SECTION

I

I-1

FORESHADOWING OF SURFACE WATER TEMPERATURES AT ST. ANDREWS, N.B.

By

L. M. Lauzier[1]

ABSTRACT

Twice daily surface temperature observations have been recorded at St. Andrews, New Brunswick, Canada since 1921. In the last 42 years, the annual temperature varied between 5.4° and 8.5°C with a long-term average of 7.0°C. The various components of the annual temperature and of its régime, such as the warming and cooling, the annual maxima and minima have been related to each other and to the annual temperatures with varying degree of confidence. Regression equations have been established. These equations are used to foreshadow annual temperatures and the maximum temperatures, mainly to show if above or below average conditions are expected, and if warming or cooling from the previous year is expected. The standard errors of estimate are of the order of 0.4° and 0.6°C for the annual and the maximum temperatures respectively. Similar regression equations were established for other points of the Atlantic seaboard.

INTRODUCTION

The annual mean sea surface temperature along the Canadian Atlantic Coast shows both long and short period variations. The climatic fluctuations of the waters in the North Atlantic have been discussed at great length (UNESCO-WMO, 1963), but comparatively little has been said about the short term variations as such.

The temperature variations in the Bay of Fundy area, at St. Andrews, N.B., were compared with those at other points along the Atlantic seaboard. Due to strong tidal action in the Bay of Fundy and vigorous mixing, the temperature variations are shown to be a good index of the changes that occur over a large area (Hachey and McLellan, 1948; Lauzier, 1954, and this Symposium). In dealing with warm years and cold years, Hachey and McLellan (1948) have discussed differential warming, the vernal and aestival warming, for the waters of Passamaquoddy Bay. Taylor *et al.* (1957), and Lauzier (1957) have noticed that the increase of winter temperatures during the recent long-term warming trend was greater than the increase of annual mean temperatures in the coastal waters of the Gulf of Maine and for Passamaquoddy Bay. Among others, Mitchell (1961) studied the changes of global air temperatures and discussed the winter and annual changes.

Year-to-year variations in the annual mean, the minimum, the maximum, the warming and the cooling, as well as the interrelations of these factors were considered in some detail by Lauzier (1957). The deviations from long-term averages in maxima, minima, warming, cooling, and annual means display a definite interrelated pattern that can be used for the purpose of foreshadowing annual temperatures. Here the term foreshadowing instead of forecasting is used because the predicted temperatures are of the nature of an average, for instance, an average of monthly temperatures. It is of interest to fisheries scientists to know whether the temperatures in the forthcoming period will be above or below normal, and also if the temperatures in this period will be above or below that of the preceding period.

DATA

The twice daily observations of surface temperature at St. Andrews since 1921 up to date provide the basis for monthly and annual means. These data have been used by various authors.

Annual means

The annual mean temperature is the average of 12 monthly temperatures from January to December and the average temperature régime can be represented mathematically by a sine curve (Hachey, 1939).

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The absolute value of the change from one year to the next may be as large as 1.8°C; it was less than 0.5°C in 39% of the cases and greater than 0.9°C in 20% of the cases. The annual mean temperature curve for the period 1921-62 is shown in Fig. 1A. The overall average of annual means is 7.0°C; the extremes are 5.4 and 8.5°C, in 1923 and 1951 respectively.

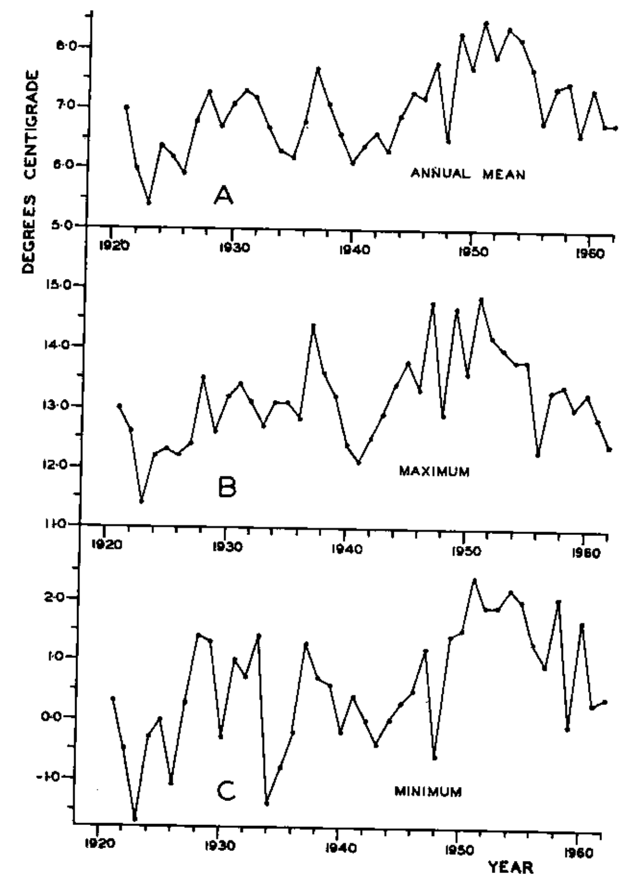

Fig. 1. Surface water temperature variations at St. Andrews, N. B. A. Annual Mean, B. Maximum, C. Minimum.

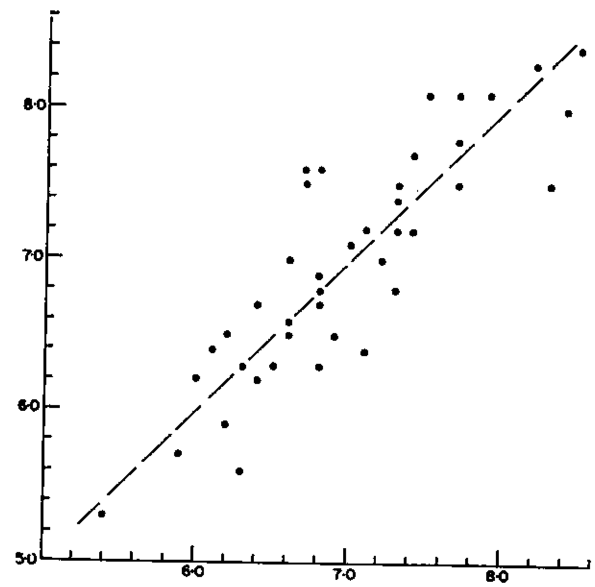

Fig. 2. Comparison of observed (O) and calculated (P) values of annual mean temperatures at St. Andrews, N. B.

Maxima and minima of monthly averages

In Passamaquoddy Bay, the maximum monthly temperature is normally reached in August, but in some years the September average might be equal to or slightly higher than the August one. The minimum monthly temperature occurs usually in February, but in some years, it is delayed until March. The variations in the maxima and the minima during the period 1921-62 are shown in the curves B and C respectively of Fig. 1. The curve of maxima follows fairly closely that of the annual means; except for a short period, 1946-52, the variations for one year to the next were relatively persistent, showing long series of warming and cooling. The curve of minima has different features; the variations seem to be erratic from the beginning of the series to the early forties. After 1942, there was a steady increase up to 1954, with the exceptions of 1948 and 1951 when the minima were somewhat out of line. The overall extremes recorded in maxima were 11.4°C and 14.9°C in 1923 and 1951 respectively. The extreme minima, -1.7°C and 2.4°C were also recorded in 1923 and 1951 respectively.

Computed from maxima and minima, warming and cooling vary from year-to-year over a very wide range; this is more so for the cooling. The same amount of warming in two different years could be related to fairly different maxima, depending on the point of departure, the minima. Similar reasoning applies to the cooling. Values of warming and cooling, adjusted to the general temperature level of the preceding period, are significant in the study of temperature régimes. The aestival warming, from June to August may account for as much as 36%, or as little as 18% of the total. The winter cooling, from December to February may account for as much as 48% or as little as 17% of the total cooling.

STATISTICAL APPROACH

Persistence and variability

Since the purpose of this paper is to establish a method of prediction of temperature values by means of regression equations based on the interrelationships between the variations of different criteria of the temperature régime in the area, it is important to know how persistent and how variable are each one of the criteria.

Observations of surface water temperatures taken at St. Andrews, N.B. since 1921, have been used to evaluate five different criteria of the temperature régime namely, the maximum, the minimum, the warming and the cooling computed from the previous two, and the annual mean. Figure 1 shows that some of the variables are more persistent than others, and also that some vary within wider limits than others. The coefficient of serial correlation (r_a) which is a measure of the persistence, has been calculated for all the variables. It is given in Table 1, together with the standard deviation (σ) of the series of observations as a whole, and the standard deviation (σd) of the difference from one year to the next.

The values given in Table 1 are comparable to a similar Table of a previous publication (Lauzier, 1957). They are generally lower for the present series, 1921-62, than for the previous series 1921-55.

In Table 1, it is shown that the annual mean was most persistent, and the cooling least persistent. The annual mean was however more persistent from 1921 to 1944 than during the decade 1945-55. This is shown in shorter periods of variations from the middle forties up to 1955 (Fig.1A). The same phenomenon was observed in the variation of the maxima (Fig. 1B). Table 1 also shows that the minimum has a relatively high standard deviation but still it has a fair degree of persistence.

TABLE 1.—COEFFICIENTS OF SERIAL CORRELATION AND STANDARD DEVIATIONS

criterion	period	r_a	σ	σd
Annual mean	1921-62	0.58	0.70°C	0.65°C
	1921-44	0.69	0.67	0.53
	1945-55	0.59	0.92	0.83
Maximum	1921-62	0.43	0.76	0.81
Minimum	1921-62	0.42	1.00	1.07
Warming	1921-62	0.22	0.77	0.96
Cooling	1921-62	-0.14	0.97	1.46

Correlation coefficients

After considering the variations of the different criteria like the minimum, the maximum, the annual mean, etc., and their order of occurrence, the joint variations of two or more criteria or their interdependence, are studied by evaluating correlation coefficients.

The reader should be aware that the criteria considered here are not absolutely independent since we are dealing with different stages of a "régime".

The correlation coefficients "r" have been based on at least 42 pairs of observations for the period 1921-62; then coefficients with values of "r" greater than 0.40 and 0.31 are significant at the 99% and 95% probability levels respectively. The coefficients calculated in the previous paper (Lauzier, 1957) for the period 1921-55 were useful to indicate which combinations of criteria did not show any correlation and also the combinations that exhibit a significant degree of correlation.

Among the latter ones, there were some spurious correlations, those relating the minimum or the maximum temperature of one year with the annual temperature of the same year.

It is of interest to consider the relationship between parameters which represent a time lag large enough to be of some value from the point of view of foreshadowing, such as between:
annual temperature of one year (T_N) and annual temperature of preceding year (T_{N-1});
annual temperature of one year and minimum temperature of same year (Min_N);
annual temperature of one year and cooling during previous autumn and winter (C_N);
maximum during one year (Max_N) and maximum during preceding year (Max_{N-1});
maximum during one year and minimum during same year (Min_N);
minimum during one year (Min_N) and minimum during preceding year (Min_{N-1});
minimum during one year and maximum during preceding year (Max_{N-1}).

The time lag varies between 10 and 12 months for the annual temperature, between 6 and 12 months for the maximum and minimum.

The correlation coefficients are listed in Table 2. These values are higher than 0.40 which is that of the 99% probability level.

TABLE 2.—CORRELATION COEFFICIENTS BETWEEN DIFFERENT CRITERIA OF THE SURFACE TEMPERATURE REGIME AT ST. ANDREWS, N.B.

	T_N	Min_N	Max_N
T_{N-1}	0.582 (1)		
Min_N	0.823 (2)		
Min_{N+1}	0.617	0.423 (1)	
Max_N	0.875 (2)	0.648	
Max_{N-1}		0.434	0.434 (1)

(1) these are the same as those listed in Table 1 as coefficients of serial correlation.
(2) the correlation between the annual temperature and the minimum and maximum respectively of the same year are spurious.

Even if the values of "r" considered are statistically significant at the 99% probability level, it is important to use, wherever possible, elements which are correlated by a coefficient of a value of 0.71 or better. Such coefficient means that at least 50% of the variance of the changes of one element can be attributed statistically to the variance of the changes of the other element.

Figure 1 shows long-term variations in annual temperatures, minima and maxima. It is suspected that the minima and the annual temperatures have a "long-term" relationship superimposed to an "annual" relationship. It is possible to "eliminate most of the long-term variations by making two new series of observations each consisting of the change from one time interval to the next" (Brooks and Carruthers, 1953). This is called the "variate-difference" correlation. The correlation coefficient for T_N Min_N is 0.82 and the coefficient for the variate-difference correlation is 0.72. It is concluded that 0.15, $(1-0.72^2) - (1-0.82^2)$, or 15% of the variance of the changes of the annual temperature could be attributed statistically to the variance of the long-term changes and 52%, $r^2 = (0.72)^2 = 0.52$, to the variance of the changes of the minimum.

FORESHADOWING FROM REGRESSION EQUATIONS

The study of correlations between the different components of the temperature régime has the ultimate purpose of foreshadowing the temperatures at least 9 or 10 months in advance. Such a requirement forcibly eliminates use of correlation between the warming during a year or of the maximum during a year and the annual temperature of the same year, because it would give predictions only 4 months beforehand; however they could be very useful in making shorter predictions. The cooling and the minimum could be used for making predictions. As mentioned before, our aim in foreshadowing temperatures is to predict the changes from one year to the next. Will the temperature level stay the same (on the average) during the next 10 months as it has been during the previous 12 months?

Will it be above or below normal, and by how much? One should realize that it is statistically easier to predict an annual temperature which is an average of twelve monthly temperatures, than a maximum or a minimum which is one monthly temperature.

For prognostication, there are two aspects to consider: 1. Are these correlations of any value to the "forecaster", and are the correlation coefficients sufficiently high to be of significant value statistically? 2. What are the physical processes involved to explain the cause and effect relationship? Question 1 was answered in the previous section. Question 2 will be considered in the discussion.

On all regression equations, the standard error of estimate $\sigma\ y, xz$ has been calculated (Snedecor, Brooks and Carruthers) as well as the standard deviation of the difference between predicted and observed values σ_{PO}. For each equation, a verification factor, V_{PO}, has been calculated; it is the percentage of cases in which observed and predicted values agree as to sign of deviation from one year to the next, (those equal to zero either predicted or observed are computed as one half). The correlation coefficients r and R for simple and multiple correlation respectively will be given for each equation.

Annual temperatures

A regression equation relating the change in annual temperatures and the cooling C_N during the previous winter has been established. The equation is based partly on the persistence of the annual temperature, and also on the cooling adjusted to the level of the previous year's annual temperature:

$$T_N = T_{N-1}\ (1.00 - 0.040\ C_N) + 3.6 \quad (1)$$
$$r = 0.70;\ \sigma_{y,x} = 0.46°C;\ \sigma_{PO} = 0.45°C;\ V_{PO} = 78\%$$

The computed values from equation (1) seem to be restricted to a much narrower range than the observed values.

A second regression equation based on a more persistent variable than the cooling has been established using the minimum temperature:

$$T_N = 0.58\ Min_N + 6.7 \quad (2)$$
$$r = 0.82;\ \sigma_{y,x} = 0.41°C;\ \sigma_{PO} = 0.38°C;\ V_{PO} = 83\%$$

The computed values from equation (2) have the same disadvantage as those of equation (1).

Based on the multiple correlation between the annual temperature of year N., the annual temperature of the previous year (N-1) and the minimum temperature of year N, an equation has been established:

$$T_N = 0.69\ Min_N + 0.14\ T_{N-1} + 5.6 \quad (3)$$
$$R = 0.83;\ \sigma_{y,xz} = 0.40°C;\ \sigma_{PO} = 0.38°C;\ V_{PO} = 88\%$$

where T_N is the annual temperature of year N, M_N is the minimum temperature which occurs normally in February, T_{N-1} is the annual temperature of the previous year (N-1).

The relationship between observed and computed values of annual temperatures from equation (3) is given in Fig. 2. As pointed out previously, we are interested in the changes from one year to another. In 88% of the cases, the predicted change, an increase or a decrease, agreed with the observed change. The absolute value of the difference between the observed and predicted value was equal to or less than 0.4°C, ($\sigma\ y,xz$), in 78% of the cases, and greater than 0.7°C in less than 10% of the cases. The standard deviations σ and $\sigma\ d$ (Table 1) are respectively 0.70 and 0.65, a much higher value than that of $\sigma\ y,xz$ which means that the 50-50 chance to get a correct prediction from equation (3) is very remote.

Maximum and minimum temperatures

Regression equations relating maximum and minimum temperatures to each other, as well as to the preceding values in the time series, have been established in an attempt to foreshadow these temperature levels at least 6 months in advance. They are:

$$\mathrm{Max}_N = 0.42\ \mathrm{Min}_N + 0.20\ \mathrm{Max}_{N-1} + 10.3 \quad (4)$$
$R = 0.67$; $\sigma_{y,xz} = 0.59°C$; $\sigma_{PO} = 0.57°C$; $V_{PO} = 81\%$

$$\mathrm{Min}_N = 0.27\ \mathrm{Min}_{N-1} + 0.34\ \mathrm{Max}_{N-1} - 4.5 \quad (5)$$
$R = 0.67$; $\sigma_{y,xz} = 0.77°C$; $\sigma_{PO} = 0.97°C$; $V_{PO} = 64\%$

where

Max_N is the maximum temperature of year N
Min_N is the minimum temperature of year N
Max_{N-1} is the maximum temperature of the previous year (N-1)
Min_{N-1} is the minimum temperature of the previous year (N-1)

From equation (4), the absolute value of the difference between the observed and the predicted value was equal to or less than 0.6°C in 73% of the cases. From equation (5), the equivalent difference was equal to or less than 0.8°C in 54% of the cases.

It should be noted that while the standard error of estimate is approximately 60% of the standard deviations for the annual temperature, it becomes approximately 75% for both the maximum and minimum.

It is concluded that, for prediction purposes, the value of equation (4) is dubious and that equation (5) should be used very cautiously, while equation (3) could be used advantageously.

