesting cases, but the analysis was completed for the annual means and the monthly mean at both lightvessels where

Table 5 Seven Stones April monthly means regression

Source	Sum of squares	D of F	Mean square	Exp.value mean square
Slope	$b^2 \sum_{t=1}^{k} n_t(x_t - \bar{x})^2 = 1.97$	1	1.97	$\sigma^2 + \beta^2 \sum_{t=1}^{k} n_t(x_t - \bar{x})^2$
About regression	$\sum_{t=1}^{k} n_t\left\{(\bar{y}_t. - \bar{y}..)^2 - b^2(x_t - \bar{x})^2\right\} = 6.79$	$K - 2 = 12$	0.57	$\sigma^2 + \frac{1}{k-2} \sum_{t=1}^{k} n_t B_t^2$
Residual	$\sum_{t=1}^{k} \sum_{i=1}^{n_t} (y_{ti} - \bar{y}_t.)^2 = 7.38$	$N - K = 28$	0.26	σ^2
Total	$\sum_{t=1}^{k} \sum_{i=1}^{n_t} (y_{ti} - \bar{y}..)^2 = 16.14$	$N - 1 = 41$		

the significance of the regression had been established. For the April means in Table 5 a significant variance ratio of the "about regression" over "residual" will indicate the existence of the B_t, as can be seen from the expected values of the mean squares. In this case, $F_{12,28} = 2.15$, which is just significant at the 5 per cent level, from which we conclude that there is reasonably good evidence of departure from linearity, so we should consider carefully whether or not a more complex curvilinear model should be attempted. We also see, by comparing the mean squares of "slope" and "residual", that $F_{1,28} = 7.47$ is almost significant at the 1 per cent level (7.6), but of course we are already aware of the significance of the overall regression. Evidence of significant departure from linearity was only found at the Seven Stones Lightvessel at just above the 5 per cent level for the monthly means during April and October, and would not therefore, in my view, justify the extra work involved in attempting to fit a higher order model. However, at the Varne the monthly mean regression for July showed significant departure at 1 per cent and we could not therefore accept a linear model in this case.

It might be thought that another method of grouping could be to group the months seasonally, i.e. January-March, April-June, July-September, etc., and hence retain a longer sequence of data. In fact these analyses were carried out for these seasonal groups and at both lightvessels significant departure from linearity was indicated, normally at the 1 per cent level. The winter 3-monthly group (January-March) for Seven Stones is given in Table 6 as an example. Here the comparison of the "about regression" and "residual" mean square gives an F ratio of 2.008, which is just significant at 1 per cent. This result would appear to be contrary to the results obtained for the three individual months alone. The explanation is that the apparent significance shown by Table 6 is spurious, because the data in the individual 3-month groups are not normally distributed, and hence the F test in this case is not valid. The residual variation will in fact be platykurtic and hence there is a considerably greater chance of obtaining a larger variance ratio than would be indicated by the F tables. This particular illustration is included to show the importance of the underlying assumptions which are often assumed and then neglected, and this can of course often lead to misleading conclusions.

Table 6 Seven Stones winter group regression

Source	Sum of squares	D of F	Mean square
Slope	3.14	1	3.14
About regression	26.66	40	0.67
Residual	26.89	81	0.33
Total	56.70	122	

Conclusions

Thus, to summarize, it might be concluded that at Seven Stones there has been a significant linear average upward trend of about 0.9°C in annual means over the 60 years, and that there has been no evidence of an upward trend in the August monthly means, but that in all other months there has been a significant positive regression which tends to be more marked in the autumn months but is not significantly so. At the Varne Lightvessel, if the highly significant negative anomalies for 1915-18 are omitted, there is no statistically significant evidence for a general warming of the surface water as indicated by the annual means or the monthly means from December to May. During the remainder of the year the rate of increase in monthly means has been similar to that at the Seven Stones Lightvessel. Hence we might conclude that the similar increase in surface temperature at the two locations in the autumn is largely due to an increase in the influx of Atlantic water over the period, but that the warming trend has not penetrated as far as the Varne in the winter and spring because of the proximity of the continental land mass and its winter cooling. The absence of an upward trend at the Seven Stones in August is more interesting and could possibly be explained by the existence of a short-term thermocline which produces a higher order of surface temperatures and temperature fluctuations, which swamp the evidence for a steadily rising trend (of much smaller proportions) due to an increased Atlantic influx; but the aim of this paper is to suggest a possible form of analysis which includes critical statistical testing for the large masses of data occurring in the ICES Atlas, rather than to draw valid hydrographic conclusions from so small a sample as two fields. This, it seems to me, is necessary before we can expect to grasp the full quantitative significance of long-term environmental trends and anomaly data and apply the conclusions to biological occurrences.

