Hydrographic conditions off the northeast coast of Iceland in relation to meteorological factors

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ABSTRACT

The relationship between oceanographical and meteorological variables off northeast Iceland is re-examined and analyzed statistically. The analysis confirms the previous hypothesis of a strong connection between the oceanographical conditions east of Langanes, northeast Iceland, and air temperature and N–S winds about 90 days prior to the observations. Since hydrographic conditions north of Iceland are known to depend largely on the influx of Atlantic Water from the Irminger Sea, and the average travel time of this water from the northwest coast to the region east of Langanes is about 3 months, this time lag corresponds closely to the expected one.The results of the numerical analysis indicate that the air temperature is a more important factor than the winds, although the hypothesis of an independent effect of the wind cannot be rejected. The effect of air temperature on the influx of Atlantic Water is believed to be indirect: air temperature variations leading to corresponding variations in horizontal density gradient across the shelf whereby the coastal circulation is affected. Some evidence for this is provided.

Introduction

Oceanographically the Iceland Sea[2] is a region of great contrasts, since it consists of water masses of diverse characters and different origin. Their distribution in time and space varies greatly, not only from season to season, but also from year to year.

It has been shown (Stefánsson, 1962) that in late winter, spring and the first part of summer the uppermost 200 meters of water in the shelf area north of Iceland consist mainly of mixtures of two water types, Atlantic Water ($t = 7.0°C$, $S = 35.15$ ‰) and North Icelandic Winter Water ($t = 1.4°C$, $S = 34.84$ ‰). The former is derived from the area west of Iceland and enters the Iceland Sea off the northwest coast. The latter is formed north of Iceland in winter by vertical mixing of Atlantic Water and cold arctic waters occupying the upper layers in the region between Iceland and Jan Mayen. The proportion of Atlantic Water decreases in the direction of flow from west to east along the north coast of Iceland. During summer the winter water is gradually replaced by subsurface arctic water moving in from the north. Its t, S characteristics are similar to those of North Icelandic Winter Water. Meteorological conditions may to some extent modify the water types formed, especially the North Icelandic Winter Water. Penetration of drift ice to the North Icelandic coastal area or intrusion of Polar Water from the East Greenland Current drastically changes the hydrographic conditions in the surface layers. However, owing to the low density of Polar Water or melted water from ice, its effect will generally not be significant in the deep-lying water strata. In the period 1930–1962 drift ice was only rarely observed in the coastal area north of Iceland, except for occasional scattered floes in late spring and summer, mainly affecting the conditions in the western part of the area.

North of Iceland seasonal changes are detected down to a depth of at least 300 meters. It has been shown (Stefánsson, 1962) that two kinds of seasonal variations can be distinguished viz. (*a*) hydrographic variations directly associated with changes in the sun's altitude and (*b*) variations in the relative magnitude of At-

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[2] The Iceland Sea is here defined as the sea area between Iceland, Greenland and Jan Mayen (for exact limits see Stefánsson, 1962, pp. 30–31).

lantic Water. The Atlantic influence was found to increase in spring and reach a maximum in summer. In autumn and winter it is greatly reduced.

The Atlantic influx has also been found to differ considerably from year to year. Such annual variations are most easily identified at intermediate depths, between 50 and 200 meters.

It is the object of this paper to investigate the relationship between these observed variations and meteorological variables. Specifically, previous hypotheses concerning causal connection between winds, air temperature and oceanographic conditions will be re-examined and tested statistically.

Previous studies of year to year variations

On the basis of data available for the period 1924–1960 a preliminary study was made of the most likely causes of year to year variations in temperature and salinity north of Iceland during the summer season (Stefánsson, 1962). Three main factors were considered, viz. (1) variations in the extension of drift ice, (2) meteorological factors concurrent with hydrographic observations and (3) variations in the strength of the North Icelandic Irminger Current.

A distinct correlation was found to exist between surface temperature in the western part of the area and the frequency of drift ice at the northwest coast. Also, the surface salinity was closely associated with the ice conditions. Furthermore, a weak, but significant correlation was found between the sea surface temperature and the concurrent air temperature. This association may be both direct and indirect, e.g. the sea surface temperature drops when drift ice approaches the area. Sea surface temperatures north of Iceland will also depend on the advection of Atlantic Water from the southwest.

With regard to conditions below the seasonal thermocline, the influx of Atlantic Water appeared to be the dominating factor. The effects of winds on the Atlantic influx were examined by testing two hypotheses: (1) that the influx of Atlantic Water to the North Icelandic shelf area is dependent upon the easterly or westerly wind component, (2) that southerly winds intensify the flow of Atlantic Water northward along the west coast of Iceland and lead to increased influx of this water to the area north of Iceland. Conversely, northerly winds in the region west of Iceland would be expected to reduce the northward flow of Atlantic Water. Since the ocean area west of Iceland represents the source of Atlantic Water penetrating the North Icelandic shelf region, the second hypothesis was a priori considered more plausible.

As a measure of the wind, pressure differences were used: between Akureyri, north Iceland, and Vestmannaeyjar south of Iceland for the east-west component, between Djúpivogur, east Iceland, and Stykkishólmur, west Iceland, for the north-south component.

For testing the first hypothesis temperatures in July at intermediate depths (50–200 meters) at the "permanent" oceanographic station S (Fig. 1) were compared to the mean difference in air pressure between Vestmannaeyjar and Akureyri, computed for 10 days' intervals over a period of 60 days prior to the date of the oceanographical observations. The result was that no significant correlation could be found between hydrographical conditions at station S in July and the east-west wind component in the 60 days' period prior to the working of the station.

For testing the second hypothesis, temperature and salinity at the two stations S and L (Fig. 1) were correlated with the average monthly pressure difference between Djúpivogur and Stykkishólmur in various months during spring and summer. At station S the strongest correlation of temperature or salinity with the south-north wind component was found for the average monthly wind component 1½ month prior to the date of the oceanographical observations. East of Langanes at station L the best correlation was found for a time difference of 3 months. These lags correspond approximately to the time it takes the mean coastal current to transport the water from the region off the northwest coast (off Látrabjarg, see Fig. 1) to the station in question (Hermann & Thomsen, 1946; Stefánsson, 1962). For these time differences the correlation was highly significant, for other time differences the correlation was either less significant or not significant at all. From these results it was postulated that southerly wind is the dominating factor affecting the influx of Atlantic Water to the area north of Iceland.