DISCUSSION

This study of the variations of sea water temperatures at St. Andrews, N.B. was made to relate the various components of the annual temperatures or the various phases of the temperature régime, between themselves and also with the annual temperatures. It was possible to evaluate, statistically, the interrelationship of cooling, the level of the annual mean, maximum and minimum temperatures. From the relationship between the different criteria, considering their persistence, it was possible to establish regression equations, and from these make an attempt to foreshadow annual temperatures, maximum and minimum temperatures.

The equations chosen are not the only ones that can be fitted to the data. In all cases it was assumed that there is a linear relationship between each pair of variables. Consequently the sum of the squares of the deviations between the predicted and observed values is at or near a minimum. The highest percentage of agreement between the observed and predicted change (either an increase or a decrease) from one year to the next is also considered. Under these assumptions the equations are considered to be valuable to the "forecaster".

The average temperature régime of such coastal waters as those of St. Andrews, where ice is not generally formed, can be represented mathematically by one sine curve (Hachey, 1939). Therefore, the average temperature over one cycle could be estimated by the general equation:

$$T_N = K\ (\mathrm{Max}+\mathrm{Min}) + \text{constant}$$
K being approximately 0.5

Such equations have been calculated as well as others by the method of multiple regression. It should be pointed out that all the correlations are spurious, and that the foreshadowing value of these equations is somewhat limited covering only a four-month period. However they could be used for predicting, in August and in February, twelve month averages for periods ending in December and in June respectively from equations:

$$T_{J_A - D} = 0.54\ \mathrm{Max}_N + 0.31\ \mathrm{Min}_N - 0.3 \quad (6)$$

for the period January - December with $V_{PO} = 87\%$, and

$$T_{J_Y - J_u} = 0.34\ \mathrm{Max}_{N-1}\ 0.51\ \mathrm{Min}_N + 2.3 \quad (7)$$

for the period July to June with $V_{PO} = 88\%$

The standard deviations between predicted and observed values, σ_{PO}, are 0.25 and 0.23 for equations (6) and (7) respectively. Even if the four-month predictions have been previously discarded as such, those based on equations (6) and (7) would be useful in connection with an "extrapolated" curve for twelve-month moving averages.

This numerical "forecasting" seems to be solely statistical. A priori, it does not seem to consider the variations of the factors controlling the temperature variations, such as heat transfer across the air-sea boundary, the heat content of the whole body of water under consideration, or advection and mixing. The processes involved have been considered using to a large extent the temperature and salinity data from monthly observations made at a deep station in the Bay of Fundy. The effect of these processes on the different components of the temperature régime have been estimated. Hachey's theory of the replacement of Bay of Fundy waters (1934), used later by Bailey (1957) has been applied, with some modification, to a much longer period of observations, including 1924-62 data. The results indicate a good agreement with theoretical considerations. The scope of this paper does not permit expanding on the details of such considerations.

In general we might say that changes in the minimum and maximum temperatures from one year to another are attributed mainly to changes in the circulation and in the heat transfer at the air-sea boundary as well as between layers. These three are a complex function of the meteorological conditions - wind, air temperature, evaporation, precipitation - eventually of the run-off from rivers and of oceanographic conditions. The variability in wind mileage, air temperature and run-off are greater in the autumn and winter seasons, during the cooling period, than in the spring and summer seasons during the warming period. So is the variability of minimum and cooling as compared to that of maximum and warming (of Table 1). The coefficients of partial correlation from equations (6) and (7) show that the major part of the changes in 12-month averages are related to changes in the minimum which is the end point of the cooling period as compared to the maximum which ends the warming period. It seems then that a general temperature "level", a temporary régime, is likely to be established during the cooling period of the annual cycle and that its effect seems to persist for the following 8-10 months. Variations from "normal" in the factors responsible for the circulation, the heat transfer, etc. during the warming period of the annual cycle do affect the temperature régime but do not seem to counterbalance the established temperature level. It seems then that a high annual temperature is better related to a lack of cooling during the preceding autumn and winter than an intense warming during the year. Finally, let us keep in mind that successive oceanographic phenomena, as weather phenomena, do not occur at random. Oceanographic conditions of this month have a bearing on the conditions of next month, the conditions of this year on those of next year.

The foreshadowing of annual temperatures by this method seems to be modestly satisfactory on statistical bases. The changes in the "independent variables", the different components of the temperature régime, are indicative of changes in the processes involved in controlling the annual temperature of the water and its variations.

Regression equations relating the annual temperature to its persistence and the minimum temperature, (equation 3) have been calculated for other areas along the Atlantic seaboard. The areas were picked because of availability of published data and also because the factors responsible for the temperature régime such as circulation, heat transfer at the air-sea boundary, stratification, tidal mixing, etc. are somewhat different than those experienced in the Bay of Fundy. The equations are given in an appendix for Boothbay Harbour, Maine, Atlantic City, N.J., Halifax, N.S. and Sambro Lightship, off Halifax, N.S. It was most unfortunate that the data at Halifax and Sambro were so discontinuous, yielding only 24 and 16 years of annual temperature data respectively. Considering the high multiple correlation coefficient for all areas and the high percentage of agreement between the observed and predicted sign of variation, except for Halifax Harbour, it is felt that this type of foreshadowing could be of considerable value to the "forecaster" of the marine environment.

SUMMARY

1. Year-to-year variations of water temperatures at St. Andrews, N.B., are presented.

2. The various components of the temperature régime, the annual means, the maxima and the minima vary in a similar fashion but the range of variations over the 42-year period is the smallest for the annual means and the greatest for the minima. The warming and cooling vary erratically.

3. The variables such as the annual means, the maxima and the minima are shown to be persistent, as compared to the warming and cooling. Of the five variables, the minima have the highest standard deviation.

4. The correlation coefficients have been calculated between several variables. The maxima and minima show respectively significant correlations with the annual temperatures. However it seems that a high annual temperature is better related to a lack of cooling, during the preceding autumn and winter, than an intense warming during the year.

5. Multiple correlation coefficients have been calculated and regression equations established in an attempt to forecast annual temperatures, maxima and minima. The standard errors of estimate are 0.40°C for the annual temperatures, 0.59°C for the maxima, and 0.77°C for the minima.

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APPENDIX

1. Regression equations for annual temperatures at:

Boothbay Harbour, Maine.	$T_N = 0.41\ Min_N + 0.14\ T_{N-1} + 6.7$
Atlantic City, N.J.	$T_N = 0.39\ Min_N + 0.21\ T_{N-1} + 8.9$
Halifax Harbour, N.S.	$T_N = 0.41\ Min_N + 0.33\ T_{N-1} + 4.8$
Sambro Lightship off Halifax	$T_N = 0.41\ Min_N + 0.25\ T_{N-1} + 5.7$

2. Pertinent information

		Boothbay Hr.	Atlantic City	Halifax Hr.	Sambro LS
Number of years		42 (1906-1948)	47 (1913-1920) (1924-1962)	24 (1927-1962)	16 (1937-1960)
Annual Temp.	average	7.8°C	12.2°C	7.7°C	8.4°C
	max.	9.2	13.7	9.4	10.0
	min.	6.3	10.9	5.9	7.2
Min. Temp.	average	0.1	2.0	0.9	1.4
	max.	3.3	5.4	2.6	3.8
	min.	-1.7	-1.2	-0.5	-0.2
σ annual temp.		0.75°C	0.65°C	0.69°C	0.79°C
Coefficient of multiple correlation		0.709	0.798	0.613	0.731
Standard error of estimate		0.54°C	0.41°C	0.57°C	0.58°C
V_{PO}		82%	83%	67%	87%

I-2

FACTORS AFFECTING WATER TEMPERATURE IN THE SEAS NORTH OF NORWAY

By

John Harvey[1]

ABSTRACT

The correlation between the rise of the Barents Sea cod fishery and the increase in the mean water temperature along the Kola section is noted. The factors leading to an increase in water temperature in this region are then considered. They are divided primarily into advective and non-advective factors. Using temperature and salinity data from two stations, S and W, in deep water west of Bear Island, correlation coefficients are established between water temperature in each 100 m layer between 0 and 600 m at station S and

a) meteorological parameters during the preceding ten days at Bear Island,

b) transport of water northwards between the two stations,

during the whole year and during different parts of the year. The relative importance of the advective and the non-advective factors in determining water temperature at various depths, and in different seasons, are then discussed.

INTRODUCTION

The climatic improvement which has been taking place in northern Europe and the adjacent part of the Arctic during the present century (Hesselberg and Johannessen, 1958) has been considered by many writers to have brought about the rise of the great cod fisheries in the seas north of Norway since 1925. The great increase in catch by trawlers in this region has been due partially to the use of larger ships and to the improvements in fishing methods, but it seems certain that there has also been a considerable increase in the size of the cod stocks. Hill and Lee (1957) suggested that this could have been brought about by an increase in the strength of the West Spitsbergen current, carrying eggs and larvae more quickly from the Lofoten spawning grounds to the nursery grounds on the Spitsbergen Bank during the spring and summer months. The environmental conditions on the banks, notably the water temperature, may be expected to have affected the survival of the young cod and the distribution of the adult cod. Blacker (1957) has examined the distribution of various species of benthos in this region, both between 1878 and 1931, and between 1948 and 1955, and found that the "Atlantic" species which require water temperatures exceeding 2°C extended considerably further north in the latter period than they did in the earlier one. He suggested that the change had been brought about both by changes in the mechanical transport of larvae by water movement and by changes in the physical environment, in particular the water temperature. Woodhead and Woodhead (1959) have found that cod in the Barents Sea are apparently limited in their distribution by low water temperatures. The limiting temperature was found to vary during the course of the year in relation to endocrinally controlled changes in physiology, but during the greater part of the year it was found to be 2°C. Cod avoid water of a lower temperature, and if trapped in cold water are likely to die. Thus if the water temperatures, either on the nursery grounds to which the larvae are carried by the West Spitsbergen current, or on passage to these nursery grounds, are below this limit, the survival of the larvae, and hence the recruitment to the stock, will be poor. It is therefore pertinent to examine the changes in water temperature in this region and the factors which have brought them about.

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THE CHANGES IN WATER TEMPERATURE ON THE KOLA SECTION

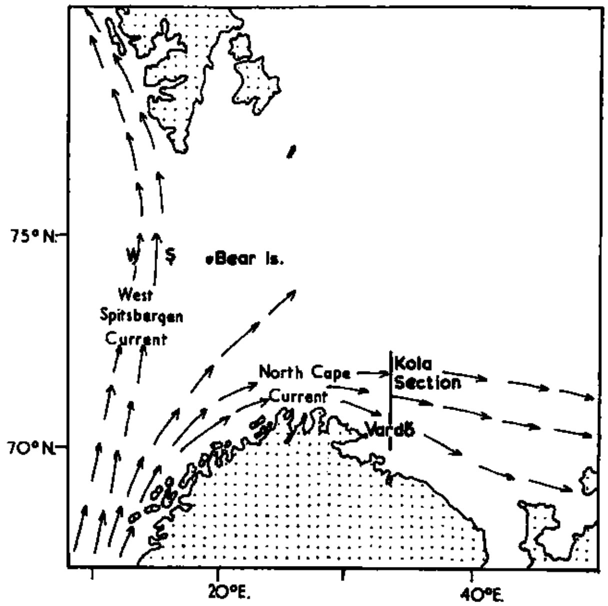

Fig. 1. Positions of places referred to in the text.

Few long period records of water temperature are available for this region. Jensen (1939) assembled the records available to him up to 1936, but although they indicated a general increase in water temperatures they were too scattered to permit any firm conclusions as to the actual changes which had taken place. Observations have been made of water temperature along the Kola Meridian between 70°30'N and 72°30'N since 1900 from which mean, mid-monthly temperatures for the 0-200 m layer and the 0-50 m layer have been obtained. The section is shown in Fig. 1. I am extremely grateful to the Polar Research Institute of Marine Fisheries and Oceanography, Murmansk, who supplied the Fisheries Laboratory, Lowestoft with this data. In Fig. 2 the mean values for the 0-200 m layer between 1921 and 1960, excluding those for the years 1940-45, are shown plotted against time, in the form of 5 yearly running means. The increase between the mid-1920's and the late 1930's, when the great rise in the fisheries took place, is very marked. Since 1945 the 5 yearly running mean temperatures have been mainly above the overall mean value, but lower

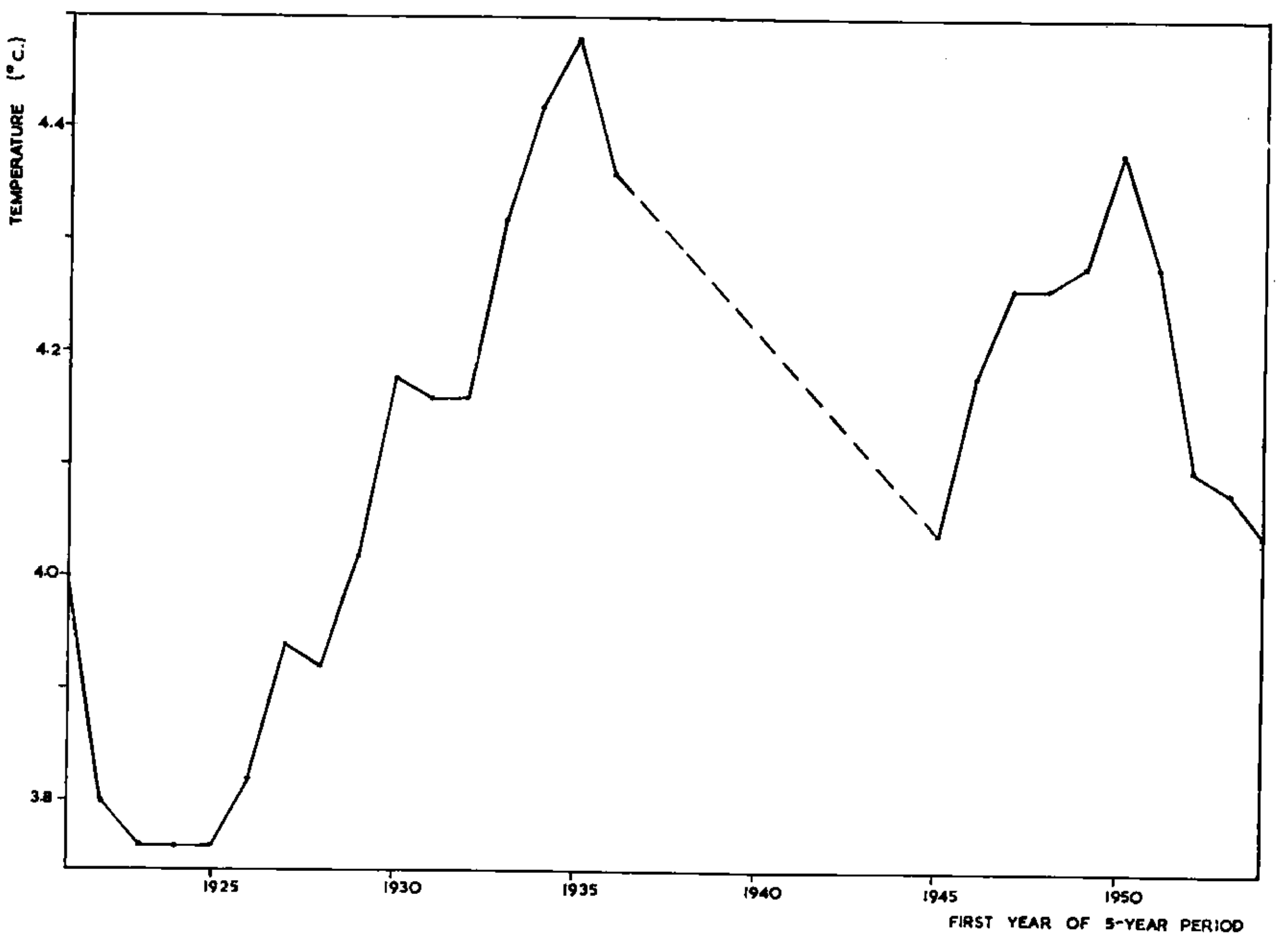

Fig. 2. Water temperature of the 0-200 m layer on the Kola Section (5 yearly running means).

than the maximum reached in the 1930's. Inspection of the annual mean values shows a somewhat different pattern to have existed before 1940 from that which has existed since 1945. The root mean square of the differences between annual mean temperatures of successive years was 0.39°C for the period 1921 - 39, 0.55°C for the period 1946 - 58. In the earlier period a general trend towards warming is evident, whereas in the latter period the year to year variations completely obscure any general trend.