References

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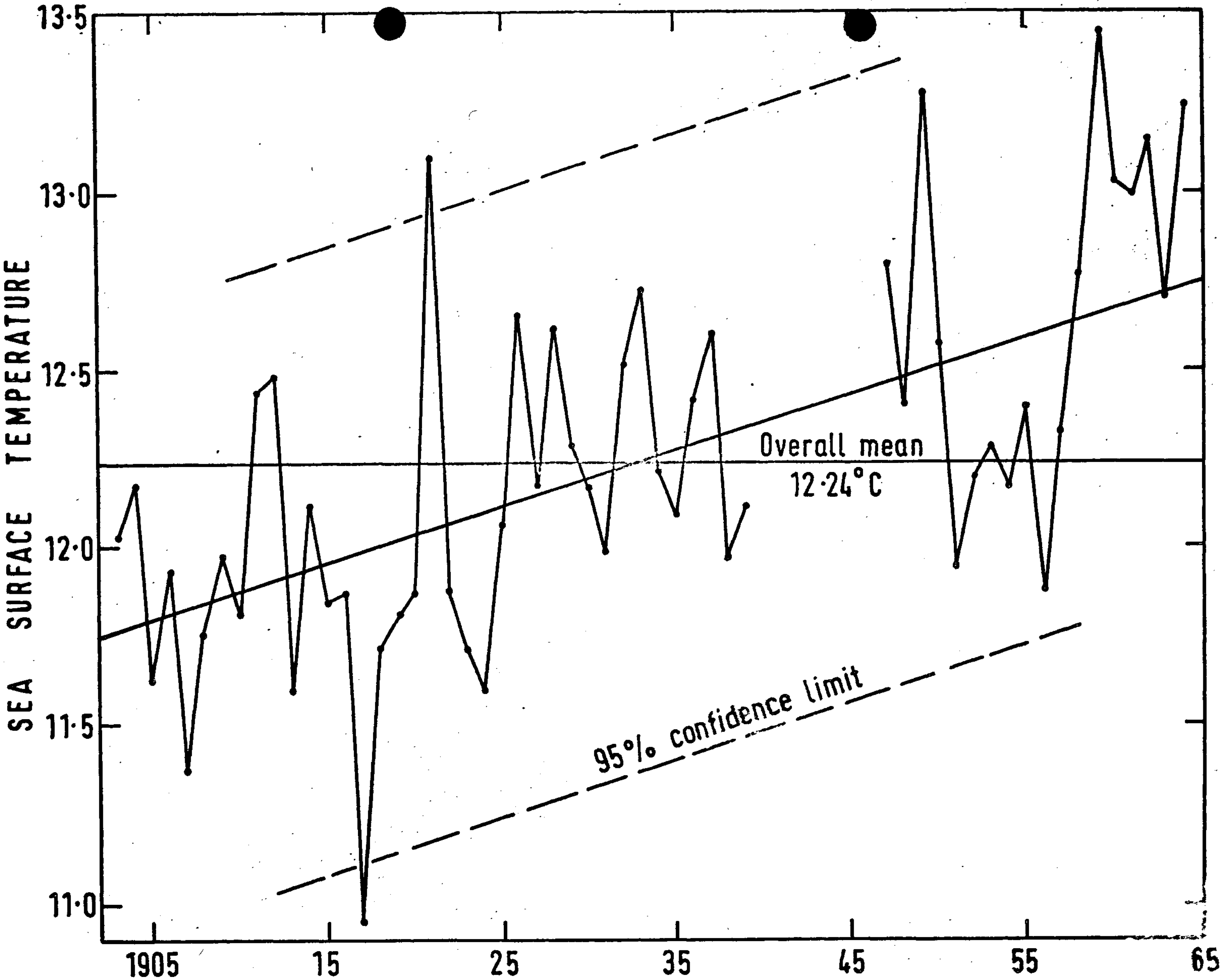

Figure 1 Annual means of sea surface temperatures at the Seven Stones lightvessel.