It was also found that the air temperature along the North Icelandic coastal area in spring

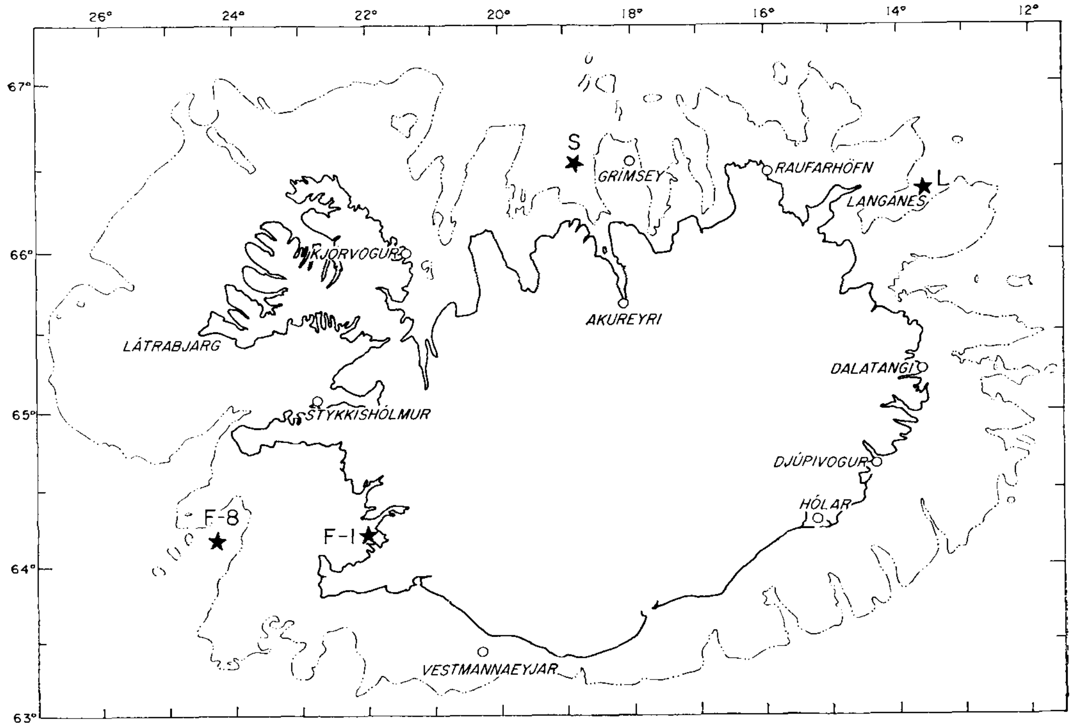

Fig. 1. Locations of hydrographical and meteorological stations referred to in the text.

is closely correlated with the hydrographic conditions at station L in late summer. This correlation was believed to result mainly from an association between high (low) air temperatures and southerly (northerly) winds, although an independent effect of the air temperature was also considered possible.

Material

Comparison of year to year variations in different parts of the area north of Iceland revealed that the maximum variations in temperature and salinity at intermediate depths occur east of Langanes (station L) in August. Therefore, data from station L were chosen in the present study. The temperature and salinity deviations in August of different years at this station, as well as average values of temperature and salinity and standard deviations, are given in Table 1.

The meteorological data used in our analysis consisted of one observation a day. As a measure of the air temperature along the North Icelandic coast, average values of the three meteorological stations Kjörvogur, Grímsey and Raufarhöfn were chosen. The north-south wind component was estimated as the pressure difference between east and west Iceland. Since measurements of barometric pressure were discontinued at Djúpivogur in 1960, differences between Hólar and Stykkishólmur were used (Fig. 1).

Local conditions can have a considerable effect on the air temperature but the use of three stations reduces this source of error. Besides, the stations at Grímsey and Raufarhöfn are likely to be relatively free from such disturbances because there are no large mountains in the neighborhood. Single measurements of barometric pressure are considered fairly representative for the surrounding area, but of course a difference between two values is more sensitive to errors than the average of three values.

There will be some difference between the pressure gradient off Látrabjarg and the gradient estimated by the observations at Hólar and Stykkishólmur. Since the atmospheric lows

Table 1. *Deviations in temperature and salinity*[a] *in August at station L (66°22′ N, 13°35′ W)*