The temperature trends may be considered during particular parts of the year only. The pattern is very similar in all cases, as is the range, showing that the changes in mean annual temperatures were brought about by changes in temperature during all parts of the year. If, however, the mean temperatures of the 0-50 m layer only are considered, for which mean values are available for every month from 1929 - 40 and 1945 - 58, it is found that there were greater changes in temperature in the summer and autumn months than in the winter and spring, *e.g.* the lowest February mean temperature was 3.0°C, the highest 4.5°C; the lowest August mean temperature was 6.5°C, the highest 9.2°C. From this it may be concluded that the greater part of the warming between 0 and 50 m took place in late summer and autumn. Figure 3 shows 12 monthly running means of temperature in the 0-200 m layer. From it 18 well defined stationary points, where there is a change in the trend of the graph, may be identified. More than 75% of these occur at points representing the

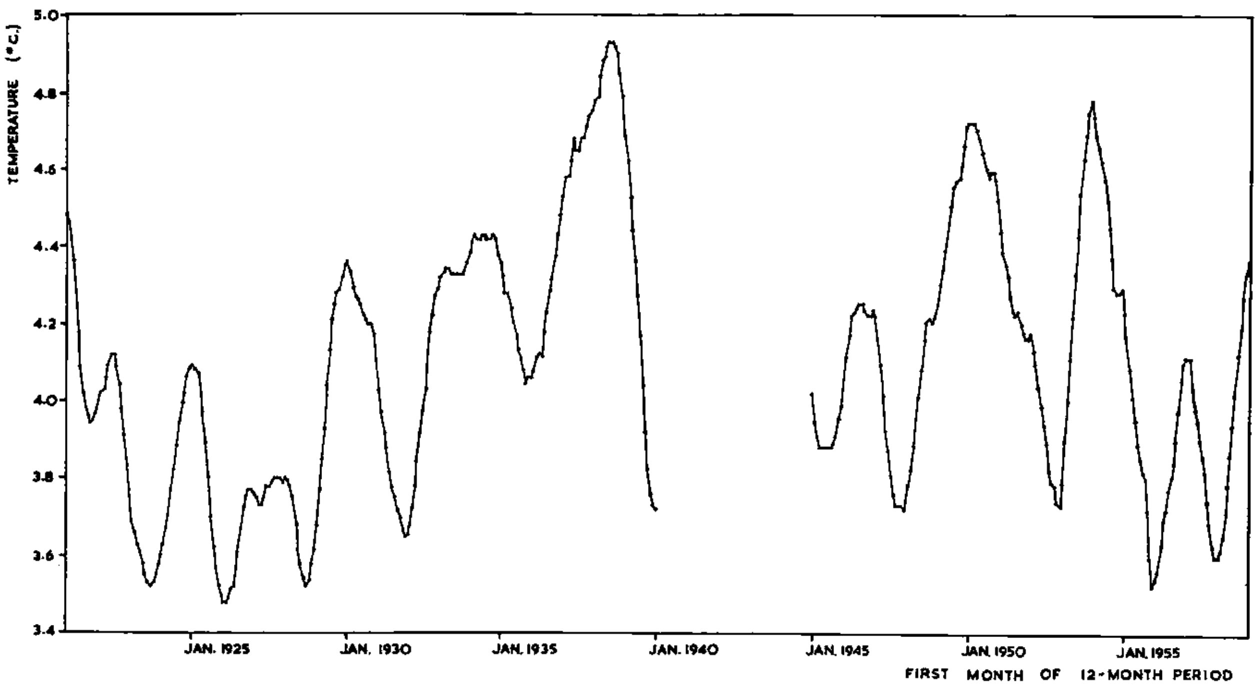

Fig. 3. Water temperature of the 0-200 m layer on the Kola Section (12 monthly running means).

temperatures of 12 monthly periods beginning with one of the 5 months October to February inclusive. Hence it may be concluded that the majority of trends are established during these months and that they then persist for at least the following 12 months. This is in agreement with Drogaitsev (1959) who found that the water temperature in the 0-200 m layer during each month from January to October inclusive was closely related to an indice of meridional heat transport in the preceding late autumn.

Other Russian workers, analysing the factors which control the temperature of the water along the Kola Section, have come to differing conclusions. Their results, which have been summarised by Lee (1963), disagree mainly regarding the relative importance of the advection of heat in this region; *e.g.* Denisov (1958) considers local meteorological factors to be of prime importance, advective factors accounting for only 17% of the observed variation, whereas Seryakov (1960) finds that advection accounts for 56% of the total amount of heat received in the southern half of the Barents Sea during each year.

In order to ascertain that a relationship exists between the changes in the water temperatures in the Kola Section and the meteorological changes which took place, correlation coefficients have been established between water temperature in the 0-200 m layer on the Kola Section and (a) air temperature at Vardö, (b) southerly and westerly components of the wind at Bear Island. In all cases the correlation coefficients have been determined with various time lags between the two sets of data in order to find that at which each was greatest. The mean water temperatures for each period December-November were used as this appeared to be most suitable from the analysis of the 12 monthly running means described above. Table 1 shows the correlation coefficients obtained, and also the probability that the coefficient will reach each value between two sets of the same number of figures, selected at random. Where this probability exceeds 0.1 the correlation must be

TABLE 1. CORRELATION COEFFICIENTS, AND THE PROBABILITY OF THEIR EXISTING IN TWO RANDOM SETS OF FIGURES, BETWEEN 12 MONTHLY (DECEMBER - NOVEMBER) MEANS OF WATER TEMPERATURE OF THE 0-200 M LAYER ON THE KOLA SECTION AND (A) 12 MONTHLY MEANS OF AIR TEMPERATURE AT VARDO, (B) 12 MONTHLY MEANS OF SOUTHERLY WIND COMPONENT AT BEAR ISLAND, (C) 12 MONTHLY MEANS OF WESTERLY WIND COMPONENT AT BEAR ISLAND (1921-40 AND 1945-58). (MO. = MONTH).

(a)	12 monthly air temperature preceding 12 monthly water temperature by:								
	17 mo.	14 mo.	11 mo.	8 mo.	5 mo.	2 mo.	-1 mo.	-4 mo.	-7 mo.
Correlation Coefficient	+0.19	+0.21	+0.45	+0.74	+0.72	+0.78	+0.53	+0.21	+0.08
Probability	>0.1	>0.1	0.009	<0.001	<0.001	<0.001	0.002	>0.1	>0.1

(b)	12 monthly wind component preceding 12 monthly water temperature by:							
	13 mo.	11 mo.	9 mo.	7 mo.	5 mo.	3 mo.	1 mo.	-1 mo.
Correlation Coefficient	+0.38	+0.54	+0.43	+0.45	+0.30	+0.37	+0.30	+0.10
Probability	0.03	0.001	0.01	0.009	0.1	0.04	0.1	>0.1

(c)	12 monthly wind component preceding 12 monthly water temperature by:							
	13 mo.	11 mo.	9 mo.	7 mo.	5 mo.	3 mo.	1 mo.	-1 mo.
Correlation Coefficient	+0.24	+0.29	+0.33	+0.31	+0.25	+0.37	+0.26	-0.02
Probability	>0.1	>0.1	0.08	0.1	>0.1	0.04	>0.1	>0.1

considered to be insignificant. The significance increases as the probability decreases, and when the probability is less than 0.001 the correlation is highly significant. The highest correlation coefficients exist between the water temperature and the air temperature at Vardö when the 12 monthly mean values of air temperature were taken for periods preceding those for water temperature by between 2 and 8 months. The correlation coefficients between water temperature and the southerly and westerly wind components at Bear Island show a similar pattern but are generally smaller. The southerly wind shows the highest correlation with water temperature when it precedes it by 11 months whereas the westerly wind, which almost invariably shows lower correlation coefficients than the southerly wind, is most closely related to the water temperature when it precedes it by 3 months.

These correlation coefficients suggest that there is either an external factor, bringing about the changes in the meteorological conditions and in the water temperature, which affects the former more rapidly, or that the changes in the meteorological factors considered are themselves responsible for the changes in water temperature. The changes in air temperature are obviously not brought about directly by the changes in water temperature.

WATER TEMPERATURES AT STATION S

Observations of temperature and salinity have been made at two stations, S and W, along a section extending westwards from Bear Island across the West Spitsbergen Current in latitude 74° 25'N on 36 occasions between 1949 and 1958 from the Ministry of Agriculture Fisheries and Food Research Vessel *Ernest Holt*. Station S is sited at 16° 08'E and is just off the continental shelf in a depth exceeding 900 m; station W sited at 13° 00'E is in a depth exceeding 2,000 m (Fig. 1).

Station S is in a similar position to the Kola Section, each being located in a branch of the Norwegian Current, and, being close to the atmospheric Arctic Front, each subject to similar meteorological conditions at the surface. The variations of water temperature at Station S may therefore be expected to result from similar factors to those which bring about the variations along the Kola Section. At Station S, however, temperature variations, and the factors which bring them about, can be examined to a considerably greater depth.

Method

The temperature observations at station S have been used to determine the mean temperature of each 100 m layer between the surface and 600 m on each of the 36 occasions when observations were made. These values were then compared with the factors comprising the heat budget which were thought most likely to have varied from year to year and thus to have brought about changes in the water temperature.

The terms involved in the heat budget of the sea can be divided primarily into the advective and the non-advective terms. Assuming that variations in the vertical advection of heat are small compared with those in the horizontal advection, and that the West Spitsbergen Current dominates the horizontal advection of heat in this region, the advective term may be considered to depend on the temperature and strength of the West Spitsbergen Current. Hill and Lee (1957) have used the temperature and salinity data from stations S and W to calculate the transport of water northwards between these two positions and between the surface and 400 m, using the hydrodynamical method, and these values may be used as a measure of the strength of the West Spitsbergen Current. Its temperature will depend on its strength, as the more quickly the water moves northwards the less it will be cooled. Hence the volume transport of the water northwards between stations S and W has been taken as a measure of the advective term in the heat budget at station S.

The most important non-advective terms are the radiation, the evaporation and the convection terms. If the radiation received on a horizontal surface outside the earth's atmosphere is considered to remain constant from year to year, variations in the radiation received by the water surface from year to year result from variations in cloudiness. Similarly the effective back radiation from the sea surface at a particular temperature is dependent upon cloudiness and relative humidity. The convection term is dependent on the wind velocity and the difference between the surface water temperature and the air temperature. Changes in water temperature can, therefore, be brought about by changes in wind velocity or in air temperature. Similarly the evaporation term is dependent on wind velocity and on the difference between the surface water temperature and the air temperature, and also on the relative humidity of the air. Thus the atmospheric factors which enter into the heat budget of the sea, and which could bring about year to year changes in sea temperatures, are cloudiness, relative humidity, air temperature and wind velocity. Seasonal changes, however, may be partly brought about by the annual cycle of radiation received from the sun.

In order to determine the importance of each item in the heat budget of the different water layers, correlation coefficients have been determined between each of these items and the mean temperatures of the various water layers at station S on each of the 36 occasions when observations were made.

The most suitable meteorological data available are those from Bear Island, approximately 83 km to the east of station S. As the cause of the variations in water temperature are being sought, the meteorological data have been averaged over the 10 days before observations were made at station S, on each occasion, and these 10 day mean values correlated with the water temperatures. The only volume transport values available, however, are those calculated for the actual occasions when the temperature observations were made, and simultaneous values for volume transport and temperature have therefore had to be used. It is, however, thought that oceanographical conditions change much more gradually than atmospheric conditions, and the volume transport values should

TABLE 2. CORRELATION COEFFICIENTS, AND THE PROBABILITY OF THEIR EXISTING IN TWO RANDOM SETS OF FIGURES, BETWEEN WATER TEMPERATURE AT STATION S AND FACTORS FROM THE HEAT BUDGET;
(A) ACTUAL VALUES, ALL YEAR;
(B) DEVIATIONS FROM MONTHLY MEAN VALUES, ALL YEAR;
(C) DEVIATIONS FROM MONTHLY MEAN VALUES, 28TH MAY - 27TH SEPTEMBER ONLY;
(D) DEVIATIONS FROM MONTHLY MEAN VALUES, 30TH NOVEMBER - 1ST MAY ONLY.

(a)	Volume Transport		Air Temperature		Cloud Cover		Relative Humidity		Wind Velocity	
Temp. of water layer between	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility
0-100m	0.10	>0.1	0.70	<0.001	0.24	>0.1	0.37	0.03	-0.89	<0.001
100-200m	0.42	0.01	0.41	0.01	0.09	>0.1	0.16	>0.1	-0.25	>0.1
200-300m	0.59	<0.001	0.24	>0.1	-0.01	>0.1	-0.01	>0.1	-0.06	>0.1
300-400m	0.70	<0.001	0.08	>0.1	-0.07	>0.1	-0.10	>0.1	0.32	0.05
400-500m	0.81	<0.001	0.04	>0.1	-0.01	>0.1	-0.07	>0.1	0.56	<0.001
500-600m	0.78	<0.001	0.10	>0.1	0.08	>0.1	0.01	>0.1	0.51	0.001
0-600m	0.65	<0.001	0.34	0.04	0.07	>0.1	0.09	>0.1	-0.06	0.1

(b)	Volume Transport		Air Temperature		Cloud Cover		Relative Humidity		Wind Velocity	
Temp. of water layer between	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility
0-100m	0.31	0.1	0.52	0.003	0.29	>0.1	0.12	>0.1	-0.40	0.03
100-200m	0.52	0.004	0.46	0.01	0.57	0.001	0.21	>0.1	-0.04	>0.1
200-300m	0.56	0.002	0.45	0.01	0.50	0.005	0.14	>0.1	-0.01	>0.1
300-400m	0.58	0.001	0.46	0.01	0.44	0.02	0.20	>0.1	0.12	>0.1
400-500m	0.69	<0.001	0.51	0.004	0.48	0.008	0.23	>0.1	0.22	>0.1
500-600m	0.69	<0.001	0.54	0.002	0.43	0.2	0.20	>0.1	0.11	>0.1
0-600m	0.68	<0.001	0.57	0.001	0.51	0.004	0.20	>0.1	-0.01	>0.1

TABLE 2 - CONTINUED.

Temp. of water layer between (c)	Volume Transport		Air Temperature		Cloud Cover		Relative Humidity		Wind Velocity	
	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility
0-100m	0.01	>0.1	0.35	>0.1	-0.62	0.003	-0.37	>0.1	-0.65	0.02
100-200m	0.74	0.006	-0.14	>0.1	0.38	>0.1	0.11	>0.1	0.12	>0.1
200-300m	0.72	0.008	0.06	>0.1	0.54	0.07	0.22	>0.1	0.07	>0.1
300-400m	0.58	0.05	0.24	>0.1	0.52	0.08	0.38	>0.1	0.08	>0.1
400-500m	0.71	0.01	0.27	>0.1	0.50	0.1	0.34	>0.1	0.05	>0.1
500-600m	0.67	0.02	0.36	>0.1	0.22	>0.1	0.12	>0.1	-0.21	>0.1
0-600m	0.76	0.004	0.26	>0.1	0.29	>0.1	0.10	>0.1	-0.18	>0.1

Temp. of water layer between (d)	Volume Transport		Air Temperature		Cloud Cover		Relative Humidity		Wind Velocity	
	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility	Coeff-icient	Proba-bility
0-100m	0.44	>0.1	0.61	0.04	0.66	0.02	0.34	>0.1	-0.22	>0.1
100-200m	0.42	>0.1	0.64	0.02	0.64	0.02	0.34	>0.1	-0.19	>0.1
200-300m	0.48	>0.1	0.63	0.03	0.49	>0.1	0.19	>0.1	-0.11	>0.1
300-400m	0.56	0.06	0.67	0.02	0.46	>0.1	0.26	>0.1	0.07	>0.1
400-500m	0.73	0.007	0.73	0.007	0.58	0.05	0.35	>0.1	0.28	>0.1
500-600m	0.77	0.003	0.65	0.02	0.61	0.04	0.36	>0.1	0.29	>0.1
0-600m	0.63	0.03	0.70	0.01	0.62	0.03	0.33	>0.1	0.03	>0.1

therefore be fairly representative of the periods over which the meteorological data have been averaged. Table 2(a) shows these correlation coefficients, (each of which have been determined from 36 pairs of variables), together with the probability of their reaching each value by chance.

The existence of a significant correlation coefficient between two sets of variables does not necessarily mean that there is any cause and effect relationship between them. In particular, meteorological and oceanographical data such as that used to obtain the orrelation coefficients in Table 2(a) will almost certainly have seasonal trends, and similar se sonal trends in two sets of variables may lead to a significant correlation coefficient existing between them even though there is no interdependence of the two. In order to eliminate the effects of these seasonal variations, deviations have been determined from mean monthly values based only on the data used in calculating the correlation coefficients. This was done because these were the only data available for water temperature and water transport, and the use of meteorological data from other occasions might have biased some meteorological monthly mean values in favour of years for which no oceanographical data is available. In order to smooth the data all oceanographical observations made within the 5 week period centred on each calendar month were taken into account in calculating the mean value for that month.

Although the meteorological observations extended over the period of 10 days immediately preceding each set of oceanographical observations, they were taken in each case to relate to the same month or months as the oceanographical observations which they preceded. The mean monthly values obtained are based on 4 or more values in 8 months, but on less than 4 in the remaining 4 months. The average monthly temperatures of each water layer thus determined are shown in Table 3.

TABLE 3. AVERAGE MONTHLY TEMPERATURES (°C) OF VARIOUS WATER LAYERS AT STATION S (1949-58)

	Month	Jan.	Feb.	March	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
No. of occasions from which mean calculated		1	2	5	4	7	5	5	2	4	2	4	5
Water Layers	0-100m	5.9	6.2	4.8	4.8	5.2	5.7	6.5	6.8	6.9	7.2	6.0	6.1
	100-200m	5.7	6.2	4.7	4.7	4.9	5.1	5.6	6.1	5.6	6.1	5.9	6.1
	200-300m	5.2	6.0	4.5	4.4	4.7	4.7	5.0	5.6	4.9	5.1	5.4	5.6
	300-400m	4.8	5.6	4.1	3.9	4.2	4.0	4.2	4.6	4.2	4.4	4.7	4.9
	400-500m	4.3	4.7	3.5	3.0	3.6	3.4	3.5	3.4	3.4	3.6	3.7	4.1
	500-600m	3.8	3.9	2.8	1.9	2.7	2.5	2.7	2.4	2.6	3.1	2.5	3.2
	0-600m	5.0	5.4	4.0	3.8	4.2	4.2	4.6	4.8	4.6	4.9	4.7	5.0

It was considered that deviations from monthly means based on less than 4 values were unsatisfactory and therefore the observations for these 4 months - January, February, August and October - were omitted from this part of the study. Deviations from the monthly mean were determined for each of the remaining 29 values, the deviation from the average of the two mean values being used where an observation had been included in two 5 week periods. These deviations from the monthly means were then correlated in the same way as the actual values described above. The correlation coefficients obtained are shown in Table 2(b).

It is possible that particular items in the heat budget will be of greater importance in bringing about changes in water temperature during some parts of the year, than during others. The relative importance of atmospheric factors, which operate at the surface, and advection, which operates throughout the water column, in bringing about changes in water temperature in different layers will vary according to the amount of vertical mixing which takes place. As one of the main causes of this mixing is the extent of warming or cooling at the surface by the evaporation and convection terms, two seasons have been defined according to the differences between surface water temperature and air temperature, each of between 4 and 5 months duration. During the first period (28 May to 27 September) the surface water temperatures generally exceeded the air temperatures by lesser amounts than they did during the second period (30 November to 1 May).

In determining correlation coefficients between water temperature and the various factors in the heat budget during each of these seasons, the same deviations from monthly normals were used as above, again omitting those for the months where the mean values were based on less than 4 observations. Twelve sets of observations remain during each period, and the correlation coefficients obtained are shown in Tables 2 (c) and 2 (d).