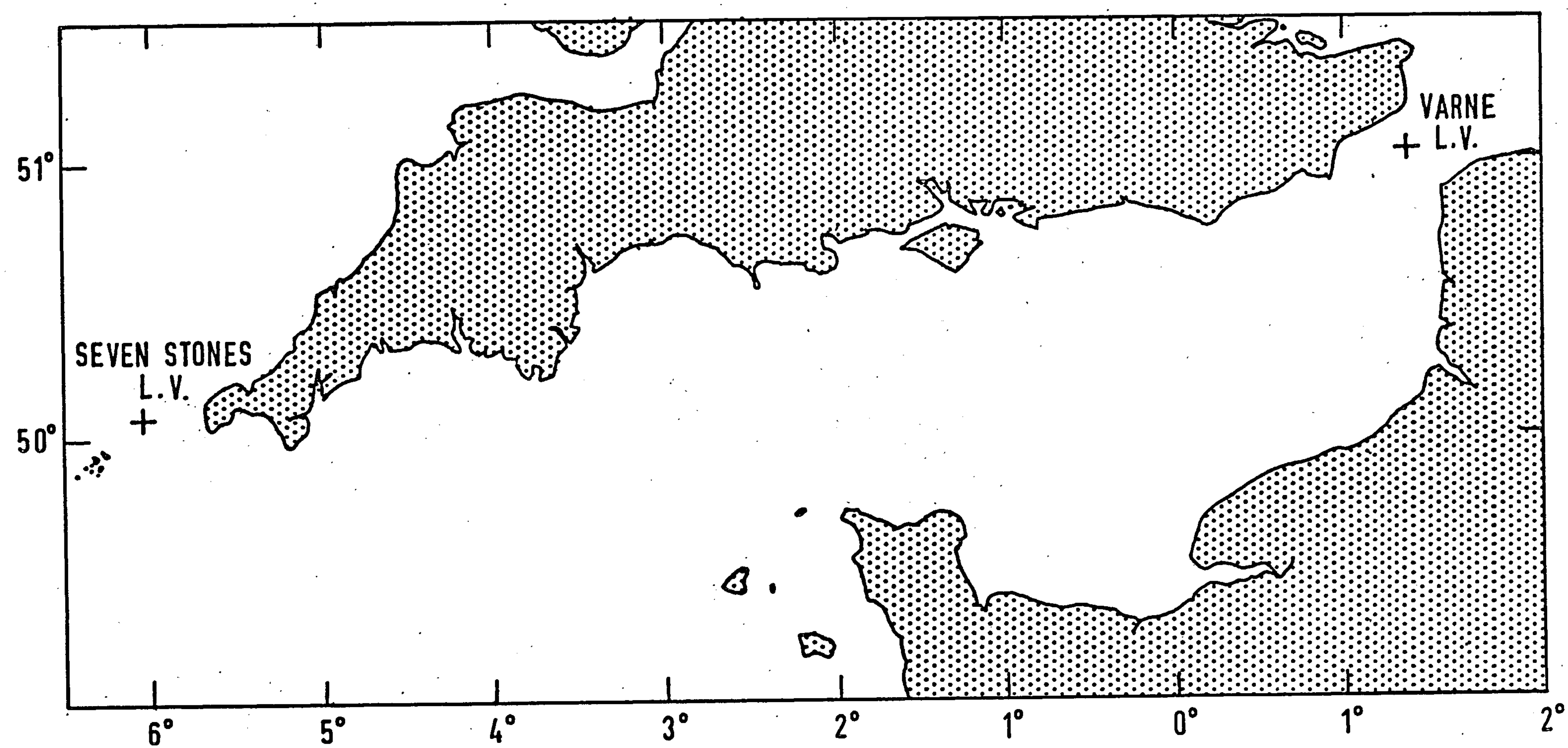

Figure 2

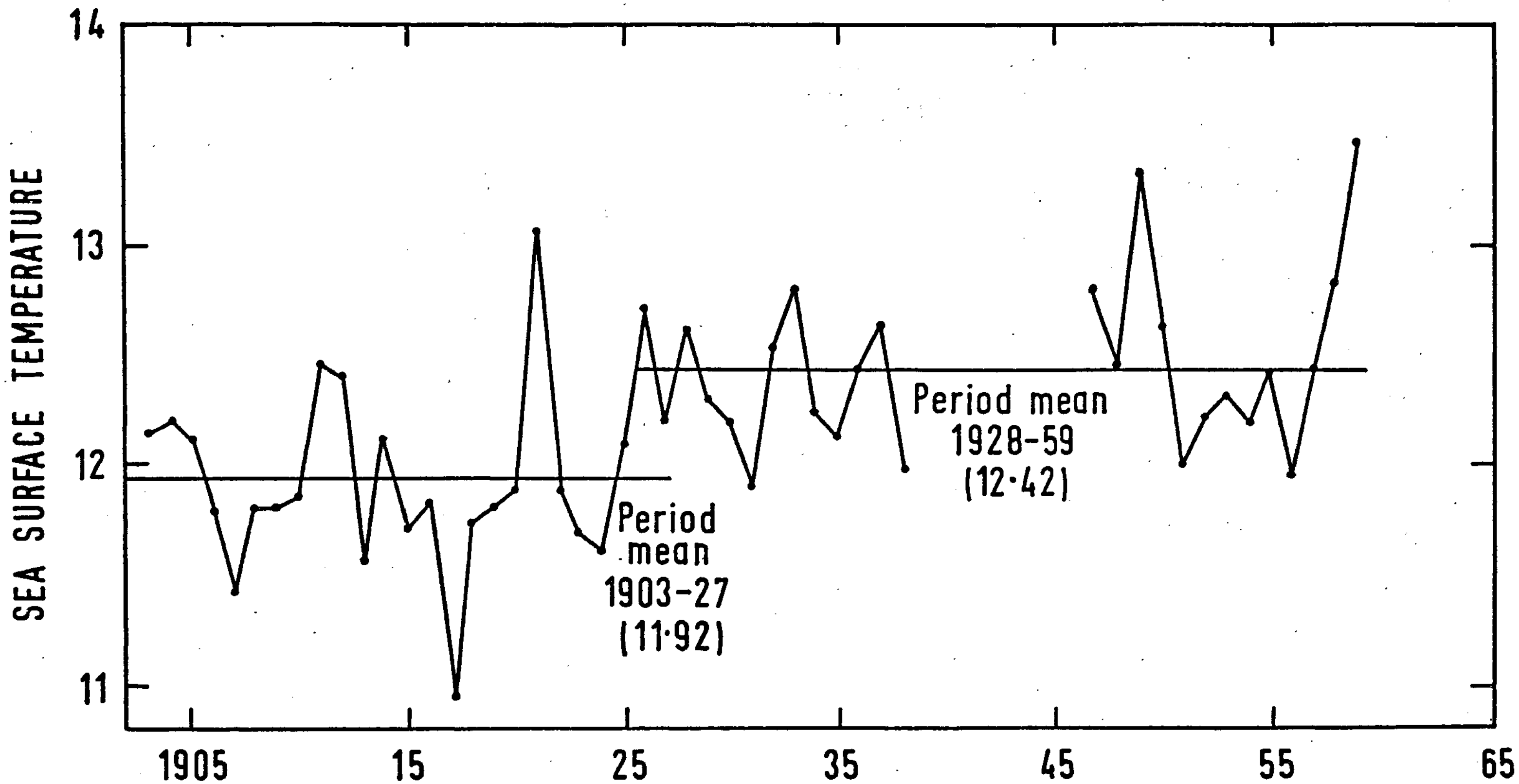

Figure 3 Annual means of sea surface temperatures at the Seven Stones lightvessel (after Southward).