Year	0 m		20 m		50 m		75 m		100 m		150 m		200 m	
	T°	S ‰	T°	S ‰	T°	S ‰	T°	S ‰	T°	S ‰	T°	S ‰	T°	S ‰
1934	0.71	−0.36	0.67	−0.31	−0.93	0.03	−1.05	−0.07	−0.85	−0.09	−0.88	−0.14	−0.49	−0.12
1935	−0.24	0.22	−0.09	0.19	0.54	0.13	0.41	0.06	0.50	0.04	0.51	0.04	−0.02	0.01
1936	1.06	0.11	0.89	0.07	2.86	−0.18	2.50	0.01	1.88	0.06	1.27	0.13	0.50	0.13
1938	0.56	−0.30	−0.13	−0.31	−1.02	−0.10	−0.29	−0.02	−0.05	−0.01	−0.52	−0.09	−0.42	−0.10
1939	1.03	0.08	0.87	0.10	0.81	0.20	0.68	0.12	0.81	0.10	0.61	0.11	0.12	0.08
1947	1.60	−0.03	1.74	−0.08	1.54	0.00	1.45	−0.02	1.29	0.00	1.46	0.05	1.60	0.12
1948	−0.30	0.04	−0.80	−0.07	−1.59	−0.17	−1.08	−0.14	−0.64	−0.07	−0.41	−0.11	−0.55	−0.06
1949	−0.49	−0.41	−0.33	−0.18	−3.39	−0.21	−2.75	−0.19	−2.38	−0.15	−1.74	−0.12	−1.84	−0.14
1950	0.27	−0.41	0.63	−0.42	−0.29	0.07	−0.19	0.04	−0.55	−0.02	−0.41	−0.02	−0.30	−0.03
1951	0.05	0.03	−0.60	0.06	0.21	0.02	−0.15	0.05	−0.51	0.02	−0.58	0.03	−0.96	0.01
1954	0.65	0.00	−0.26	0.13	1.09	0.03	1.06	0.01	0.97	0.03	1.24	0.04	1.34	0.00
1956	−1.75	0.26	−1.31	0.20	−0.02	−0.01	−0.42	−0.01	−0.28	−0.02	0.04	−0.02	0.39	−0.02
1957	0.05	0.20	−0.19	0.18	0.57	0.15	0.60	0.09	0.75	0.03	0.18	0.02	0.73	0.03
1958	−2.15	0.16	−1.33	0.12	−1.15	−0.02	−1.27	−0.07	−1.01	−0.06	−1.03	−0.06	−1.06	−0.04
1960	1.05	0.08	1.52	0.04	0.06	0.16	0.57	0.11	0.61	0.07	0.62	0.09	0.98	0.10
1961	0.08	0.28	0.12	0.24	0.32	0.12	0.05	0.08	0.16	0.10	−0.04	0.08	−0.20	0.05
1962	0.10	0.09	−0.02	0.16	0.15	0.10	0.12	0.09	0.06	0.08	−0.01	0.06	−0.26	0.04
1963	−1.84	−0.05	−1.41	−0.08	0.51	−0.26	−0.33	−0.20	−1.23	−0.10	−1.26	−0.13	−0.71	−0.11
1964	0.44	0.04	0.55	0.05	1.51	0.03	1.19	0.00	0.89	0.01	0.93	0.00	1.06	0.01
1965	−0.95	−1.01[a]	−0.56	−1.06[a]	−1.80	−0.33[a]	−1.09	−0.27[a]	−0.44	−0.18[a]	0.00	—	0.00	—
Average[a]	8.55	34.61	8.13	34.65	5.31	34.88	4.93	34.95	4.61	34.97	4.04	34.97	3.50	34.95
S. D.[a]	1.02	0.22	0.89	0.19	1.38	0.13	1.15	0.10	1.00	0.07	0.88	0.08	0.87	0.08

[a] Salinity deviations and mean based on the period 1934–1964.

tend to move eastward and average values over several days are used in our analysis, this source of error will be reduced. A time difference of a day or so is of no importance.

Mathematical model

In this study only linear relations will be considered. The connection between the observations is then given by the convolution integrals

$$T(t) = \int_0^\infty W_{TP}(t')\,P(t-t')\,dt' + \int_0^\infty W_{TQ}(t')\,Q(t-t')\,dt' + N_T(t) \quad (1)$$

and
$$S(t) = \int_0^\infty W_{SP}(t')\,P(t-t')\,dt' + \int_0^\infty W_{SQ}(t')\,Q(t-t')\,dt' + N_S(t), \quad (2)$$

where $T(t)$ and $S(t)$ are sea temperature and salinity at the time t, P is the pressure difference between Hólar and Stykkishólmur, Q is the average air temperature of the meteorological stations at Kjörvogur, Grímsey and Raufarhöfn, N_T and N_S are variables that account for measurement errors and deviations from the model described by equations (1) and (2), $W_{TP}(t')$ is the weight attached to the value of $P(t-t')$ in determining $T(t)$, and W_{TQ}, W_{SP} and W_{SQ} are analogous weight functions which determine how T and S depend on past values of P and Q.

Linear models like those given by equations (1) and (2) occur frequently in time-series analysis. Observations of the variables, here T, S, P and Q, are used to gain information about weight functions.

Numerical analysis

The meteorological variables and the sea temperature and salinity are time-series and the weight functions could be estimated from the spectra and cross-spectra of these (Akaike, 1965). Observations of T and S are too sparse for the estimation of spectra. Although the spectra of the dependent variables are not needed for the estimation of the weight functions this prevents the calculation of coherencies which deprives spectral analysis of one of its main advantages. Our problem is also one where time is a more natural dimension than frequency. Spectra were therefore abandoned in favour of covariances.

In order to reduce the computation a low-pass filter was applied to the meteorological data. The filter is described by the equation

$$Y(j) = \frac{1}{64}\sum_{i=-7}^{7}(8-|i|)\,X(j+i), \quad (3)$$

where $X(j)$ is an observation on the day j and $Y(j)$ a filtered value centered around j. The filtering was carried out by taking twice the moving average of 8 values (Blackman & Tukey, 1959, pp. 129–135). The filtered value on the day of the oceanographical observations was used and every fifth value of the filtered meteorological data prior to this date. For each year 32 values, spanning a time interval of 160 days, were analyzed.

The air temperature has a large annual variation which must be taken into account, and a complication arises because the oceanographical observations are not carried out on the same day each year. The average and a least squares estimate of a sine-wave with wavelength one year were subtracted from the filtered values, counting the time each year from the day of observation of T and S. This implies that in a year when the observation was carried out say on the 8th of August, the same adjustment was made to the values on 8/8, 3/8, 29/7 etc. as to the values on 28/8, 23/8, 18/8 etc. in a year when the observations took place on the 28th of August. This seems preferable to making the same adjustment to the same time of the year regardless of the day of observation. By this procedure some account is taken of the great difference it makes to the air temperature during the 160 days preceding the observation whether the observation is carried out in the beginning or at the end of August. The average was also subtracted from P, T and S, and in the following it will always be assumed that the mean of these variables is zero.