DISCUSSION

The tables show that highly significant correlation coefficients exist between certain factors in the heat budget and the water temperatures in various layers at station S, and between deviations from monthly normals of factors in the heat budget and similar deviations from monthly normals of the water temperatures in the various layers. The volume transport of water between 0 and 400m between stations S and W shows the most consistently significant correlation with water temperature in all of the tables, demonstrating the considerable importance of the advection of heat by the West Spitsbergen current on water temperatures in this region. The correlation coefficients between volume transport and water temperature in Table 2(a) are slightly more significant than those in Table 2(b) for the water temperatures of the layers below 200m but the converse is true above 200m, suggesting that volume transport and water temperature above this depth have opposing seasonal trends, whereas below this depth they have common seasonal trends. Both sets of coefficients show a general increase with depth. From Tables 2 (c) and 2 (d) it can be seen that higher correlation coefficients generally exist during the summer period than during the winter period, although this is certainly not so between volume transport and water temperature in the uppermost 100m layer.

Air temperature and water temperature have a common seasonal trend in the upper layers (above 100m), as might be expected from the direct effect of the sun's radiation as well as from any interaction between the two. Below 100m, however, water temperatures appear to follow seasonal trends opposed to those of air temperature, and hence although significant correlation coefficients exist between air temperature and water temperature at all depths in Table 2 (b) no such significant correlation coefficients are found below 200 m in Table 2 (a). Perhaps surprisingly, Table 2 (b) shows that there is little variation in the correlation coefficients between the deviations of air temperatures from monthly normals and those of water temperature in successive 100 m layers to 600 m. This is indicative of the fairly strong vertical mixing which generally occurs throughout the year in this region. Tables 2 (c) and 2 (d) show a considerable contrast, however, between the relationship between air temperature and water temperature in summer and that in winter. In summer, when the difference between surface water temperature and air temperature is generally least, the correlation coefficients between the air temperature and water temperature deviations from monthly normals are insignificant for water temperatures in each 100 m layer, whereas in winter they are highly significant at all depths. This is because the major term in the heat budget in which the air temperature appears, is the net convection term, which is generally considered to be proportional to the difference between surface water temperature and air temperature, and which will therefore be of greatest importance in the heat budget when this difference is greatest.

Correlation coefficients between water temperature and cloud show similar trends to those between water temperature and relative humidity in all of the tables, as is to be expected by the close relationship between cloud and relative humidity— a higher relative humidity will give rise to an increase in cloud and a lower relative humidity to a decrease. In Table 2 (a) a significant correlation exists between relative humidity and the water temperature of the upper 100 m whilst in Table 2 (b) highly significant correlations exist between cloud and water temperature in all layers below 100 m. The absence of a significant correlation in the upper 100 m, however, where any changes brought about by variations in the cloud cover would be expected to be most marked, suggests that the relationship is an indirect one. An external factor which would bring about similar changes in the cloud cover and in the volume transport, which also shows higher correlation coefficients with water temperature below 100 m than above it, seems the most likely reason for this relationship. The external factor is very probably the southerly wind component which Hill and Lee (1957) have shown to be related to the volume transport, and which would be expected to be closely related to the cloud cover also.

Whereas relative humidity does not show any significant correlation with water temperature in Tables 2 (c) and 2 (d) cloud cover shows a number of highly significant correlations, positive in all cases but one. This contrast between a highly significant negative correlation between cloud cover and the water temperature in the upper 100 m in summer, and a highly significant positive correlation between the same factors in winter is, however, to be expected from the way in which cloud cover appears in the heat budget. Its main effect is to reduce radiation, whether incoming or outgoing. During the summer, incoming radiation exceeds outgoing radiation and hence an increase in cloud cover will reduce the heat gained by the surface water. In winter, however, there is little incoming radiation and it is exceeded, in this region, by the outgoing radiation. An increase in cloud cover in winter, therefore, leads to a reduction in the heat lost by the surface water. Again the positive significant relationships between cloud cover and water temperature in the deeper layers in both tables suggest the indirect relationship referred to above.

The correlation coefficients between wind velocity and water temperature in Table 2 (a) show a significant negative correlation existing with the upper 100 m of water, and significant positive correlations existing with the water layers below 300 m. Comparison with Table 2 (b), however, shows the positive correlations with the deep water to result primarily from common seasonal trends. The negative correlation between wind velocity and the temperature of the upper 100 m of water is highly significant during the summer period, as shown in Table 2 (c) but insignificant during the winter period, as shown in Table 2 (d). This is because the wind velocity affects water temperature by promoting vertical mixing, and thus increasing the loss of heat by evaporation and net convection. During the winter the rapid loss of heat from the surface water gives rise to strong vertical mixing which thus continues in the absence of any wind. In summer, however, when the net loss of heat from the surface water is greatly reduced, or even reversed, the wind velocity becomes very much more important in promoting vertical mixing.

CONCLUSIONS

The changes in water temperature in the seas north of Norway which have been inferred by many authors, both from changes in climate and from the changes in marine fauna which have been observed, are confirmed by the data from the Kola Section. The short term variations of water temperature between 0 and 600 m at station S between 1949 and 1958 have been related to the most probable causal factors in the heat budget. The dominant causal factor appears to be the horizontal advection of heat, but other factors become of greater importance with regard to water at particular depths, and at particular times of year. Atmospheric factors are most important in the upper layers, as would be expected. Cloud and wind velocity show particularly high negative correlations with the temperature of the upper 100 m of water in the summer period, whilst air temperature and cloud show similarly high positive correlations with the temperatures of each 100 m layer of water to 600 m in the winter.

I wish to express my gratitude to Mr Arthur Lee for his advice and encouragement during this investigation.

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I-3

IS OCEANOGRAPHIC FORECASTING (HYDROSIS) FEASIBLE FOR FISHERIES?

By

T. Laevastu[1]

ABSTRACT

This paper presents a brief review of present practices of weather and oceanographic forecasts and examines future needs and the feasibility of improvements.

SHOULD FISHERIES ESTABLISH FORECASTING SERVICES?

Fisheries trade is one of man's occupations which is most exposed to the weather and the sea. In order to plan successful fishing trips or to determine where to fish, there is a need for both weather and oceanographic forecasts. The following brief summary will examine the needs in fisheries for improved and extended weather and oceanographic forecasts and the best possibilities for issuing such forecasts for fisheries purposes.

It is quite obvious that the time has come when the fisheries research should be divided into two parts: One, for basic research and the other for fisheries services, mainly in the form of forecasts. As the fisheries trade does not possess a strong organization for processing such forecasts, collaboration should be sought with the existing weather services, which, in most cases, are more than willing to provide such collaboration. Benefits of such services are obvious in terms of economic returns as well as through support to further research to fill existing gaps in the knowledge, necessary for forecasting both the behaviour of fish and of its environment.

TYPES OF FORECASTS CURRENTLY GIVEN AND THEIR ADEQUACY

Weather forecasts

The North Atlantic is at present well served by a number of countries with 24-hr forecasts given in coded form as well as in plain language (both in local and in the English languages). Those forecasts are mainly meant for merchant shipping and, only in a few special areas, for high seas and coastal fisheries.

Medium range weather forecasts are especially useful for planning high seas fisheries. They are prepared only by a few countries a few times a week and their availability to fisheries varies. Difficulties exist in transmitting those forecasts to the vessels at sea.

The seasonal weather forecasts, although issued by several countries, are still very general and inaccurate, and are not too useful for fisheries. However, fisheries would be interested in the analyses of the past season's weather, especially with respect to wind anomalies and the resulting anomaly of wind currents and the accompanying changes of water temperature.

Oceanographic forecasts

Wave forecasts are at present prepared for the North Atlantic by the USA. Other countries prepare such forecasts on an experimental basis and for routing a number of ocean-crossing ships.

Wave forecasts are only available in exceptional cases to large fishing vessels. In certain instances there is, however, a need and economic gain in routing fishing vessels to and from distant fishing grounds, based on extended weather and sea (wave) forecasts.

No current forecasts are issued at present. However, there is a need for such forecasts, both

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for bottom trawling and for pelagic fisheries. As the knowledge on the behaviour of fish in respect to currents accumulates, there is a need for long-range hindcasts for the currents and current anomalies on fishing grounds.

The U.S. Naval Oceanographic Office issues, at present, 10-day temperature charts for the North Atlantic. A general sea surface temperature chart for Northern Hemisphere is also prepared by the U.S. Fleet Numerical Weather Facility in Monterey, California. Thermocline depth predictions are also made for limited areas in the North Atlantic. However, before oceanographic forecasts have any real, direct value and demand by fisheries skippers, some educational work must be made among fishermen and skippers by distributing and popularizing the knowledge on fish behaviour in relation to temperature structure and of other environmental factors.

Fisheries (biological) forecasts

No general biological forecasts in general terms have been issued to fisheries, but limited forecasts of various kinds have been attempted in the past, such as forecasts of the year-class strengths; forecasts of the arrival of winter spawning herring in Norwegian coastal waters, etc. The ICES working group on the telecommunication of oceanographic observation in the Norwegian Sea is working on a comprehensive, but specific, fisheries forecasting scheme. There are possibilities of issuing a variety of biological forecasts which would be useful, especially for fishing industries for planning purposes and could be issued regularly for different major fishing grounds.

SPECIAL REQUIREMENTS AND FUTURE PROSPECTS OF FORECASTING SERVICES FOR FISHERIES

Weather forecasts

The present 24-hr forecasts fill most of the requirements for frequented shipping lines. However, in many areas, there is a need for special coastal forecasts, as the coastal weather differs considerably, at times, from that on the land and that farther offshore. Further improvements of medium range weather forecasts could be achieved by careful analysis of the existing peculiarities in these areas, and by establishing special and local forecasting models. Obviously, all improvements can be made only on the basis of good and complete weather reports from those fishing areas and therefore, effort should be made to recruit a number of fishing vessels as voluntary observing and reporting vessels. This recruitment could be connected with short courses in meteorology to skippers which can be done during the off-season of the given fisheries.

Many fishermen might not be familiar with the present available weather services and here, short courses and pamphlets could also help. Furthermore, different countries could make further effort through port meteorological officers meeting all fishing vessels and providing them with the necessary materials, especially with the charts of forecast areas and the times of forecasts. (There is a slight discrepancy in the names and boundaries of forecast areas from different countries.)

Oceanographic forecasts

It is highly desirable for fisheries that future wave forecasting should include the sea and weather routing of trawlers from distant fishing grounds. The medium range prognosis of weather should be given to the trawler, including expected wave conditions on the fishing ground and on the way from the ground to the port, in order to enable the skipper to make proper decisions on when to start returning home.

The separation of swell and sea could be made in the wave forecasts and the reporting of wave parameters should be adapted to the prevailing boat sizes on given fishing grounds. Forecasting the average length and height is not always sufficient for fisheries. Wave forecasts should also be given in plain language, in more descriptive form than present ones, and some special features such as the cross seas should be included in the forecasts.

Current forecasts are not issued at present mainly because of lack of knowledge. Currents in a given location are not strictly correlated with the prevailing weather (winds) in this given locality, but are determined by the wind fields over large areas. The wind currents could be estimated from the prevailing wind systems as well as from the changes of atmospheric pressure and occasionally as caused by inertia currents. Current forecasts could be included in the weather forecasts and should also include data on the tidal currents. Special tidal current charts (ebb and flood) should be provided to the fishermen and the forecasts should give the slack waters (or specific direction in relation to tidal ellipse in case of rotary currents) in any given area so that the fishermen can interpolate the currents from the charts provided. The current prediction should include information on movement and sharpness of current boundaries.

The depth of the thermocline can be predicted at present with some degree of accuracy, especially when this is supported by field observations. Therefore, a number of bathythermographs should be provided to fishing vessels for observing and reporting the temperature structure. In certain cases, it is sufficient to predict only the sea surface temperature, temperature at the current boundaries, and the depth in which the thermocline is expected to intercept the bottom.

Detailed forecasts on thermocline depth could be issued to certain fisheries, *i.e.*, herring fishery, tuna fishery, etc. The average depth of the thermocline could be given and its possible magnitude of fluctuations indicated. It should also include indications on the sharpness of the thermocline and the sea surface temperatures.

Fisheries forecasts

A variety of direct fisheries forecasts could be issued, such as the estimation of the arrival of fish to spawning grounds, the availability of fish in different areas as reported by a number of fishing vessels, depth of the occurrence of schools, etc.

In biological forecasting, two different ways could be followed: One way would be to explain to the fishermen the existing knowledge on the behaviour of fish in different hydrographic conditions and to leave the conclusions up to the fishermen. Another way would be to make analyses and issue an exact fisheries forecast for the fishermen which would include the optimum depth of the fish schools (*e.g.*, often related to sharp thermoclines), the aggregation of these schools in different areas, the possible arrival of spawners in a given spawning ground, the dispersal of fish in different wave and current conditions, etc. Furthermore, the actual occurrence of fish could be reported as observed in the actual fishery. However, the latter one is a questionable proposition because fishermen usually do not like to report their position, the fishing, and their actual catches in order to avoid crowding of given small fishing grounds.

THE AVAILABILITY AND REQUIREMENTS OF BASIC OBSERVATIONAL DATA FOR FORECASTING PURPOSES

The present observations on fishing grounds are sparse, indeed, and in order to establish accurate forecasts, a much denser net of observations is required. The accuracy of the weather reports from fishing vessels should be greatly improved. There is a possibility that a number of fishing vessels and/or companies could establish special scouting vessels which would not only make observations of the weather and aquatic environment, but also would analyze the data, make different forecasts, and report the occurrence of fish. The existing fisheries protection vessels could be used for this service. The codes devised by the ICES working group may be most appropriate for such observational and forecasting services.

EXPECTED ACCURACY OF SPECIFIC FORECASTS FOR FISHERIES

As in any forecast, in the beginning the fisheries forecasting would be more an art than a science and great errors might be made. However, fishermen should be informed about the possible errors so that the future confidence in such forecasts would not suffer. The accuracy of the present weather forecasts leave much to be desired in the "sparse areas." The wave forecasts are closely connected with the forecasts of winds and are reasonable in accuracy. However, new ways must be found to describe the actual sea for fisheries purposes. The thermocline forecasts have just been started for naval purposes. They are reasonably accurate in certain areas, but in others, there are considerable difficulties caused by large internal waves, which at present, are unpredictable; and by more permanent depressions of thermocline, which seem to move around. These depressions seem at times to be connected to wind convergences and might be predictable with reasonable accuracy in the future. There should be no difficulties in predicting offshore tidal currents in the future; however, prediction of wind currents and permanent flow need considerable research work.

It is quite obvious that considerable emphasis should be devoted, in the beginning, to the verification of the forecasts through which additional experiences will be gained.

ORGANIZATIONAL ASPECTS OF FORECAST SERVICES FOR FISHERIES

Analysis messages could be broadcast to fishing vessels where the skippers would make the necessary plottings and analyses. This possibility, however, is limited because the skippers are extremely busy while fishing and have no time to make good analyses on board. Hence, there remains the possibility that several companies might get together to establish a scouting vessel which would take care of the observations and analyses and direct the fishing fleet of several companies accordingly. The same can be made on the basis of governmental service as at present done to some extent by Germany on the "distant fishing grounds."

There are areas where several nations are interested in the same fishery, and inter-governmental cooperation might be useful. An experiment is being carried out in the Norwegian Sea at present through ICES.

The success of the forecasts and services depends primarily on several factors outside the reach of the forecaster. The first is a requirement of educational work among fishermen and fishing industries, explaining the present knowledge on fish behaviour in relation to environment and to the westher. Second, the availability of different forecasts should be made known to fisheries and the use and accuracy should be explained. The success of all forecasts depends on the reporting of actual data and this can only be improved if the fishermen cooperate and see the value of such forecasts.

I-4

DAILY HEAT EXCHANGE IN THE NORTH PACIFIC; ITS EFFECTS ON THE OCEAN AND ITS RELATIONS TO WEATHER

By

T. Laevastu[1]

ABSTRACT

The oceanographic and meteorological significance of heat exchange between the sea and the atmosphere is briefly summarized. The components of heat exchange between the sea and the air over the North Pacific have been computed by five degree squares for a number of days. The computation procedure is described. The accuracy of these computations has been investigated and found to depend mainly on the meteorological data and their manipulation. Most of the heat exchange features are of large scale and relatively long-lived. Sample distributions of different components are illustrated.

A preliminary analysis of heat exchange has been made in respect to oceanographic and meteorological factors. The following conditions suggest themselves as a result of this preliminary analysis:

1. A remarkably high loss of heat from the sea occurs during the winter along about 22°N from the Asian coast to about 155° E and along the Asian coast itself. The depth of the thermocline in these heat-loss areas is determined by convective stirring. This high heat loss suggests furthermore the formation of intermediate waters at relatively low latitudes and along the western coasts of the oceans in general.

2. The comparison of the charts of Q_a (the sum of latent heat and sensible heat transfer) with the weather charts shows that the patterns of these heat exchange components are closely related with wind patterns; cyclonic circulations prevailing over positive Q_a "centers" and anticyclonic circulation over negative Q_a centers in the western parts of the oceans.

3. The dissipation of North Pacific cyclones seems to occur over areas where Q_a is low and/or negative, and no sharp Q_a gradients exist in the vicinity. This seems to be predictable a few days ahead.

4. The birth of cyclones seems to occur at certain defined places at the fronts where Q_a gradients and "centers" are created. These births might also be predictable about one to two days ahead, before they can be recognized on surface symoptic charts.

SIGNIFICANCE OF HEAT EXCHANGE

More than 40 years ago, Helland-Hansen and Nansen (1920) published a pioneering work about the temperature variations in the North Atlantic Ocean, and indicated some possible ways to predict the year-to-year variations, with the condition that more thorough investigations be conducted to clarify some open questions raised by them, especially in respect to the regulating action of thermal conditions on the circulation of the atmosphere. Relatively few follow-up works have appeared during this past 40-year period and one of the main reasons might be that symoptic oceanography has not yet been established. Namais (1962) emphasized the importance of the feed-back systems between the ocean and the atmosphere and stated: "Such studies suggest that the time has arrived for synoptic oceanography to take its place alongside synoptic meteorology." He also suggested that the history of meteorology indicates that imaginative hypotheses are initially required in such complex fields as the study of climatic anomalies and of sea-air interactions.