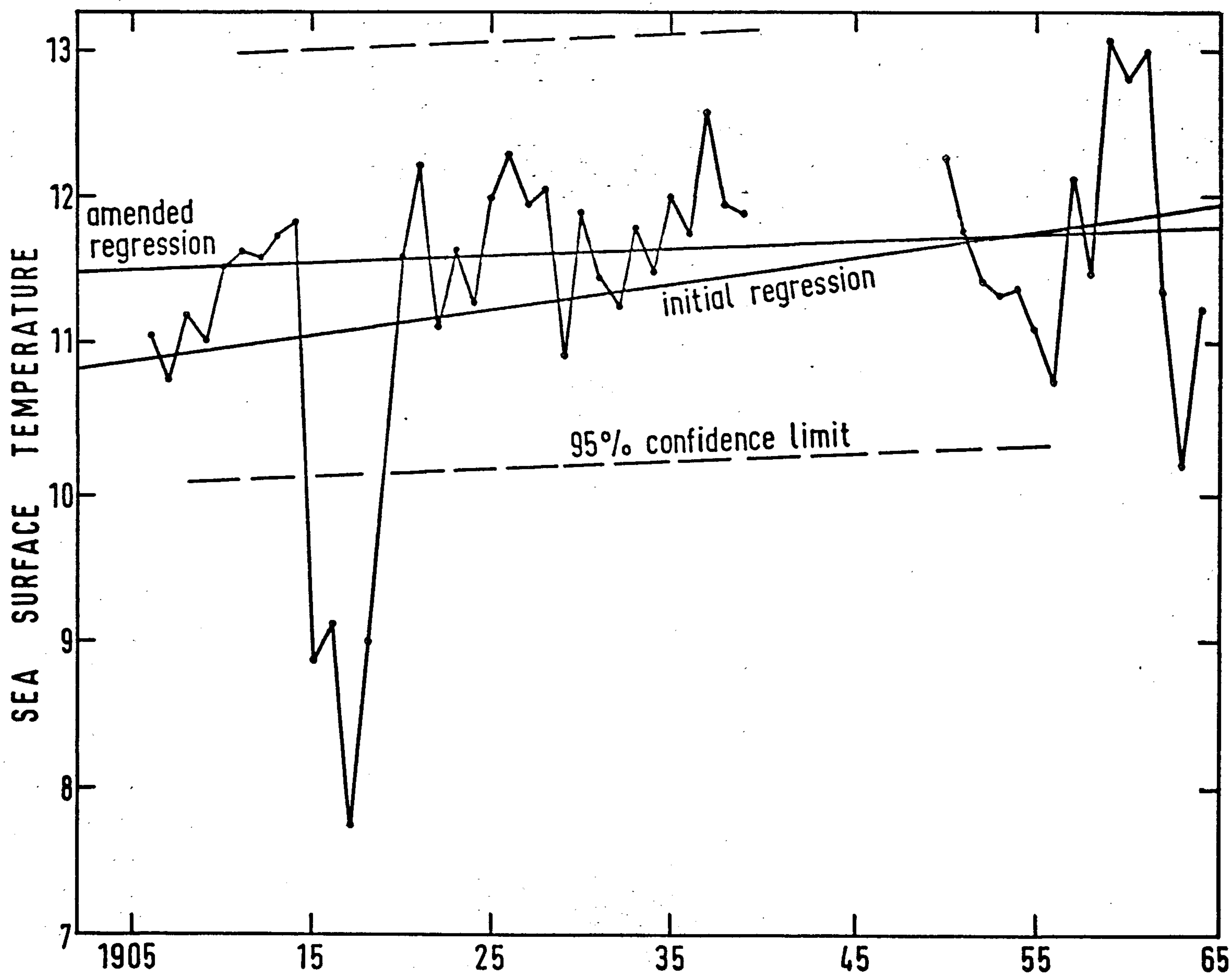

Figure 4 Annual means of sea surface temperatures at the Varne lightvessel.

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