The data consist of a finite number of discrete values and equations (1) and (2) are replaced by the sums

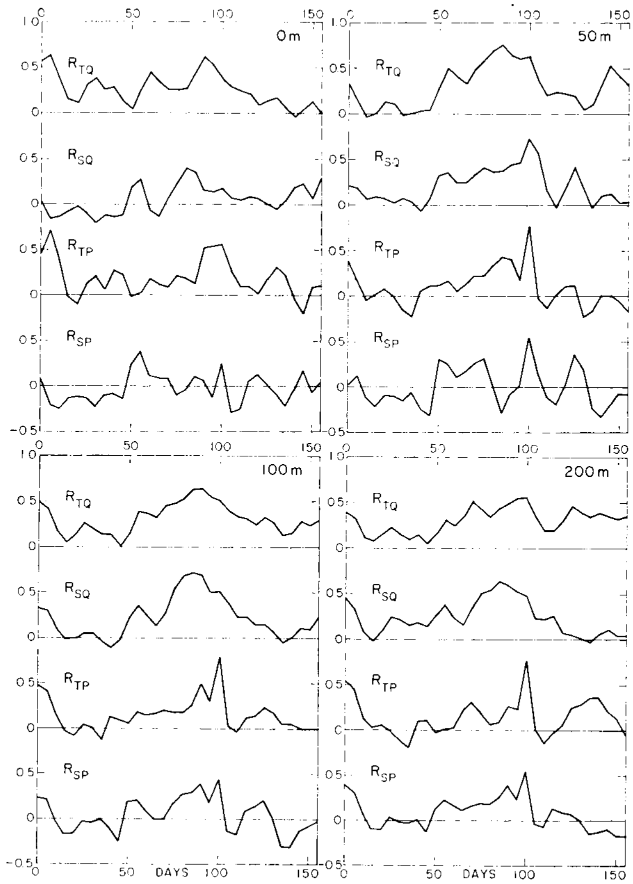

Fig. 2. Correlations of sea temperature (*T*) and salinity (*S*) with air temperature (*Q*) and pressure difference (*P*) as functions of time, at the sea surface, 50 meters, 100 meters and 200 meters.

$$T(j) = \sum_{i=0}^{31} W_{TP}(i)\,P(j-i) + \sum_{i=0}^{31} W_{TQ}(i)\,Q(j-i) + N_T(j), \qquad (4)$$

$$S(j) = \sum_{i=0}^{31} W_{SP}(i)\,P(j-i) + \sum_{i=0}^{31} W_{SQ}(i)\,Q(j-i) + N_S(j). \qquad (5)$$

The unit in the indices represents 5 days unless otherwise stated.

Before further investigating equations (4) and (5) we introduce the new functions

$$\left.\begin{aligned} C_{TP}(k) &= E[T(j)\,P(j-k)], \\ C_{PP}(k) &= E[P(j)\,P(j-k)] = C_{PP}(-k), \\ C_{PQ}(k) &= E[P(j)\,Q(j-k)] = C_{QP}(-k), \end{aligned}\right\} \qquad (6)$$

etc., and

$$R_{TP}(k) = C_{TP}(k)/[V_T\,V_P]^{\frac{1}{2}}, \quad \text{etc.,} \qquad (7)$$

where E stands for expectation and V_X is the variance of X. It will be assumed that the covariances of P and Q are independent of the time of the year and can be written as functions of time-lags only.

The number of observations that can be used for estimating C_{TP} and V_T in equation (7) is equal to the number of observations of T, but V_P is estimated from 32 values of P each year that T is measured. This makes R_{TP} somewhat different from usual correlation coefficients. Numerical estimates of R_{TP}, R_{TQ}, R_{SP} and R_{SQ} are presented graphically in Fig. 2.

By minimizing $E\,[N_T(j)^2]$ we obtain:

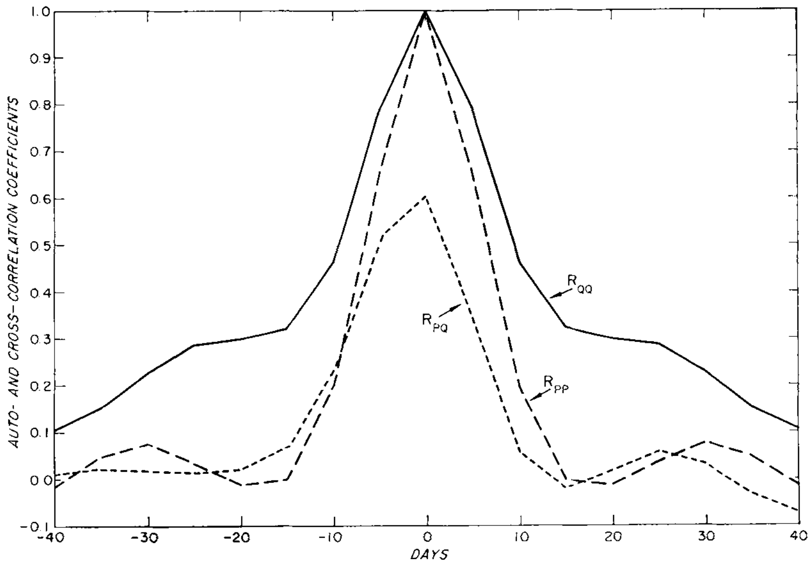

Fig. 3. Auto- and cross-correlation coefficients of air temperature (Q) and pressure difference (P) as functions of time.

$$\left.\begin{aligned} C_{TP}(k) &= \sum_{i=0}^{31} W_{TP}(i)\, C_{PP}(k-i) \\ &\quad + \sum_{i=0}^{31} W_{TQ}(i)\, C_{QP}(k-i), \\ C_{TQ}(k) &= \sum_{i=0}^{31} W_{TP}(i)\, C_{PQ}(k-i) \\ &\quad + \sum_{i=0}^{31} W_{TQ}(i)\, C_{QQ}(k-i). \end{aligned}\right\} \quad (8)$$

With k assuming the values 0–31 this provides 64 equations for solutions of the 32 values of W_{TP} and W_{TQ} respectively. Analogous equations for W_{SP} and W_{SQ} are obtained by minimizing $E[N_S(j)^2]$.

There are only 20 observations of each of the variables T and S and yet the cross-covariances C_{TP}, C_{TQ}, C_{SP} and C_{SQ} were estimated for 32 values of the time-lag. With such a small number of observations an attempt to estimate the 32 values of the weight functions in equations (4) and (5) is not justified. The obvious method of reducing the number of covariances by filtering over a longer time interval would fail if the physical relationship between the oceanographical and meteorological characteristics were confined to a few days. Covariances corresponding to longer time intervals are easily calculated from those of shorter intervals, but of course not vice versa. Fig. 2 shows that at most depths there are large covariances for $k = 0$ and 1 (0 and 5 days). After that most of the covariances are rather small for more than a month but increase again, and have a rather broad maximum at a time lag of about three months before the oceanographic observations.