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Considerable knowledge has been accumulated on the influence of temperature on the behaviour of fish. Most of this knowledge has been summarized by Hela and Laevastu (1962). Considering this knowledge and other pertinent factors, it seems that we are now approaching the prediction stage in fisheries where the fisheries authorities might be devoting part of their energy to servicing the fisheries through a variety of fisheries forecasts. It seems natural that one of the first services would be the prediction of sea surface temperature and thermal structure within depth. Obviously, these predictions must be connected with actual surveys and measurements, at least in the beginning.

The forces which cause changes in the sea are of atmospheric origin, therefore, the present study deals with the energy (mainly heat) exchange between the sea and the atmosphere. It was initiated for evaluating the possibility of forecasting the temperature structure of the sea over large oceanic areas, and for forecasting the depth of the thermocline.

Besides oceanographic objectives, the present study might also have some meteorological significance. As pointed out by Petterssen (1956), the energy necessary for setting the atmosphere in motion and for maintenance of winds is of solar origin. He indicated that for maintenance of frontal zones, it is necessary to have over-all temperature contrasts. These temperature contrasts are achieved by the unequal exchange of heat between the surface of the earth and the atmosphere. Petterssen (*op. cit.*) also emphasized that the configuration of the temperature contrasts might determine, to a large extent, the movement of the cyclone centers at sea level.

Namias (1962) stated that it is possible that interactions between abnormal surfaces may be largely responsible for climatic fluctuations on all time scales. These abnormal surfaces affect the feed-backs and these feed-backs may play major roles in weather patterns as increasing synoptic statistical evidence indicate. In order to discover those abnormal surfaces, heat exchange computations are required.

A number of seasonal investigations of heat exchange have been carried out in the past by, *e.g.*, Jacobs (1951), Albrecht (1960), Mosby (1962), and Seckel (1962). However, the daily heat exchange computations are scarce. One of the best treatise on this subject is by Petterssen, *et al.* (1962) which deals with two components of heat exchange (sensible heat and latent heat) in relation to Norwegian cyclone models.

COMPUTATION OF HEAT EXCHANGE COMPONENTS

The heat budget and formulas for computation of different heat exchange components are given in the appendix to this paper. For a detailed discussion on the origin and accuracy of these formulas, reference is made to previous works of the present author (Laevastu, 1960, 1963). For computation of the local changes, heat advection is of primary importance. This advection is not considered in the present paper. It requires detailed knowledge of the surface currents. The present possibilities for prediction of those currents are also summarized by the present author (Laevastu, 1962).

The "hand" computation of heat exchange over large sea areas is time consuming. Use can be made of a number of nomographs which are found in Laevastu (1963). The heat exchange formulas are being programmed through a large computer in Monterey (Wolff, pers. comm.) and it is hoped to make use of those programs in the future.

Data

The meteorological data reported by voluntary observing and reporting merchant vessels form the basis for any heat exchange computation and oceanographic forecast. The data coverage is, in general, sufficient on frequented merchant ship routes, but is very scarce from areas away from these routes. No possibilities are in sight for improving these coverages, but it may be possible to improve the coverage from fishing grounds by recruiting more fishing vessels as observing and reporting vessels. The accuracy of the data leaves much to be desired. This situation could be improved by intensive instruction of the observers on board and by more careful and frequent checking of the ships' instruments.

The daily reported sea surface temperatures are too few for the construction of a detailed picture of daily surface temperature distribution. In some areas, the ten-day running averages could form a reasonably accurate basis as the sea surface temperature is much more conservative than the air temperature. Perlroth and Simpson (1962) concluded that the synoptic sea surface temperature chart for a period of a month can be constructed with a high degree of reliability. Such monthly charts can be used for present purposes by interpolating surface temperature by, *e.g.*, 5-day groups from one month to another.

The monthly average sea surface temperature charts for 1956 and 1957 (United States Bureau of Commercial Fisheries, Biological Laboratory at Stanford, 1962) have been used in the present work. Meteorological data for the present computations were taken from daily series of synoptic weather maps (United States Department of Commerce, Weather Bureau).

The air temperatures are unfortunately reported to a full Fahrenheit degree (or 0.5°C). As the sea-air temperature difference is used in most computations, it would be desirable to have both sea and air temperatures reported with $\pm$ 0.1°C. Great inaccuracies in the reporting of the dew point have been noted, and in many ship reports the dew point is entirely missing. These shortcomings are rectified to some extent by contouring the distribution of a given property before computing the averages by five degree squares.

The actual reported winds can deviate considerably, at times, from the isobaric gradient winds. Therefore, in the present work, the main emphasis has been put on the actual reported winds. An accurate estimation and plotting of the cloudiness data is difficult. In the present work, both the actual reported cloudiness and the frontal models of Bergeron have been taken into consideration in determining the cloudiness patterns. In case of scarcity of data, climatological data were used to fill the gaps.

Computation procedure

Each weather element necessary for heat exchange computations was plotted on different base maps and contoured and the average values for five degrees were computed from this distribution. After obtaining the averaged values of the elements by five degree squares, it would be possible to make punch cards and to perform heat exchange computations by computer; however, in most cases, only three parameters are used for individual computations and these are already written down on charts. Therefore, it was found simpler and more economical to "hand" compute the heat exchange components, using the nomographs.

Obviously, in computing the five degree square averages some involuntary smoothing of the values would occur, and the computed values might not exactly present the actual heat exchange in a given location and time. However, in most cases, we are not concerned with the actual values, but rather with the gradients and heat exchange patterns and the existing procedure is hence sufficiently accurate for this purpose.

Accuracy and errors

If exact values of the heat exchange components over the sea are desired, the computations should be made for 12-hr periods, utilizing the noon and midnight values of meteorological parameters. However, this work would be very time consuming and would offer little in improved accuracy because the inter-diurnal changes of properties are much bigger than the diurnal ones. These inter-diurnal changes along the western sides of the oceans are very much bigger than over the eastern sides. In most cases, it seems to be sufficient to make computation with synoptic data for a 24-hr period, using noon data. For several research purposes, more accurate computation would be desired and will be attempted when the formulas have been programmed for the computer.

The errors caused by inaccuracies in empirical and semi-empirical formulas are much smaller than the inaccuracies caused by the averaging procedure of meteorological elements and the errors in the meteorological reports themselves.

Estimation of the possible magnitude of errors caused by subjective analyzing of meteorological data was obtained by having the same computations done independently by two workers, using data with different origin (historic weather maps for the northern hemisphere and synoptic weather maps from the Weather Bureau, Honolulu Office). Considerable differences in individual values of heat exchange components were observed in some locations, however, the patterns remained approximately the same and the differences were relatively small at large gradients. The positions of the isopleths were, on occasion, considerably different in the areas where the distribution of given properties was flat.

Another set of computations was made by different workers, using the same data, but one set used two and a half degree squares, the other, five degree squares. Again, differences were noted but the patterns remained approximately the same. Obviously, the two and a half degree square computations revealed many more details.

The statistical treatment of the errors and accuracies of these computations is complex and too lengthy for this paper. References on this subject are made in an interim report (Laevastu, 1963) and in an extensive report in preparation. The general conclusion of this accuracy study may be briefly stated:

1. The accuracy depends largely on the accuracy, density and manipulation of meteorological data.

2. Considerable differences in subjective analyses between different workers can occur especially in Q_e and Q_h where the gradients are relatively flat.

3. However, most of the heat exchange features are of a large scale and relatively pronounced and persistent from day to day (Fig. 6 and 7) and the heat exchange computations are consistent and significant in respect to these large-scale features and in respect to sharper gradients.

EXAMPLES OF DISTRIBUTION OF DIFFERENT HEAT EXCHANGE COMPONENTS OVER THE NORTH PACIFIC

A few examples of the heat exchange components are presented in Fig. 1 to 11. The radiation received on 15 February, 1957 is shown in Fig. 1. This is given as insulation by given cloudiness

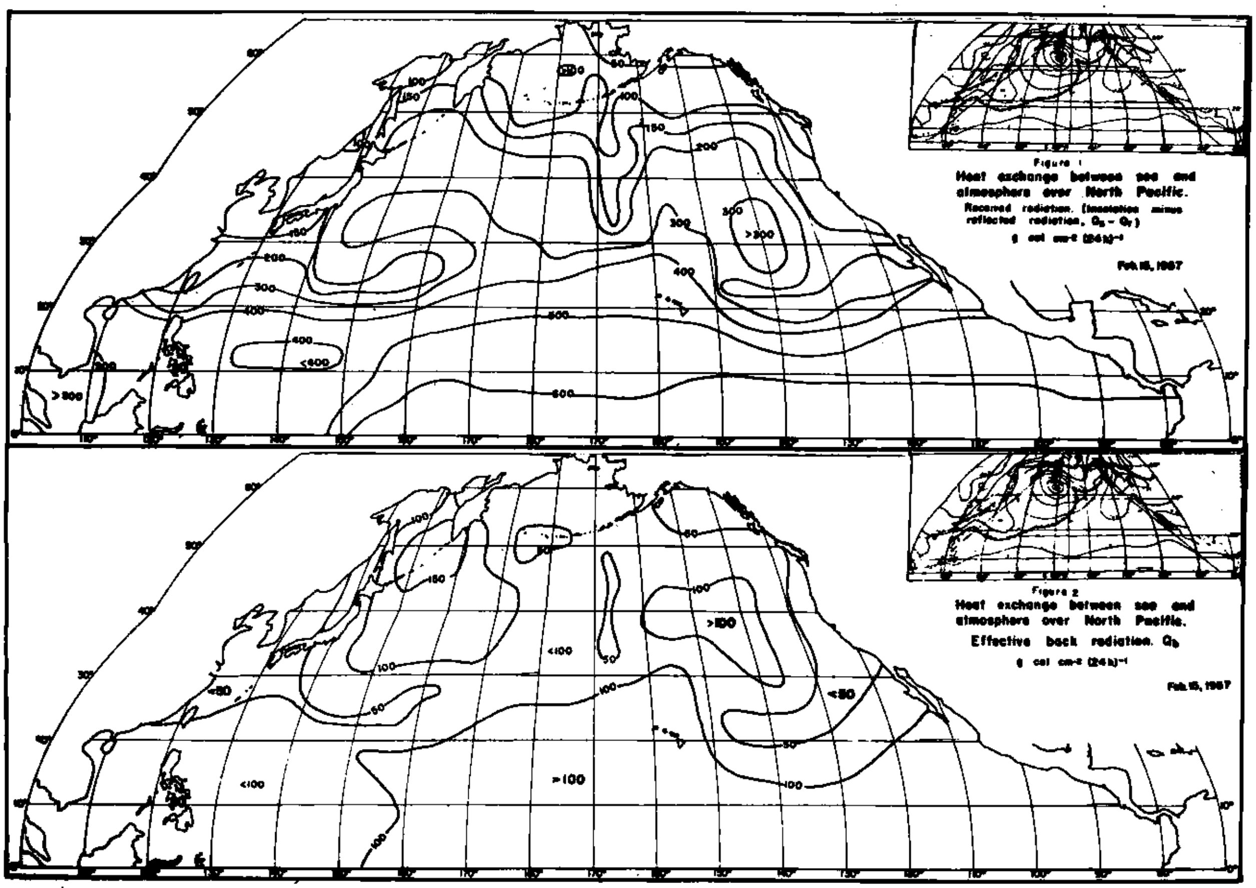

Fig. 1 and 2.

minus reflected radiation ($Q_s - Q_r$). In general, it has been noted that the sharper gradients of $Q_s - Q_r$ coincide with sharper gradients of sea surface temperature (oceanic fronts) and with higher cloudiness at atmospheric fronts.

The effective back radiation on the same date is given in Fig. 2. This heat exchange component is a function of cloudiness and of relative humidity and sea surface temperature. The transfer of sensible heat on the same day is given in Fig. 3. This component shows higher values and greater variability along the western side of the oceans. High positive values are found where relatively cold air dominates and low and/or negative values are found in warm sectors and in or near the center of anticyclonic circulations.

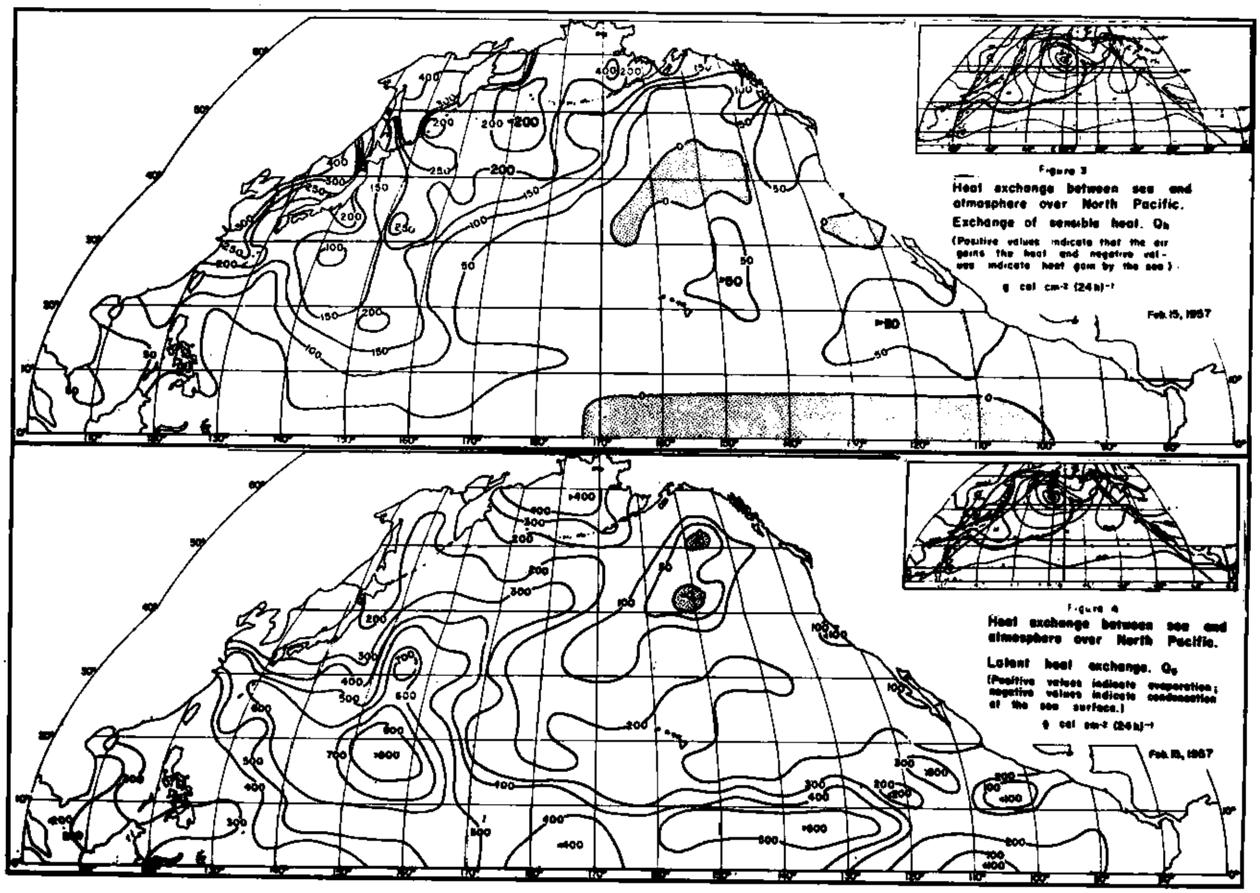

Fig. 3 and 4.

The latent heat of vaporization is the largest component of the transfer of heat from the sea surface to the atmosphere. The Q_e is shown on Fig. 4. Its patterns roughly coincide with the patterns of the transfer of sensible heat. The transfer of sensible heat and latent heat of vaporization/condensation are summed together and mapped as sea-air exchange (Q_a) in Fig. 5 to 7. The first of these figures show the Q_a in February, whereas the two following figures illustrate two consecutive days in May. Further discussions on those charts are found in Chapter 5. The total heat exchange (Q_T) is given in Fig. 8 to 11, illustrating the differences in various seasons. The total heat exchange is most pertinent to the oceanographic problems and is discussed in the next chapter.

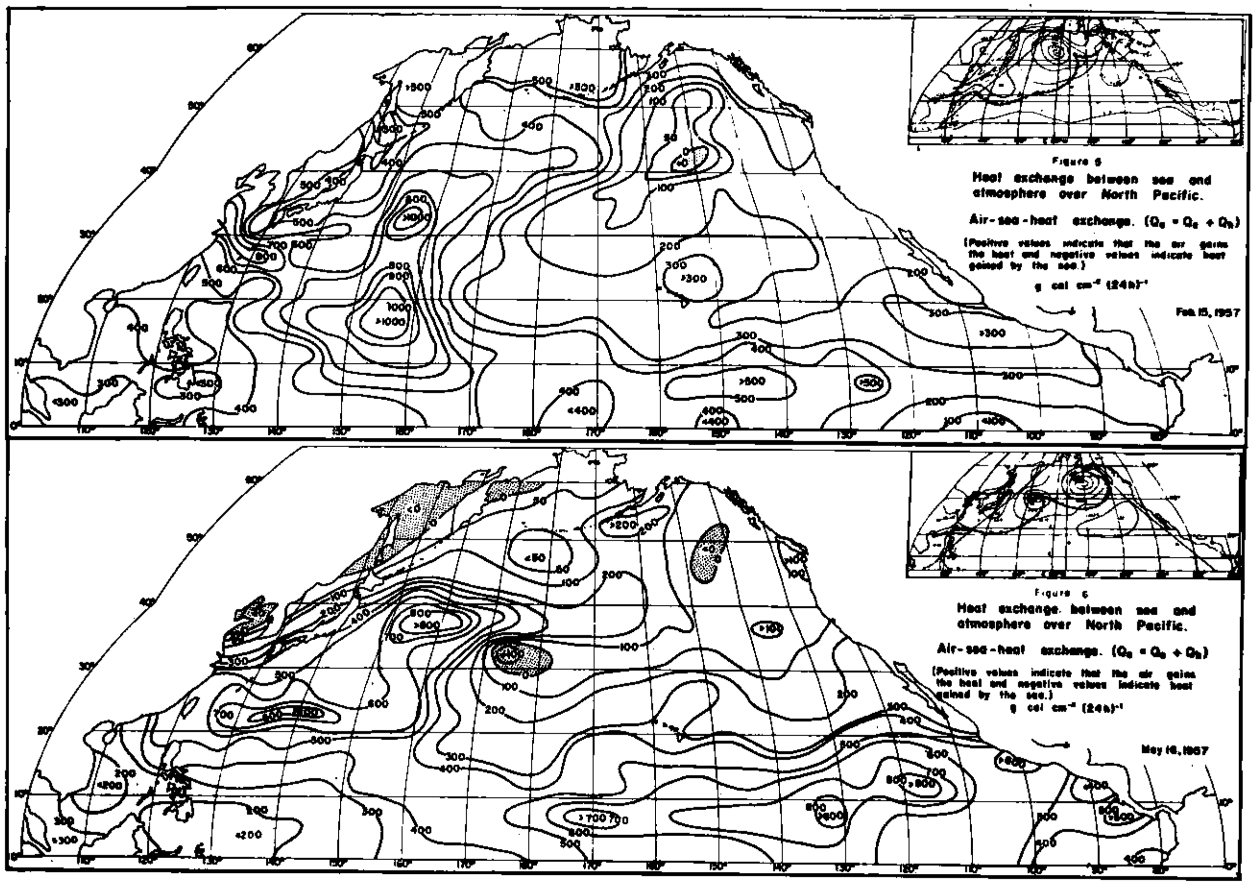

Fig. 5 and 6.