Numerical results

Fig. 2 indicates that investigation of the maximum at 90 days prior to the oceanographic observations could be carried out with time interval longer than 8 days. We introduce the functions

$$\left.\begin{aligned} C'_{TP}(k) &= E\left[T(j) \sum_{l=-2}^{2} P(j-k+l)\right], \\ C'_{PQ}(k) &= E\left[\sum_{l=-2}^{2} P(j+l) \sum_{l=-2}^{2} Q(j-k+l)\right], \end{aligned}\right\} \quad (9)$$

etc., and use V'_P and V'_Q for the variance of the sum of five consecutive values of P or Q. We define also

$$R'_{TP}(k) = C'_{TP}(k)/[V_T V'_P]^{\frac{1}{2}}. \quad (10)$$

For the estimation of V'_P and V'_Q only values of $P(i)$ and $Q(i)$ 80–100 days ($i = 16$–20) before

Table 2. *Numerical estimates of maximum correlation coefficients*

Depth, m ...	0	20	50	75	100	150	200
$R'_{TP}(k)$	0.61	0.50	0.63	0.66	0.60	0.54	0.42
k (days)	95	100	90	90	90	90	90
$R'_{TQ}(k)$	0.50	0.44	0.73	0.72	0.63	0.64	0.53
k (days)	95	95	90	90	90	90	90
$R'_{SP}(k)$	0.09	0.01	0.15	0.31	0.42	0.46	0.48
k (days)	90	90	100	90	90	90	90
$R'_{SQ}(k)$	0.27	0.27	0.57	0.62	0.68	0.67	0.60
k (days)	85	90	95	95	85	85	85

the oceanographic observations were taken into account. This makes little difference to R'_{TP} and R'_{SP}, but R'_{TQ} and R'_{SQ} are considerably reduced compared to the results that would have been obtained by normalizing with V'_Q calculated from the values in Fig. 3. This is because the variance of the temperature at the time of the maximum is greater than the average variance over the whole time interval used in the investigation.

Table 2 shows R' for the value of k that gave the largest R'.

The choice of summing over 5 values of P and Q was arbitrary and for most depths a smaller number would have provided a larger R'_{TP} and a larger number a larger R'_{TQ}. In neither case would this make any great difference, nor would small changes in the choice of k.

The probability that a correlation coefficient calculated from n pairs of observations from non-correlated normally distributed variables is greater than given values or less than minus these values can be written

$$P[|\varrho_n| > x] = p \tag{11}$$

and for given values of p, x can be found from statistical tables (Fisher & Yates, 1963). Some hypotheses will now be tested concerning the correlation of temperature and salinity at station L with meteorological observations.

The robustness of the sample distribution of the correlation coefficient against deviations from normality of the population distributions of the variables was investigated by Gayen (1951). He found that when the population correlation coefficient $\varrho = 0$ the sample distribution is fairly robust even for small samples.

Tests for linear relationships can be based on the tails of the distribution of ϱ_n. The error due to non-normality in determining x for a given ϱ increases towards the tails of the distribution. Because of this we have used $p = 0.05$ in equation (11) throughout, although in many cases our results would also have been "significant" with a considerably lower p.

Investigation of histograms and comparison with the estimates of the standard deviations indicate that with the exception of the salinity in 1965 the assumption of normality is not unreasonable for our variables. But with only 20 observations small deviations from normality cannot be detected. Changes in the hydrographic or meteorological conditions since 1934 could disturb normality and so could the procedure applied for the seasonal adjustment of the air temperature.

For $p = 0.05$ and $n = 20$ the tables give $x = 0.44$. All except two values of R'_{TP} and R'_{TQ} are well above this level. This is a good support for the hypothesis that a positive correlation of T with P and Q is due to influx of warm Atlantic Water off Vestfirðir, provided there is sufficient evidence from observations other than those included in our estimates of R' that it takes the current about 90 days to flow the distance along the north coast of Iceland to Langanes.

If on the other hand we disregard all information except the data from which Table 2 is calculated the R's should rather be compared with x in the equation

$$P[|\varrho_{n,m}| > x] = 0.05, \tag{12}$$

where $|\varrho_{n,m}|$ is the largest value of $|\varrho_n|$ obtained from m samples of n pairs from a popula-

Table 3. *Numerical estimates of maximum correlation coefficients*

Depth, m ...	0	20	50	75	100	150	200
$R'_{TP}(k)$	0.75	0.58	0.77	0.78	0.74	0.70	0.55
k (days)	90	90	90	90	90	90	90
$R'_{TQ}(k)$	0.53	0.49	0.73	0.73	0.68	0.70	0.56
k (days)	85	80	85	85	85	90	90
$R'_{SP}(k)$	0.10	0.03	0.11	0.49	0.53	0.58	0.59
k (days)	90	90	90	80	90	90	90
$R'_{SQ}(k)$	0.28	0.26	0.57	0.69	0.74	0.74	0.65
k (days)	85	85	90	90	85	85	85

tion of non-correlated two-dimensional normally distributed stochastic variables. There is some question about the appropriate choice of m because of the serial correlation of P and Q, but it appears reasonable that the lowest values of k should be left out. With $m = 5$, $x = 0.56$. Even with some doubt regarding the distribution of our variables, several values in Table 2 ought to be significant at the 95 % level without the *a priori* assumption about a time lag of 90 days.

The correlation of P and Q with salinity is not significant at 0 or 20 meters depth. As the year 1965 was left out, n is 19 and for $p = 0.05$ in equation (9), x is 0.46. The largest correlation coefficient between the salinity and the pressure difference is 0.48 at 200 m depth, but the correlation with the air temperature is high at 50–200 m depth.

Fig 3 shows that there is a considerable correlation between the pressure difference and the air temperature, and using the same values of P and Q as in previous estimates of R', we get $R'_{PQ} = 0.59$. A high correlation between P and Q could lead to a significant correlation of both of these variables with the oceanographic variables, even if the causal relationship is only with one of the meteorological variables. This can be investigated by use of the partial correlation coefficients:

$$R'_{TP/Q} = \frac{R'_{TP} - R'_{TQ} R'_{PQ}}{\sqrt{(1 - R'^2_{TQ})(1 - R'^2_{PQ})}} \qquad (13)$$

and analogous for other partial correlation coefficients. $R'_{XY/Z}$ is the correlation coefficient of X and Y after that part of their variance which can be attributed to Z has been eliminated (Hald, 1957, p. 625).

In order to test the values of partial correlation coefficients the number of observations in equation (11) is reduced by one which gives $x = 0.46$ and 0.48 for the temperature and salinity respectively at the level of $p = 0.05$. The largest $R'_{TQ/P}$ is 0.57 at 50 m depth and the values at 75 and 150 m are also > 0.46. The largest values of $R'_{TP/Q}$ is 0.45 at 0 m. $S'_{SQ/P}$ is 0.59 at 100 m depth and the values for 50–150 m are > 0.48.

As will be discussed later, some change took place in the characteristics of the artctic water mixing with the eastflowing Atlantic Water after 1962. Therefore, a separate analysis was made for the period 1934–1962. Table 3 gives the results of the numerical estimates of R' for this period.

Most of the R's are larger than in Table 2, especially the correlation of the oceanographic observations with pressure difference. Because of the reduction in the number of observations the 95 % level is increased to 0.48 and for the partial correlation coefficients to 0.50. The outcome of the same tests as applied to the results from 1934–1964 or 1965 is similar. A noticeable exception are the partial correlation coefficients $R'_{TP/Q}$ and $R'_{TQ/P}$. $R'_{PQ}(0)$ is 0.63 when 1963–1965 are left out and as there is a 5 days difference in k for some depths, we also need $R'_{PQ}(-1)$, which is 0.62. The highest value of $R'_{TP/Q}$ is 0.63 at 0 m depth and the values at 50, 75 and 100 m are also > 0.50. The $R'_{TQ/P}$ are now all < 0.50. The roles have thus been reversed from the values in Table 2, where the temperature of the sea had a stronger correlation with the air temperature than the pressure difference. Regarding this somewhat peculiar result of the estimation of the partial correlation coefficients it should be pointed out that they are based on estimates of correlation coefficients from populations where $\varrho \neq 0$. Gayen (1951) shows that for large $|\varrho|$ estimates are sensitive to deviations from normality.

Prediction

If the weight functions are known, equations (4) and (5) can be used to predict $T(j)$ and $S(j)$. The properties of linear systems are completely determined by the various auto- and cross-covariances. They were estimated from the observations and because of the small number of observations the variance of the estimates is rather large. Equation (8) can be simplified by omitting all except a few of the largest covariances. Even then the solution of the weight functions is highly sensitive to small changes in the covariances and therefore a poor estimate of the true weight functions. In order to investigate the quality of a numerical prediction we return to the sum of the five filtered values of pressure and air temperature from 80–100 days before the oceanographical observations and call them P' and Q' respectively and write

$$T = W'_{TP} P' + W'_{TQ} Q' + N_T, \qquad (14)$$

$$S = W'_{SP} P' + W'_{SQ} Q' + N_S. \qquad (15)$$

By changing the physical dimensions so that the variances of T, S, P' and Q' are all equal to one, the correlation coefficients in Tables 2 and 3 are estimates of the covariances. As before, all these variables are deviations from mean values. These equations can be solved in the same way as equations (4) and (5) by minimizing the variance of of N_T and N_S and the solution is analogous to equation (8). In both tables the covariances vary with depth. With $E[T P'] = R'_{TP} = R'_{TQ} = 0.70$ and $E[P'Q'] = 0.60$ the solution of equation (14) gives $W'_{TP} = W'_{TQ} = 0.44$. The predicted deviation from the mean of the sea temperature is:

$$T_{\text{predicted}} = W'_{TP} P' + W'_{TQ} Q'. \qquad (16)$$

The quality of the prediction can be investigated by calculating the variance of the difference of the true value and the predicted value

$$E[(T - W'_{TP} P' - W'_{TQ} Q')^2] = E[N_T^2]. \qquad (17)$$

By using the values above, assuming that the variances and covariances are estimates and taking into account the number of degrees of freedom lost in estimating the weight functions (Rao, 1965, p. 186), the estimate of $E[N_T^2]$ is 0.43 and the standard deviation 0.66.

If no account is taken of meteorological or hydrographic observations the best prediction of T would probably be the average. Since the standard deviation of the sea temperature for 50–200 m depth is 0.87°–1.38°C (Table 1), the 95 % confidence limits are 1.83°–2.90°C. By using $T_{\text{predicted}}$ as defined by equation (16) the 95 % confidence range is reduced to about 66 % of this.

In practice prediction would be based on the calendar year rather than on a time scale measured from the August observation off Langanes. The average May air temperature at Kjörvogur, Grímsey and Raufarhöfn 1931–1960 was 3.9°C. The average pressure difference in May between Hólar and Stykkishólmur in the same years was 0.4 mb. Our estimates of the standard deviation of the average of the sum of five consecutive values of $P(i)$ and $Q(i)$ for this part of the year were 1.7 mb and 2.0°C respectively.

As an example we take a year when the average values of $P(i)$ and $Q(i)$ at 5/5, 10/5, 15/5, 20/5 and 25/5 are 1.9 mb and 6.0°C respectively. For a depth where the standard deviation of T is 1.2°C, $W'_{TP} = 0.44 \times 1.2/1.7$°C/mb and $W'_{TQ} = 0.44 \times 1.2/2.0$. The predicted value of the deviation from the mean of the sea temperature in mid-August at this depth

$$T_{\text{predicted}} = 0.44 \times 1.2 \left[\frac{1.5}{1.7} + \frac{2.1}{2.0}\right] = 1.0\text{°C}.$$

It should be emphasized that the reliability of the prediction will be considerably reduced, if the hydrographic conditions in the North Icelandic shelf area change due to other factors than influx of Atlantic Water, such as was the case during the years 1963–1967.

Discussion

The statistical analysis confirms the hypothesis of a strong connection between the oceanographic conditions off Langanes in August and meteorological factors about 90 days prior to the observation. As we have shown, this time lag corresponds closely to the expected one, if we assume that the influx of Atlantic Water to the shelf area northwest of Iceland is primarily governed by meteorological factors.