TOTAL HEAT EXCHANGE AND ITS EFFECTS ON THE OCEAN

The boundaries of the change of heat exchange from positive to negative values have several oceanographic consequences. In the positive heat exchange areas, the depth of the thermocline is determined mainly by forced mixing, *i.e.*, mixing by wave action. In the areas of negative heat exchange, the thermocline depth is determined by convective stirring, but only if this stirring reaches deeper than the forced mixing. A further consequence is the formation of deep and intermediate waters in highly negative areas of total heat exchange.

Sharper total heat exchange gradients are usually found in the vicinity of atmospheric fronts, in general between 30-40°N and along about 22°N lat, from the Asian coast to about 155°E, especially during the winter. These energy exchange gradients coincide roughly with the oceanic fronts and raise the question of whether the oceanic fronts are caused by the heat exchange differences or whether the heat exchange differences are caused by the fronts. This cause-effect principle is being investigated. Local cooling is also apparent at some places along the coast of Central America and off the Central and South Asian coast. Locally, this cooling might lower the temperature so that these locations may give the impression (by surface temperature distribution) of areas of coastal upwelling.

Of significance in many oceanographic problems, especially in respect to seasonal cooling and heating and in fluctuations of thermocline depth are the highly negative heat exchanges along the western sides of the oceans and the seasonal movement of the southern boundary of these negative areas. The charts of Q_e (*e.g.*, Fig. 4) indicate condensation of water at sea surface. Some further computations are necessary to determine whether this condensation might have any noticeable influence on the sea surface salinity.

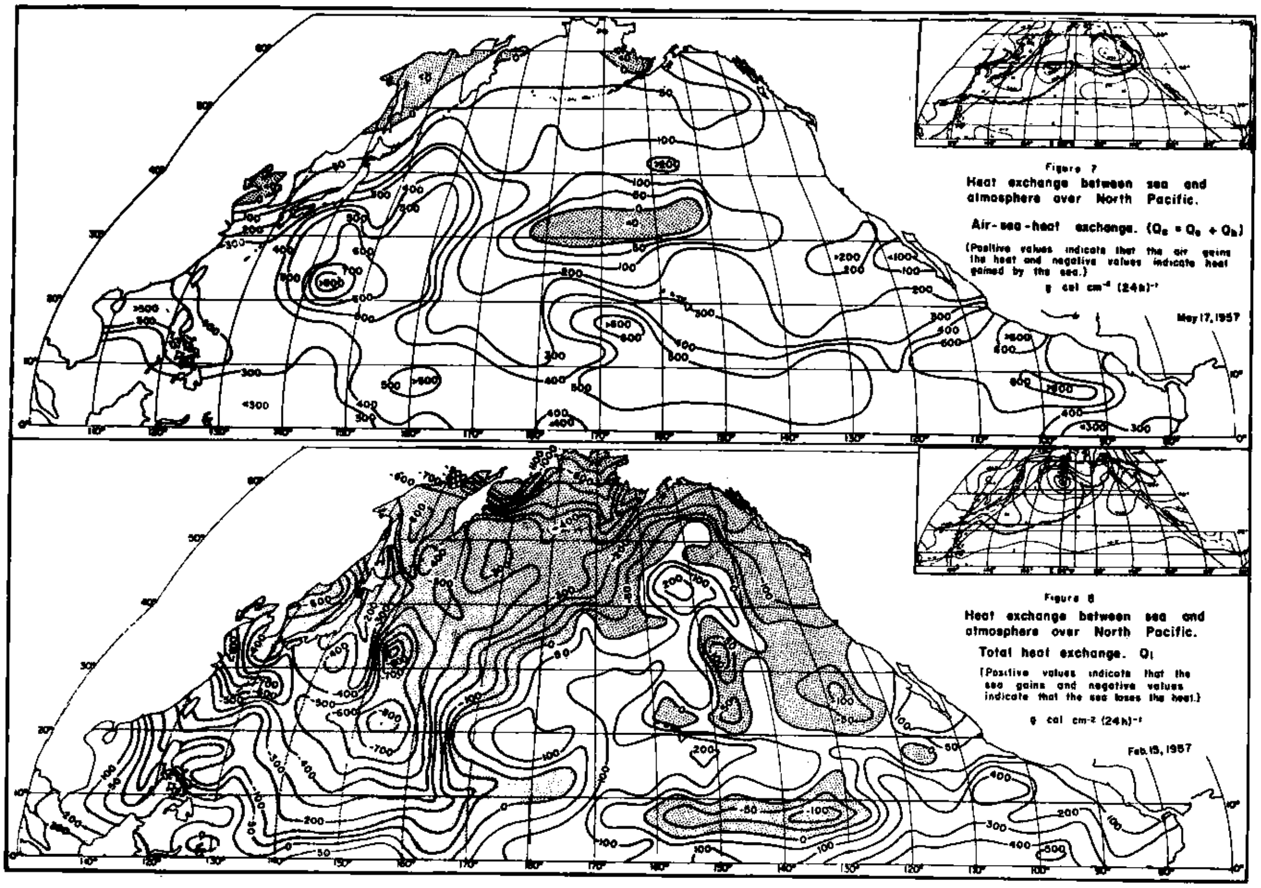

Fig. 7 and 8.

The results of the total heat exchange computations (Fig. 8 to 11) seem to point out some necessity for revision of presently accepted views on the formation of intermediate and deep waters in the North Pacific. This revision, based on total heat exchange, must of course be checked with oceanographic data.

The peculiar high loss of heat at low latitudes centered about 22°N, 155°E, and at 27°N, 162°E, on 15 February 1957 might indicate the general area of formation of intermediate water masses at such low latitudes. This area might also be the area of origin of the waters for countercurrents under the equatorial current system. It is, of course, necessary to investigate the persistency of negative Q_1 in this area. The areas of high losses of heat along the Asian coast during the winter (Fig. 8 to 11) might be the areas of formation of bottom waters. Whether these bottom waters reach the ocean basins or are mixed while passing over the shallow areas (*e.g.*, the China Sea) is an open question. This high loss of heat along the western coast is expected to cause local changes of bottom water temperature, changes in current patterns and variations of local convergences, which are important factors for fisheries. A more detailed investigation of these mechanisms in relation to heat exchange is contemplated. It seems possible that heat exchange computations, together with computation of advection might be specially useful for estimating the changes of water temperature along the western sides of oceans.

THE PATTERNS OF SEA-AIR EXCHANGE IN RELATION TO WEATHER

Though the description of the meteorological results of this work is not the prime purpose of this paper, some preliminary results are worth pointing out. Comparing the present data with the data obtained by Petterssen, *et al.* (1962), one can find considerable similarity in the patterns of

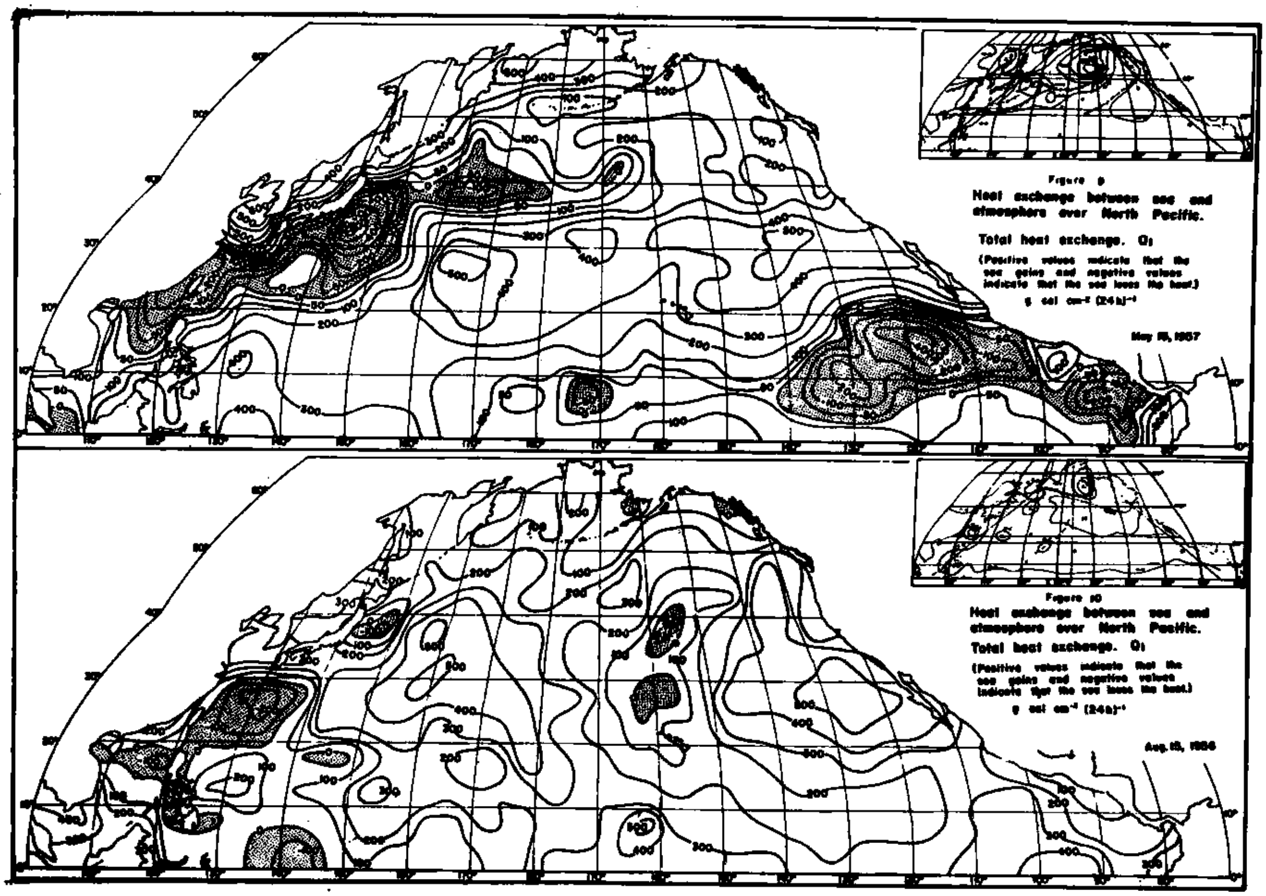

Fig. 9 and 10.

Q_a in the Northwest Atlantic and in the Northwest Pacific, despite the differences in grids and in formulas used. However, the warm sectors of Petterssen, Bradbury and Pedersen do not show the negative values of Q_a as our computations do. The forementioned authors conclude that their results indicate that the heat and cold sources, associated with eddy transfers of sensible heat from the ocean surface with the liberation of latent heat in the cloud systems, contribute significantly to the cyclone development.

Our data (not reproduced here) show some possible ways of how blocking anticyclones are formed, especially during the month of August. Some generalization of the data indicates that the formation of cyclones and anticyclones is directly related to the heat exchange. On the cause and effect principle, one could assume that cyclonic circulation should prevail over positive areas of Q_a and anticyclonic circulation on negative areas. This seems to be confirmed by our study (Fig. 12).

Petterssen (1956) stated that the major components of motion are along the gradients of the thermal advection and are such that cyclones move in a direction from cold to warm advection while anticyclones move in the opposite direction. This seems to be partly confirmed by our study. Strong winds are found to be predictable from Q_a distribution even in cases where they cannot be predicted from the rather flat distribution of pressure. The heat exchange patterns seem to be determined largely by the direction of the movement of the air in relation to the direction of the sea surface isotherms and it seems that the formation of cyclones and anticyclones is largely determined by the heat and cold sources at the surface. A further detailed investigation and possible proof of this should come from future studies.

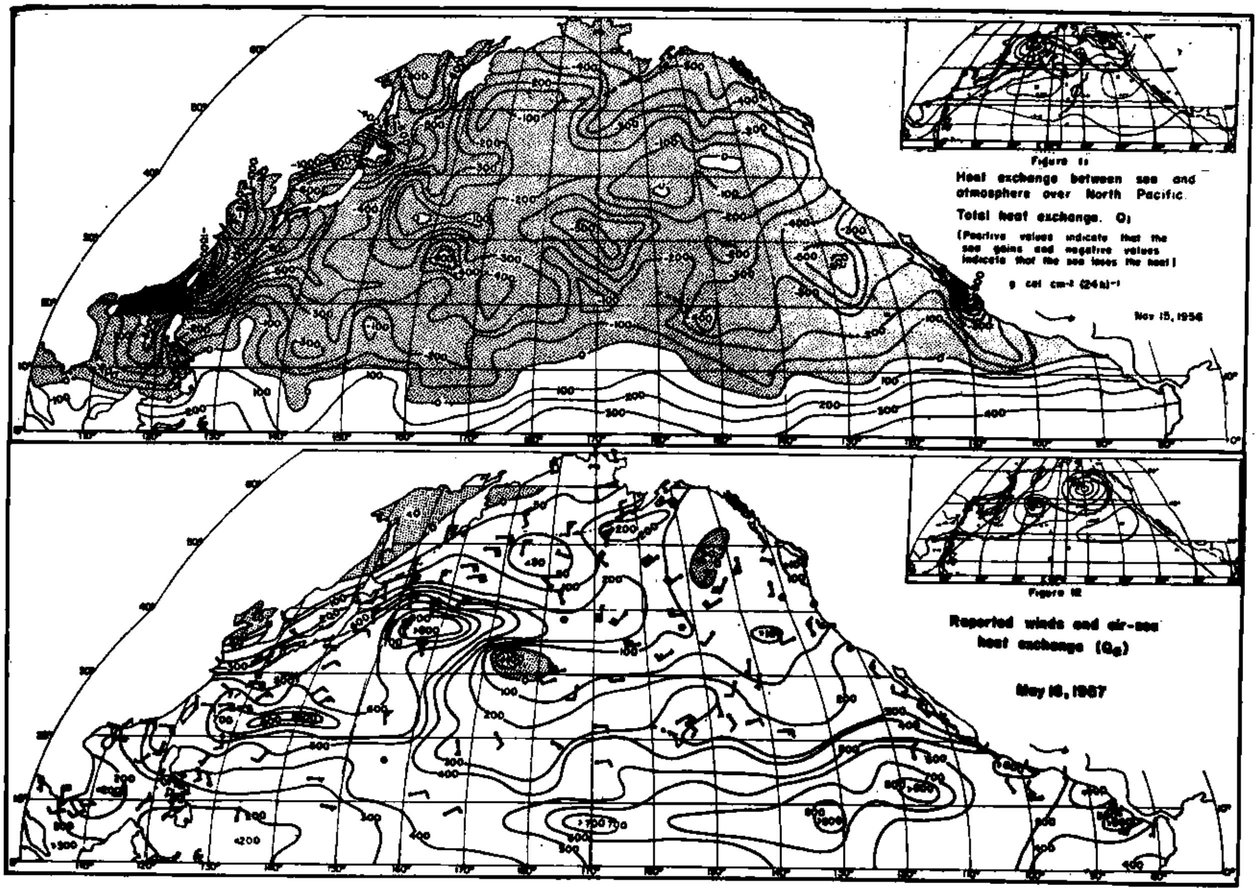

Fig. 11 and 12.

No comparison has as yet been made between the total heat exchange and the depth of the thermocline and/or change of sea surface temperature, because considerably more data are required for such a comparison. It seems to be certain, however, that the heat exchange computations will form a basis for future detailed oceanographic forecasts. These computations will also make it possible to forecast or prognosticate the surface current field. This attempt will be made within this project, but, unfortunately, the verification of these current prognoses will be only partial because no actual current data are available for open areas. However, the heat advection computed as a difference between measured and computed local change might prove to be a means, though very indirect, for confirmation of the current field.

ACKNOWLEDGEMENT

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APPENDIX

FORMULAS FOR COMPUTING HEAT EXCHANGE BETWEEN THE SEA AND THE ATMOSPHERE

The following is a condensed summary of formulas for computing of heat exchange between the sea and the atmosphere. Detailed description and discussion of the formulas and procedures as well as the nomographs are given by the present author in other publications (Laevastu, 1960 and 1963).

The amount of heat used in the change of temperature in a given locality and time can be represented by Formula (1) (for notations and units used, see end of this summary):

$$(1)\quad Q_s + Q_B + Q_{wt} + Q_k + Q_f + Q_c - Q_b - Q_r - Q_h - Q_e + Q_p + Q_v = Q_1$$

The amounts of Q_B, Q_{wt} and Q_k are found in the major part of the oceans to be <1% of Q_s or even very much smaller and can therefore be ignored for practical purposes. The formula can be reduced to:

$$(2)\quad Q_s + Q_f + Q_c + Q_p - Q_b - Q_r - Q_h - Q_e + Q_v = Q_1$$

Q_f can be ignored in offshore areas and Q_p needs to be taken into account if there is a considerable amount of precipitation, if the temperature of the precipitation differs considerably from the temperature of the sea surface, and especially if the precipitation comes down as snow or hail. Q_c and

Q_e are computed with the same formula where the negative values give Q_c.