Previous investigations based on data from 1934–1960 indicated a closer correlation than here found. The explanation of this difference is partly that in the previous studies temperature and salinity observations, made at different dates in August, were correlated with the mean monthly meteorological values for May rather than 80–100 days before the actual observations. This affected especially the year having the largest deviations, viz. 1949, and led to a higher correlation than here found, where the dates of the observations have been taken into account. Another explanation, although of minor importance, is that the previous investigations had indicated that pressure differences between Stykkishólmur and Djúpivogur gave a slightly closer correlation with the hydrographic conditions than did the pressure differences between Stykkishólmur and Dalatangi or Hólar. These explanations, however, do not account for the whole difference, which must therefore be partly attributed to the observations made after 1960.

In this study it has been assumed that Atlantic Water entering the North Icelandic shelf area from the Irminger Sea mixes with winter water and/or arctic water of relatively uniform characteristics. This holds approximately true up to the year 1962. Investigations made in 1963 (Istoshin & Shmarina, 1965, Jónsdóttir, 1965) and 1964–1967 (Malmberg, 1967) show clearly a much greater polar influence in arctic waters of the oceanic area between northeast Iceland and Jan Mayen than in the preceding years. Thus within the area between 67° and 69° N and 11° and 15° W, the mean values of temperature and salinity in the uppermost 100 meters of water were 1.44°C and 34.83 ‰ respectively for the period 1950–1958, but 0.17°C and 34.58 ‰ respectively for the period 1964–1967. It follows that during the last few years the water component mixing with Atlantic Water has been considerably colder and less saline than before. Furthermore, the distribution of drift ice in the North Icelandic coastal area has been greater in the years 1963, 1965 and 1967 than during the preceding three decades. These cirumstances explain the relatively poor correlation found between meteorological factors and temperature and salinity after 1962. Since the salinity decrease is even more conspicuous than the temperature decrease, the correlation of meteorological factors with salinity is affected to a greater extent than the correlation with temperature.

Near the sea surface the characteristics of the inflowing Atlantic Water are modified by a number of external factors, such as short-periodical heating and cooling, upwelling due to winds, drift ice, fresh water run-off and precipitation. On the other hand, the proportion of Atlantic Water decreases with depth, especially below 150 meters, and the maximum retention of orginal characteristics is found below the seasonal thermocline, usually within an intermediate layer between 50 and 200 meters. Therefore, the highest correlation of sea temperature or salinity with meteorological conditions in the past would be expected for intermediate depths which is essentially what the results of the numerical analysis show. It will be noted, however (Tables 2–3), that the correlation with sea temperature has a maximum for depths of 50 and 75 meters, but the correlation with salinity has a maximum for depths of 100–200 meters. Furthermore, the correlation with temperature is significant for 0 and 20 meters, whereas with salinity it is not. These results are easily explained by the fact that salinity is much more sensitive to external factors than is temperature.

It will be seen from Fig. 2 that while the correlation as a function of time has a maximum for a time lag of about 3 months, there exists a significant correlation between the sea temperature and the concurrent air temperature or pressure difference. This concurrent correlation is greatest for the surface layer, as would be expected, but it is also significant for depths $\geqslant 100$ m. With regard to the surface layer it can be explained by variations in solar radiation affecting simultaneously the temperature of the air and the sea surface, but conduction of heat from the sea to the air may also contribute to the correlation found. Another explanation referring to depths below the thermocline is that northerly winds, generally associated with low air temperatures, may give rise to geostrophic currents in the wind direction causing an intrusion of cold, subsurface arctic water from the north, whereas southerly winds east of Langanes may prevent such an intrusion.

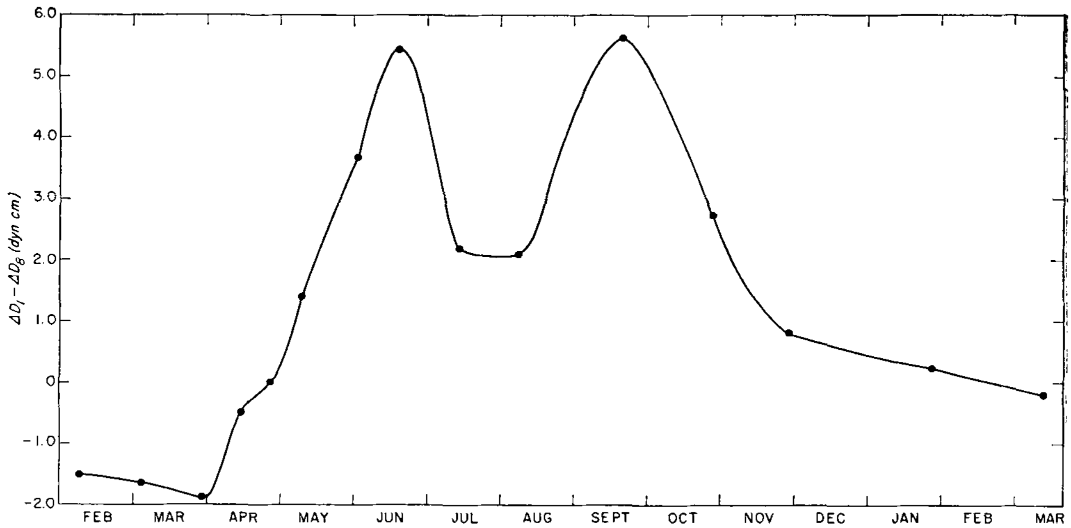

Fig. 4. Seasonal variations of the difference in dynamic height of the sea surface relative to the 300-decibar surface between stations F-1 and F-8.

While the results of the numerical analysis indicate that hydrographic conditions east of Langanes are significantly correlated with both air temperatures and north-south winds during the preceding 80–100 days, the correlation with air temperature is with one exception considerably stronger. Therefore, it appears that the air temperature is a more important factor, although the hypothesis of an independent effect of the wind cannot be rejected.

It remains to explain how the air temperature can affect the influx of Atlantic Water to the area north of Iceland. This is best done by considering seasonal variations.

On the basis of hydrographic data collected during the years 1953–1955 it was concluded (Stefánsson, 1962, pp. 178–183) that the rate of the coastal current north of Iceland changes seasonally, leading to corresponding changes in the influx of Atlantic Water. Since wind conditions are known to be highly unstable in the vicinity of Iceland and seasonal trends slight, it seems hardly possible that the relatively regular seasonal change in the Atlantic influx to the region north of Iceland results from seasonal variations in the prevailing wind system. There is, however, a seasonal change in the density distribution in the shelf area. During winter the coastal water is cooled to a greater extent than the offshore water, the reverse process taking place in summer. This leads to seasonal change in the horizontal density gradient causing increased anticyclonic coastal circulation in summer, decreased circulation in winter. By frictional effects these changes in the coastal circulation should in turn give rise to corresponding changes in the movement of Atlantic Water farther offshore. An evidence for such seasonal changes in the northgoing current west of Iceland is furnished by Fig. 4 which shows the difference in dynamic height between an offshore station and a nearshore station in Faxaflói. While variations in run-off and winds also affect the horizontal density gradient in the coastal area and thus obscure the relationship somewhat, there exists a significant correlation between air temperature and dynamic height differences across the shelf. A similar result was found for the area north of Iceland (Stefansson, 1962, Fig. 118).

But if this explanation of seasonal variations in the influx of Atlantic Water is true, it follows that *in years with unusually high air temperature*, say in spring, and hence a more intensive warming up, the eastflowing current north of Iceland must be relatively strong. Conversely, following a cold spring, the coastal current will be more sluggish and less Atlantic Water will penetrate the North Icelandic area. Superimposed on these variations related to the density distribution will be those caused directly by the wind conditions.

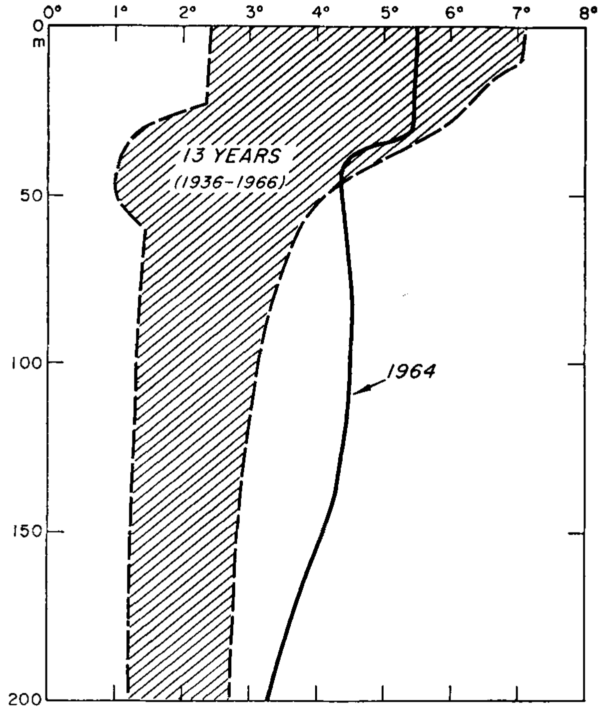

Fig. 5. Variation of temperature with depth at station L, June 13, 1964 (*solid line*), and range of temperature variations for 13 years in the period 1936–1966 (*shaded area*).

A further support for our postulate is provided by observations made east of Langanes at station L in June 1964. Compared to the August variations at this station the variations in June are normally relatively small. The year 1964 constitutes an exception, since then abnormally high temperatures were found at subsurface depths (Fig. 5). The mean air temperature for March 1964, i.e. about three months prior to the hydrographic observations, was the second highest recorded during this century. Southerly winds were also predominant during March 1964.

The deviations from the model described by equations (1) and (2) probably arise mainly from two sources: (*a*) changes in the hydrographic conditions of the area north of Iceland that are unrelated to the inflow of warm Atlantic Water, e.g. admixture of polar water from the northwest and variations in the characteristics of the arctic water mixing with the Atlantic Water and (*b*) the tacit assumption made that approximately the same current velocity, and hence the same time lag, applies to all observations. In view of the variability of the rate of the coastal current the validity of this assumption is certainly questionable. The rather broad maximum shown in Fig. 2 between 2 and 4 months prior to the observations also suggests that the appropriate time lag may be variable. Finally, it is of interest to note that whereas the correlation with pressure difference is alternately positive or negative for more than a month before the observations, the correlation with air temperature is predominantly positive. This can be explained by several factors: (*a*) there will be a direct exchange of heat between sea and air, and a parcel of warm sea water may continue to warm the overlying air masses over a considerable period after this parcel has entered the North Icelandic area, (*b*) prevailing high (low) air temperature may continue to intensify (reduce) the eastward flow of Atlantic Water and lead to increased (decreased) distribution of this water and less (greater) mixing with colder water masses, (*c*) due to the autocorrelation of the air temperature (Fig. 3) positive correlation coefficients tend to extend over a longer time interval than does the physical connection. Corresponding effects of air pressure will be either smaller or non-existing.

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ГИДРОГРАФИЧЕСКИЕ УСЛОВИЯ ВБЛИЗИ СЕВЕРО-ВОСТОЧНОЙ ЧАСТИ ИСЛАНДИИ В СВЯЗИ С МЕТЕОРОЛОГИЧЕСКИМИ ФАКТОРАМИ

Заново исследуется и проводится статистический анализ взаимосвязи между океанографическими и метеорологическими параметрами северо-восточной части Исландии. Анализ подтверждает высказанную ранее гипотезу о сильной корреляции между океанографическими условиями к востоку Ланганеса, северо-восточная Исландия, и температурой воздуха и северными ветрами за 90 суток до наблюдений. Поскольку известно, что гидрографические условия севера Исландии сильно зависят от притока атлантических вод из Ирмингеровского моря, а среднее время переноса этих вод от северо-западного побережья в район к востоку от Ланганеса порядка 3 месяцев, то такое временное запаздывание хорошо соответствует ожидаемому. Результаты численного анализа показывают, что температура воздуха является более важным фактором, чем ветер, хотя гипотеза о независимости влияния ветра не может быть отвергнута. Представляется, что температура воздуха косвенным образом влияет на поток атлантических вод: изменения температуры воздуха проводят к соответствующему изменению горизонтального градиента плотности в поперечном к шельфу направлении, посредством чего и оказывается воздействие на прибрежную циркуляцию. Приводятся некоторые данные, подтверждающие эти заключения.