The following empirical formula was used for estimating insolation from the noon altitude of the sun, the length of the day and the cloudiness:

(3) $Q_s = 0.014\ A_n t_d\ (1 - 0.0006\ C^3)$ $[\ g\ cal\ cm^{-2}(24\ h)^{-1}\ ]$

This formula is valid to $A_n = 75°$; above this value Q_{os} remains constant.

For short periods, the following formula can be used.

(4) $Q_{os} = 1.9 \sin \bar{a}$ $[\ g\ cal\ cm^{-2}\ min^{-1}\ ]$

For estimating radiation reflected from the sea surface, the following empirical formula, which is valid only for daily computations, was derived:

(5) $Q_r = 0.15\ Q_s - (0.01\ Q_s)^2$ $[\ g\ cal\ cm^{-2}\ (24\ h)^{-1}]$

For the computation of short term (hourly or three hourly) albedo, a simplified formula can be used:

(6) $Q_r = Q_s \dfrac{300}{\bar{a}}$ $[\ g\ cal\ cm^{-2}\ min^{-1}]$

For the computing effective back radiation, the linear formula of Lönnquist was adopted and a graph was constructed for the estimation of effective back radiation. The effective back radiation was corrected for the effect of cloudiness with Möller's formula:

(7) $Q_b = Q_{ob}\ (1 - 0.0765\ C)$ $[\ g\ cal\ cm^{-2}\ min^{-1}]$

The modified formula of Rohwer was found to be the most accurate for estimating evaporation:

(8) $E = (0.26 + 0.077\ V)\quad (0.98\ e_w - e_a)$ $[\ mm\ (24\ h)^{-1}]$

Convective transfer of sensible heat was computed with the formula:

(9) $Q_h = 39(0.26 + 0.077\ V)\quad (T_w - T_a)$ $[\ g\ cal\ cm^{-2}\ (24\ h)^{-1}]$

When the differences $(T_w - T_a)$ or $(0.98\ e_w - e_a)$ are negative, sensible heat is transferred to the sea or condensation of vapor takes place on the sea surface. In these conditions, high stability of the air close to the sea surface is expected, and therefore, the following modified formulas were proposed:

(10) $Q_c = 0.077\ V\ (0.98\ e_w - e_a)\ L_t$ $[\ g\ cal\ cm^{-2}\ (24\ h)^{-1}]$

(11) $Q_h = 3\ V\ (T_w - T_a)$ $[\ g\ cal\ cm^{-2}\ (24\ h)^{-1}]$

Notations and units used

A_n - Noon altitude of the sun (degrees)
E - Evaporation $[mm\ (24\ h)^{-1}\ ]$
e_a - Water vapor pressure of air (mb)
e_w - Saturated water vapor pressure at the temperature of the water surface (mb)
L_t - Latent heat of evaporation (g cal)
Q_c - Heat transfer by condensation of water vapor
Q_b - Effective back radiation from the sea surface (long wave radiation)
Q_B - Heat from the bottom of the sea
Q_e - Transfer of latent heat of vaporization
Q_f - Heat transferred by fresh water run-off

Q_h - Convection of sensible heat to and from the atmosphere
Q_k - Heat released by chemical processes
Q_l - Total heat exchange
Q_{ob} - Back radiation by clear sky
Q_p - Heat transferred by precipitation
Q_r - Reflection back from the sea surface (albedo of the sea surface)
Q_s - Total incoming radiation (solar and sky)
Q_{os} - Total incoming radiation by clear sky
Q_v - Heat transfer by advection
Q_{wt} - Heat from the dissipation of wind and tidal energy
T_a - Temperature of the air (°C)
T_w - Temperature of sea surface (°C)
t_d - Length of the day from sunrise to sunset (minutes)
t_h - Time in hours
$\underline{V}$ - Wind speed (m sec^{-1})
$\bar{a}$ - Average solar altitude (degrees)

I-5

NOTES ON THE PROBLEM OF PREDICTING NEAR SURFACE TEMPERATURE GRADIENTS IN THE OPEN OCEAN

By

C.O'D. Iselin[1]

ABSTRACT

Some of the factors are discussed which will have to be taken into account if useful predictions are to be made of the near surface temperature structure in the open ocean. A preliminary test has been carried out in the trade wind latitudes of the Atlantic with encouraging results.

Until recently it seemed rather hopeless to display near surface temperature conditions in the open ocean, except on a climatological basis. However, the availability of large computers and electronic contouring machines has very much changed the situation. In fact, the U.S. Navy is already preparing frequent synoptic northern hemisphere maps of a number of oceanographic parameters on an experimental basis.

In the case of the North Atlantic a most useful series of charts of average temperature at 200m has recently been published by Schroeder (1963). By combining this with monthly or shorter period surface temperature maps one can immediately know the difference in temperature between the surface and 200m on a seasonal and geographical basis.

If one also has available seasonal layer depth charts, then one has three points for the construction of a temperature-depth curve of the near surface waters. Since temperature at 200m varies seasonally only slightly, except in the vicinity of the permanent surface currents, and since the horizontal shifts of these can be deduced from say 10 day averages of surface temperature, the problem, to take an optimistic view, reduces itself to how best to deal with the seasonal and shorter period changes in layer depth, that is to say, in the thickness of the nearly isothermal surface layer.

Unfortunately, the file of temperature data from the North Atlantic available to Woods Hole is not yet sufficiently complete on a seasonal and geographical basis to permit monthly average layer depth charts to show adequate detail. While about 500,000 observations have accumulated and are incorporated in the Schroeder charts, and for each of these points of observation layer depth has been recorded, studies now in progress at Woods Hole make it clear that two months and possibly more will have to be combined to produce a useful set of charts showing average seasonal changes in layer depth.

This is a more variable quantity than either surface temperature or 200m temperature. The variability of layer depth is not only due to internal waves, but it also changes more gradually as a result of the present and previous winds. Especially the strength and direction of winds stronger than about 12 knots are important. In short, in the case of layer depth the ocean to as yet an unknown degree has memory for the past weather. A computer starting off with average layer depth values will have to be told how to change these in view of the recent and expected weather. It is hoped that a start on the quantitative aspects of this part of the problem can soon be made on the basis of continuous data from moored temperature sensing buoys. However, from the biological point of view it might be sufficient to know layer depth on a week by week basis to within 10%. Over very large areas, especially in the tropics, such accuracy is now achievable on

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an empirical basis.

To summarize, it does not seem too difficult a task to learn how to instruct a computer with knowledge of existing and recent winds, and cloud cover to correct the climatological temperature information in the near surface waters of the open ocean so as to produce more nearly synoptic maps.

This is certainly true under more or less average weather conditions. It will be easier to do well when the sea is losing heat to the atmosphere than during nearly calm weather in spring and summer. A modest data gathering network for the water half of the system will certainly be useful and the abilities of ships to report both meteorological and oceanographic data on a daily or shorter basis should certainly be improved, but the writer after considering these problems for some time remains optimistic about the successes that might be achieved in the near future.

Obviously the ship observation and the radio telemetering buoy program will require the same sort of international cooperation that has prevailed in meteorology for many years. As each nation develops oceanographic predicting techniques for the waters having special importance to its fisheries, and as methods and communications are standardized, it will become easier to feed the whole ocean wide task to a few major forecasting centers equipped with suitable electronic facilities.

The payoff will come when a proper marriage between meteorology and oceanography has come about. For too long each subject has been pursued more or less separately. One bottleneck in long range weather forecasting has been the sparcity of information from over the oceans. As Namias (1963) has so clearly shown, the ocean often acts as a flywheel that causes weather patterns to persist over very large areas. If the reliability of oceanographic forecasts could be improved so as to make longer range weather forecasts a possibility, then radical increases in the useful lengths of both types of forecasts becomes a probability.

So as to make these general remarks a little more specific and to perhaps throw additional light on the problem as seen by a physical oceanographer, a brief summary of the author's preliminary conclusions after returning recently on a passage from Cape Town to Woods Hole on *Atlantis II* may be of interest. The southeasterly trades were picked up two days out of Cape Town and the wind remained nearly aft for roughly 7000 miles until the ship was approaching Bermuda. On this long northwesterly slant across the whole of the Atlantic trade wind system the wind velocity varied only from about 10 knots to about 14 knots. Since our speed through the water averaged 12 knots, sometimes we were going a little slower and sometimes a little faster than the wind.

Each morning at breakfast time a prediction was made of the temperature-depth curve that would be observed during the afternoon. As far as the equator there was no advance, closely spaced information on temperature at 200m or on layer depth. The prediction simply assumed that both values would be somewhat less than in the corresponding parts of the North Atlantic during early spring. Since the ship left Cape Town on November 22, as far as the equator the surface layer was gaining heat quite rapidly. Thus a critical question each morning was whether or not a diurnal thermocline would develop within the wind stirred surface layer formed during the previous night. This depended on whether or not the early afternoon winds exceeded 12 knots and on cloud cover. While at sea the author was careful not to inspect the previous hourly bathythermograph lowerings. In other words, all that went into the forecast was the date, the latitude, and the wind and cloud cover in the early morning. Since the wind direction and velocity hardly varied at all during daylight hours, cloud cover was the critical factor in determining whether or not a diurnal thermocline would develop during the afternoon on the majority of days having 12 knot winds. Having had only a few days since returning to Woods Hole, the writer cannot now say just how successful his predictions were. This will be the subject of a later paper, but enough bathythermograms have been looked at to state that he did better in the North Atlantic where the surface layer was on the average being cooled than in the latitudes where the opposite conditions prevailed.

It is clear that the near surface thermal structure on the direct course from Cape Town to Barbados is simpler and more uniform south of the equator than on a corresponding course in the North Atlantic. The currents are weaker in the South Atlantic and there are fewer minor temperature fronts. In the North Atlantic we probably have the most difficult ocean for predictions, but this is also the ocean that we know the most about.

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I-6

FORECASTING ENVIRONMENTAL CONDITIONS IN THE FAROE-SHETLAND CHANNEL REGION

By

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It can be said at once that until hydrographical, or hydrological, parametric observations can be taken on some such pattern as that represented by the daily intake of meteorological data, effective forecasting of the marine environmental conditions of fish-life on which there is reason to believe that life to be closely dependent for its existence, maintenance, and general well-being, is scarcely a practicable proposition. That it is a desirable and practical objective, however, particularly in regions of fisheries significance, follows from certain considerations.

There can be no gainsaying, for instance, the significance of the temperature of the sea in almost all aspects and at all stages of fish life. A fundamental question, however, is whether it is always temperature *per se* which is the determining factor, in the spawning process for example, or environmental heat, of which temperature is an index. An investigation by Tait (1951) has suggested perhaps the greater relevance of the latter.

These and related studies, however, in respect of other parameters in the marine environment, such as, salinity, transparency, nutrient salt content, etc., indicate that all such factors are in fact and in their effects, fundamentally and collectively linked in the common factor of water-masses of differing physical and biological characteristics.

Still the most fundamentally reliable index of water-mass differentiation is salinity, which, although not strictly a physical property of the sea, in the terms in which it is rendered, is sufficiently close to such to justify its acceptance empirically as an index of water-mass types.

On this basis, long term researches in the Faroe-Shetland Channel region have revealed at least five distinct water-mass types to be found there, and it is the manner of their occurrence that suggests the distinct possibility of forecasting them, under the primary condition of systematic observation.

The oceanic water-mass is the only <u>permanent</u> water-mass of the Faroe-Shetland Channel region, occurring at all times as the uppermost 300-500 m layer. Borne by the North-Atlantic Drift Current, it is normally characterised by a core of relatively high salinity, and the boundary salinity of this core may be taken as an index of the quality of the oceanic water-mass. This, over a period of time of the order of 25 years, may vary between salinities of 35.25 °/oo and 35.45 °/oo. The variation is gradual, which lends to this particular phenomenon the aspect of climatic change in the sea, and the fact that it is gradual anticipates the possibility of forecasting it, provided observations in the region are sufficiently regular and systematic.

Occasionally, but again spread over a period of from 4-6 or 7 years, the oceanic water-mass of the Channel region includes water which, by its salinity (also by its biological content), of upwards of 35.50 °/oo to nearly 36.00 °/oo, as happened in 1933-34, derives ultimately from the Mediterranean Sea. The intrusion is relatively gradual, waxing to maximum intensity in about mid-period, and waning to extinction at the end of the period. In this circumstance again obviously lies the possibility of forecasting the phenomenon by systematic observation.

The bottom water-mass of the Faroe-Shetland Channel region is normally bottom Norwegian Sea water of salinity 34.90 °/oo to 34.94 °/oo, but usually fairly constant at 34.92 °/oo. This mass, however, can on occasions be totally replaced, at the peak of the 4-6 yearly phenomenon, by the intrusion, at first gradual, of one, but sometimes two, types of Arctic water-mass, the first,

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intermediate Arctic water, designated by salinities of 34.85 °/oo to 34.89 °/oo, and the second, surface Arctic water (possibly originally at least sub-Polar water) of salinity 34.77 °/oo to 34.84 °/oo. These are distinctive types; their advent and departure are characteristically gradual as that of the Mediterranean type in the oceanic water-mass, and the phenomenon of their substantial occurrence - they can appear intermittently as mere traces - lasts usually for a period of again from 4-6 or 7 consecutive years. This particular phenomenon has been shown apparently to relate to certain fisheries phenomena (Tait and Martin, this symposium).

As said in the beginning, however, the possibility of effectively forecasting these phenomena, is conditional upon observations being taken systematically and regularly, comparable with those of meteorology. The prospect of introducing such intensity and system into oceanographical observations is only now apparently coming within reach, as it were, through the development of the automatically recording, and probably telemetering, oceanographic buoy, a development which seems unquestionably to hold enormous promise for the future.

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I-7

THE POSSIBILITY OF FORECASTING OCEANOGRAPHIC CONDITIONS IN NORTHWEST EUROPEAN WATERS AND THEIR SIGNIFICANCE FOR FISHERIES

By

Jens Eggvin[1]

ABSTRACT

Oceanographical material from research ships, fixed oceanographical stations, coasting vessels, liners and weather ships has been used together with meteorological material in order to follow the flow of individual water masses. An attempt has been made to forecast hydrographic situations which, according to experience, influence fisheries in various ways.

In physical oceanography systematic and yearly observations are only available for a relatively short number of years and for those areas of the ocean that have been most thoroughly examined.

Complete and repeated observations at relatively short intervals in suitable positions are of great importance when the aim is to secure clues to certain causal connections that can supply the solution to oceanographic problems of general, as well as of special, character. This is the case, particularly in the solution of many important problems within oceanographic fishery research.

With regard to fishery research, it has been our aim, among other things, to be able to foretell something with reference to the fishing. In order to contribute hereto on an oceanographic basis, it is essential that the work be carried out on two fronts.

First, observations must be made on the oceanographic conditions during the actual fishing and on the course of the fishing. These facts, together with previous knowledge must then form the basis for the theories that fishing is dependent on certain oceanographic conditions.

Second, it is necessary to be able to foretell the hydrographic conditions during the coming fishing season.

If we are, however, to be in a position to foretell how conditions in the sea will develop some time in advance, then it is of primary importance to have equipment that allows us to follow the developments in the sea from month to month and week to week. For economic reasons, research vessels cannot operate year round in the different areas, but can, at best, only visit certain places a few times during a year. It would be of great assistance if we could supplement this with observations made at shorter intervals. We would then be in a better position to know when any comparatively great changes in the distribution of the several types of water have taken place, and what changes in different oceanographical parameters are supposed to take place. Fixed oceanographic stations of different kinds would here be of great help.

Sometimes nature herself can speak to us more clearly than usual, and if we are at the time able to make suitable observations, interesting causal connections may be discovered. For example, the southeasterly storms, prevailing in the latter half of January and February 1937, transported great masses of cold water of low salinity towards the southern Norwegian Coast from the Kattegat and the Baltic. This gave rise to a strong current which, in February, caused serious difficulties for the spring herring fishery. On account of its low salinity, the water was considerably lighter than the underlying, warmer but more saline bankwater. Even if this surface water was further cooled off the Norwegian Coast, it could not become heavy enough to sink down and be substituted by warmer water from beneath. Consequently, this surface water had to give up so much of its heat to the air that

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the freezing point was reached. This resulted in ice obstruction and the killing of fish (on one day 50,000 kg) in well boats bound for Oslo, despite the fact that the mean air temperature in February 1937 remained normal along the Skagerack Coast.

The detailed movement of the water masses in question both in extent and depth, from the time it was observed at Ferder on 30 January to when it reached the Møre Coast on 19 March, 48 days later, was successfully followed with help from various investigations, cruises with research ships, the recording of sea surface temperature and collection of samples for salinity from coasting vessels and from fixed oceanographical stations (Eggvin, 1940).

By an unavoidable freak of nature, this frigid cold water front of low salinity, made its way along the south and west coasts displacing the salter and warmer water that had been present from 0-40 m earlier. On 7 February at about 0300 hr, the front passed off Lillesand. It reached Ogna at Jaeren at 1200 hr on 18 February and passed Jaerens Reef 42 hr later. At 2145 hr on 26 February the front was 5.5 nautical miles north of the south end of Karmøy, and at 0330 hrs on 9 March it reached Askvoll in Sogn.

The average speed of the current along the various stretches of the coast was from 13 to 25 cm/sec (6.5 to 12 nautical miles a day). The average speed for the whole distance was 19.4 cm/sec or 9.75 nautical miles in the 24 hr.

As the cold water moved westwards and northwards along the coast displacing the bottom waters on the banks, the herring fishery that was being carried on at that time, suddenly ceased. It appeared that the herring left the banks and sought the deeper, warmer water.

Petterson and Ekman (1891) have shown that herring avoid this cold Baltic water along the west coast of Sweden. Hjort (1896) and Runnstrøm (1933) proved the same for the Norwegian west coast. Runnstrøm points out that, when the effects of the Baltic cold water are especially great, the quantity of herring in the spring herring fishing areas can, in some years, be reduced to a half of which, from the biological point of view should have been present. The oceanographic conditions during the spring herring fishery are, therefore, undoubtedly of great economic importance.

It has also been possible to follow such Baltic water fronts in summer, but in that season the water coming from the south was warmer than that displaced. It flowed into the fjords of the west coast bringing with it shoals of sprats, according to information from Mr Bjerkan.

The above example shows how oceanographical and meteorological conditions prevailing in the Baltic and the Skagerack at one time can indirectly influence the herring fishery on the Norwegian west coast later on. We have used the knowledge gained here in different ways concerning icedrift, front-passages at different places and influence on fisheries.

Since we have succeeded through a combination of several research methods in following, in detail, the movement of an individual mass of water over a stretch of several hundred kilometers, it must be presumed that this can also be carried out at other places, even if the oceanographical conditions should not be as favourable as they were in the area in question.

If we follow the water masses from the south coast of Norway to the Murman Bank, we will see how the boundary line separating the Atlantic water from the coastal water is found deeper and deeper as the water masses move northward and become mixed with each other. Along most of the Norwegian Coast, there is a transition layer, but off the coast of East Finnmark and farther east, the water has become almost homogenous from surface to bottom. This fact is of great practical importance for both fisheries and climate. Because of the great instability of the water masses from surface to bottom during winter along the Finnmark Coast, no ice can form there, whereas, along the south coast where there is a light water layer on the top of a heavier one, ice can form in spite of the air temperature there being so much higher than in Finnmark during winter.

It is known that there are considerable variations from year to year in the influence of the Atlantic current off the northern coast of Norway. Off the coast of East-Finnmark there is a border-area where the water from the Atlantic is strongly mixed with the colder eastern water. The position of this area shifts from year to year and it appears that the fishing at Finnmark is greatly influenced by its position. With a strong inflow of Atlantic water, certain temperature limits *e.g.* 3° or 4°C will be forced eastward and northward. On the other hand, with a slighter inflow the same temperature limits will be found to the westward and nearer the land.

At the same time, the fluctuations in the appearance of the fish varies with the oceanographic conditions. With much water from the Atlantic (warm water) present, the spring cod fishery (immature cod) takes place far from the land at East Finnmark, and to the east on the banks off Fishermans Peninsula and farther eastward. Then the distance to the fishing grounds is too great for the small vessels and open boats. If, on the other hand, little Atlantic water is present, then the above mentioned temperature limits will be found farther west and nearer the land. The fishing then takes place nearer land and over a great area of the Finnmark coast which is more favourable especially for the smaller vessels.

The theory that the spring cod fishery along East Finnmark is dependent on certain temperatures in the border area between Atlantic and eastern colder waters was published in the Lofoten report of 1936 (Lofotfisket, 1936). Observations have supported the theory.

Observations made before the spring cod fishery at Finnmark begins, should help to forecast whether the position of the above mentioned border area will be situated far to the east or to the west. The following is an example of this.

Observations from a cruise and from the fixed oceanographical stations showed us that the deep water along the Norwegian Coast in late autumn 1938, and early 1939, was very warm. This was the case, especially off Lofoten, Vesterålen and West Finnmark. Since some of this water flows on eastward to the coast of East Finnmark, the temperature should remain comparatively high there, especially while the salinity was lower than normal in the upper 50-75 m. Here, the water was light compared with the underlying layer. The vertical circulation brought about by the winter cooling would, therefore, be hindered to a certain extent. Such a state would hasten the cooling of the surface water but retard the cooling of the underlying layers.

The following forecast was printed in the Lofoten report in January 1939:

> "As conditions in the sea off the north of Norway, and to the south are, at present, it must be expected that the temperature of the deep water will remain relatively high during the spring cod fishery 1939 at East Finnmark which takes place from April to June. Consequently, it will be necessary to go far offshore (northwards) and far to the east in order to arrive at the above mentioned favourable temperature limits. From previous experience there is every reason to believe that there will be little chance for the small vessels to make reasonable catches during the coming spring cod fishery (loddetorsk) off East Finnmark".

A cruise to Finnmark by the research ship *Johan Hjort* during the actual fishing season together with observations made at the fixed stations at Ingøy and Vardø in Finnmark satisfactorily answered the question as to the correctness of the prediction.

The Lofoten cod-fisheries (February-April) takes place, as is known, in an intermediate layer between the relatively cold and slightly saline coast-water and the underlying saline and warmer Atlantic water.

The depth at which this layer is situated during the fishing varies from year to year while the fluctuations during the same year are considerably less. A strong continuous wind can, of course, cause changes in the depth of this layer but after the cessation of the wind it reoccupies its approximate depth.

The depth at which this layer will be situated during the fishing season is of the greatest importance. If it should be situated comparatively deep, then the fishing takes place in deep water and far offshore. If, on the other hand, the intermediate layer is found at more shallow depths, then the fishing takes place in shallow water, and near land.

Since a very great percentage of the Lofoten fishing is carried on from small vessels and open boats, it depends, during this rough period of the year (February-April) much on the distance to the fishing grounds. Further, if the intermediate layer should be shallow, then the fishing is best at East Lofoten, otherwise the chances are best at those fishing grounds situated far out in the fjord, West Lofoten.

Winter cooling causes the formation of this layer. The depth at which it will be situated depends on stability conditions. The intermediate layer remains shallow if the salinity of the upper layer is comparatively low and the winter cooling during the autumn and not before the winter is slight (high air temperature). Further it depends on the relative quantity of coastal water and Atlantic water.

In 1935, 1940 and 1956 the salinity in the surface water during the late autumn was comparatively high and the upper 50-75 m was almost homogenous, and the winter cooling could press the transition layer deep down in the sea. Forecasts of the depth of the transition layer in the Vestfjord (Lofoten) have been satisfactory.

During the winter of 1963, with great negative anomalies in the air temperatures and relatively low cloudiness, the cooling of the sea by radiation, conduction and also partly by evaporation has resulted in very low sea temperatures in wide areas and heavy formations of ice in the Baltic, the Kattegat and the Skagerack (Eggvin, 1963).

The density of the water in the south-eastern part of the North Sea was greater than in the other areas including the Norwegian Channel. Taking the direction of the current into consideration, it was anticipated that the deep- and bottom-water of the Norwegian Channel would be renewed by that heavy and much colder water. Further, it was expected that it would take a relatively long time (months) before normal temperature conditions could be established again in the deepest parts of the Norwegian Channel. This came true. Even in January 1964 there still remained relatively cold water which had flowed into the Channel during the previous spring.

The very cold water in the southeastern part of the North Sea and off the west and south coast of Norway hampered fishing in those areas. This situation was expected on the basis of previous experience.

SUMMARY

With the help of different research methods, it has been possible to follow individual water masses penetrating as fronts along the Norwegian Coast. Since these water masses can influence fisheries (herring and sprats), knowledge of their origin and character and of the influence meteorological agencies have on their transport and stability, has been of practical value.

Off the coast of Northern Norway (Finnmark) there is a border-area where the Atlantic water is strongly mixed with the colder eastern water. The position of this area shifts from year to year and it appears that the spring cod fishery is greatly influenced by its position. Forecasts of this position have been made.

As the Lofoten cod fishery (February-April) takes place in the transition layer between the relatively cold and slightly saline coastal water and the underlying saline and warmer Atlantic water, forecasts of the depth and, in part, the thickness of this layer have been of interest to the fishing fleet and the fishing industry.

The heavy cooling of the sea during the winter 1963 resulted in abnormal oceanographical conditions, partly of long lasting character as expected and also influenced some of the fisheries.

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SOME ASPECTS OF OCEANOGRAPHIC PREDICTION

By

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The purpose of this paper is to discuss several problems which arise in connection with the general problem of the development of oceanographic forecasting techniques. Of course, possible solutions to these problems will to a large extent be guided by the particular use to which the environmental information is to be put, and there is a broad possible spectrum of such applications. There are two requirements, however, that appear to be common to almost every attempt to extrapolate oceanographic conditions into the future: the nature of the sea surface, and the three dimensional structure of the ocean's physical variables, with special emphasis on temperature and salinity. Since the first of these has been thoroughly discussed on many occasions, this paper will confine itself to the latter.

Although there are doubtless many areas in the ocean of sufficient stability in time to permit the preparation of useful predictions by recourse to analysis of historical data alone, in those areas where significant time variability exists it seems clear that accurate predictions will only be developed if continuing surveillance of oceanographic conditions is maintained in order to provide data to use as initial conditions. I therefore believe that we can divide the process of providing environmental predictions on a synoptic basis into four separate phases:

1. The collection and transmission of the basic data.

2. The analysis of the data to define the present situation.

3. The prediction of the present situation in time.

4. The application of both the analysis and prediction to the particular practical problem being considered.

With regard to the first of these, the collection and transmission of data, it appears that the first problem is to define the work "synoptic" where oceanographic conditions are concerned. Clearly we are not dealing with a medium where time scale phenomena are comparable to those in the atmosphere, for instance. It is important to know over what period of time significant time changes do not occur, so that the data may be lumped together and considered as occurring at approximately the same time. This period will not be the same for all oceans, nor even the same for areas within an ocean. Several studies have been or are being made of this problem; one such study, conducted by the Travelers Research Center, was made for the western North Atlantic. Considering the accuracy and time and space frequency of data now available, it was found that a period of about 1 1/2 days is appropriate for very active areas such as the Gulf Stream, a period of three days for reasonably active areas such as the North Atlantic drift, and a period of 15 days or more for inactive areas well away from major current systems.

The second consideration in the collection of data is the spatial variations in the medium, which will affect the spacing of platforms from which the data is to be collected. Here again, great variability in observational requirements in the space domain is to be expected. Since so far attempts at synoptic oceanography have been dependent mainly on data collected from ships of opportunity in one form or another, there has been little control over this factor. One obvious answer is to develop platforms over which we do have control, such as aircraft and buoys; both of these approaches are being pursued. From those areas which prove to be more homogenous horizontally than expected, it will no doubt be possible in the future to require fewer observations than we either receive now or will receive in the future. At the present time, however, observational data are so

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scarce that we should collect them wherever and whenever possible, so that criteria for spatial distribution may be determined.

A third problem in data collection is that of what to collect and how accurately, and here the problem is inextricably linked with available and projected instrumentation capability. One of the things we really would like to assess and predict is the three dimension thermohaline structure. Since our instrumentation capability does not permit this measurement on a routine scale at the present time, we shall have to be content with three dimensional temperature measurements, backed up with infrequent salinity observations from specialized platforms. For those areas where horizontal variations are important, which unfortunately include a large portion of the oceans, current information is desperately needed. These at present cannot even be inferred on a synoptic basis with too much accuracy. This brings up a point which might possibly apply to variables other than currents - is data of questionable accuracy better than none at all?

I might add that all the factors that affect the obtaining of synoptic oceanographic information are linked up in various inter-relationships. For instance, decision on the period of time over which the ocean may be considered synoptic is not only a function of the oceans behaviour but also the number and accuracy of our observations as well as our ability to analyze them correctly. Should our capability increase in either of these latter fields, the synoptic period could be shortened and the data would still be meaningful. But this would then have to be balanced against the expense involved and the practical requirements of the user of the prediction.

Turning to the second phase of the problem, that of data analysis, the basic approach most employed has been to infer the horizontal field of various parameters most descriptive of the oceanic structure, such as sea surface temperature, layer depth, and vertical gradients, in a manner similar to the preparation of synoptic meteorological charts. Our ability to specify these fields without error is severely limited by the scarcity and inaccuracy of data now available routinely, it is fair to state that it is not possible now to construct a very accurate analysis of the data obtained during one rather short synoptic period, such as one day, when these data are considered independently. As mentioned above, however, the fact that the oceans exhibit more conservatism in many areas than the atmosphere does permit the grouping of data over a specified period for synoptic analysis, thus increasing the density of observations considerably. Most of the experiments carried out in this area have employed a period of three to five days as an acceptable compromise. Another factor favourable to the analysis procedure is that one does not consider each set of data independently, but rather uses continuity considerations in which each set of data is considered in light of the data that has gone before. In this way the development and the movement of analysis features may be studied from day to day, true features identified and spurious features eliminated.

A regular program of employing such techniques to provide synoptic analysis of surface and subsurface variables in the ocean has been carried on at the U.S. Naval Oceanographic Office during the past two years. Methods employed have been subjective in nature, and the charts were prepared manually. Most of the emphasis has been placed to date on analysis of the sea surface temperature, the mixed layer depth, and the vertical gradient of temperature immediately below the mixed layer. Because of the relative abundance of sea surface temperature observations and the fact that the sea surface temperature serves as an anchor for the vertical temperature trace, initial emphasis has been placed on the analysis of this variable. The picture emerging from this analysis program is one that is very complicated near the Gulf Stream with a considerable amount of fine detail, mainly consisting of alternate warm and cold tongues of surface water. In general these features are observed to be quite conservative with time, being identifiable on the charts for many days. Although some of these features have been tracked from one area of the chart to another, many of them are observed to move little, if at all. Away from major current systems such as the Gulf Stream, gradients are still observed; although not nearly so strong as those observed in the neighbourhood of the Gulf Stream, these gradients still tend to be larger than originally expected. The major problem, therefore, appears to be the amount of detail that should be included in the analysis, in light of either the actual oceanic structure or the requirements of the application.

Achieving adequate analyses of sub-surface variables is a more difficult problem, owing to the relative scarcity of data. While we have been able to collect about 100 bathythermograph observations from the western North Atlantic daily, until this number is increased the data density will scarcely be enough to permit analyses in the same detail as the sea surface temperature. For some time therefore it will be necessary to supplement direct contouring of sub-surface data with indirect assessment of the sub-surface conditions. One helpful factor has been that, in certain areas and at certain times of the year, it has been possible to use the pattern of sea surface temperature as a rough guide to the pattern of mixed layer depth. While such an analyses aid is strictly qualitative rather than quantitative, it has given rise to the idea that an organized program of statistical analysis might be able to develop relationships which would be of direct assistance in the assessment of current sub-surface conditions.

Although the initial experiments in synoptic oceanographic analyses have been carried out using manual techniques, the concept of computer analysis of these data is extremely attractive, both from the standpoint of objectivity and ease of handling the prediction problem, which almost certainly will involve mathematical computations concerned with the heat budget, vertical mixing, and horizontal advection. Experiments in this area carried out by organizations in the United States have resulted in charts which are much less detailed than the manual product; in many areas the contours are considered too smooth to represent the nature of the ocean structure adequately. The achieving of a more detailed picture by objective means will involve a much closer grid spacing in the computations; this will require a greater data density than we have at present. Although attempts are underway to increase the detail in present objectively prepared charts, for some time one of the decisions that will have to be made is the extent to which we can sacrifice detail for the sake of objectivity. The aim should be to retain as much real detail as the user of the prediction needs.

With regard to the problem of oceanographic prediction, there are many approaches that have been and are being employed to develop forecasting techniques for the variable temperature field. In general, they can be summarized by outlining four different types of approach to the problem.

The first would emphasise the factors of continuity and persistence exhibited by the ocean, as discussed above in connection with synoptic analysis. Here one assumes that day to day changes in intensity and motion of oceanographic features are relatively small, and these changes occur in a continuous manner and may therefore be projected into the future. Such a technique naturally depends on the quality and detail of the synoptic analysis available. The importance of this approach to oceanographic prediction, elementary as it is, should not be underestimated. Prior to the development of objective methods, this was the approach used by meteorologists for many years with considerable success; the slower time scale of events exhibited by the ocean should make it an even more valuable tool. It may even very well be that for forecasts of very short duration, such as a day or so, it will not be possible to surpass this method by the development of specific objective equations.

The second approach might be termed a point prediction in that it involves operating on a single vertical temperature trace. Once an initial condition, such as a bathythermograph reading, is obtained, the changes in the vertical trace are calculated in terms of predictable variables such as wind, air temperature, cloudiness, and others. Changes calculated by this means will be limited to those resulting from energy exchange at the sea surface at the point of observation. These changes will include addition or subtraction of heat at the surface, convection due to heat loss, and vertical mixing due to wind and other factors. The prediction itself consists of modifying the vertical temperature trace in accordance with the calculated changes; a considerable body of information exists to make these calculations, mostly in the form of empirical formulae developed over the years.

By far the greatest number of experiments made in oceanographic prediction have been of this type, and work of this nature has been carried on in several countries. Such prediction techniques when adequately developed could be expected to provide useful forecasts in those stable areas away from major current systems where the major effects on the ocean structure or those taken into account in this type of calculation. It could not be expected however, that this type of prediction will be completely successful in those areas where it is necessary to take into account effects of horizontal variations, such as those due to advection or internal waves. However, even in these areas such daily computations are important to indicate the magnitude of energy exchange factors.

The third approach may be termed the dynamic approach in that it involves development of mathematical models of the ocean using the hydrodynamic equations as a basis. Given such a model and at initial distribution of variables such as can be gathered by a synoptic network, numerical integrations can be carried out by high speed computers, and the conditions in the future calculated. This process is usually repeated for small intervals of time over the entire forecast period. Development of such a system will be a lengthy process; although some precedence exists for this type of forecast in meteorological procedures, there are enough important differences between the structure of the ocean and the atmosphere to warrant considerable effort in the model development. A few projects have been established in this area, and testing of various models is now underway. It will be some time, however, before such models can be used on a routine basis; the input requirements for such equations are much more stringent than those of other approaches to the prediction problem, and routine use of such models will have to await further development of synoptic data collection techniques.

The fourth approach is statistical, and such an approach assumes special significance for several reasons:

1. A certain amount of statistical analysis is required to use any other prediction technique, in that the objective analysis that serves as an input to the prediction model usually has, at least in part, a statistical basis.

2. No matter what approach is taken to prediction, it is necessary to know the statistical population within which the prediction is to be made - what might be called a first order prediction.

3. Statistical considerations are the only logical means now available of making long range predictions, for instance seasonally, in addition to possible statistical applications to short range prediction.

In the field of short range prediction by statistical means, the objective is to develop some type of regression equation which may be used to predict a specific oceanic variable for a specified period of time. A large body of historical data is of course required to employ such an approach; the analysis is so designed as to yield knowledge of those factors which had the most effect on time changes in the variable being predicted. These factors are given the most weight in the regression equation.

While we are a long way from having oceanographic prediction systems capable of meeting all the requirements that exist for them, there has been a great increase in activity in this field in recent years. Several countries have synoptic oceanographic programs, and from research on these data will come increased knowledge of the time changes in oceanic behaviour. Although these projects are not yet completed, work is actively underway in almost all the areas discussed above; the foreseeable future should see a significant increase in our capability to provide advance oceanographic information to those who operate at sea.