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Seasonal and year-to-year variations in surface salinity at the nine North-Atlantic Ocean Weather Stations

Ocean Weather Stations
Surface temperature
Surface salinity
Climatic trends
North Atlantic
Stations météorologiques océaniques
Température superficielle
Salinité superficielle
Tendances climatiques
Atlantique Nord

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ABSTRACT

Time series are presented showing the year-to-year variation of salinity and temperature from 1948 to 1977 for each season at the nine North-Atlantic Ocean Weather Stations. By comparing the time series with each other and with estimates of evaporation and precipitation in the context of the seasonal cycles of salinity and temperature, the importance of different processes to the interannual variations is assessed.

At all the stations, there was a similarity between year-to-year variations of salinity and temperature in some seasons, and between annual means at most stations, indicating that changes in oceanic advection were an important cause of salinity and temperature changes. There is evidence that water of anomalous salinity or temperature tended to be carried along with the North-Atlantic Drift and the Irminger Current.

Whereas the mean seasonal cycle of temperature shows similar timing at all the nine Weather Stations, the seasonal salinity cycle varies considerably. A large part of this variation appears to be the result of the spread of low salinity water from the northern regions during the spring to autumn months. The interannual changes of salinity during the past two decades have tended to reflect this, for salinity anomalies have tended to propagate southwards during the summer months. Thus, since the early 1960's, there has been an increase in the low salinity water reaching station Bravo in the summer, and station Charlie in the autumn. There are indications of a similar spreading of low salinity water from India to Juliett, and then to Kilo.

At stations Alpha, India and Juliett, evaporation changes may cause salinity fluctuations on occasion, especially in the winter and autumn, which are the seasons of strongest evaporation. Comparisons of salinity changes with precipitation estimates were inconclusive.

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RÉSUMÉ

Variations saisonnières et interannuelles des salinités et températures superficielles aux neuf stations météorologiques de l'Atlantique Nord.

Les variations interannuelles de la salinité et de la température aux neufs stations météorologiques de l'Atlantique Nord sont présentées pour chaque saison de la période 1948 à 1977. En comparant les séries temporelles les unes avec les autres et avec des estimations de l'évaporation et de la précipitation, on évalue l'importance relative des différents processus pour expliquer les variations interannuelles observées.

A toutes les stations météorologiques, il existe des similarités, d'une part entre les variations interannuelles de salinité et de température en quelques saisons, et d'autre part, pour presque toutes les stations, entre les moyennes annuelles, indiquant que des changements par advection océanique sont importants. Il paraît évident que de l'eau de température ou salinité anormale est entraînée par la dérive Nord-Atlantique et par le courant d'Irminger.

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Tandis que le cycle saisonnier moyen de température est semblable de station à station, le cycle saisonnier de salinité varie considérablement. Une grande partie de cette variation semble résulter de la diffusion d'eau de basse salinité provenant des régions du Nord, du printemps à l'automne. Les changements interannuels de salinité pendant les deux dernières décades confirment ce phénomène, car les anomalies de salinité tendent à se propager vers le Sud pendant l'été. Ainsi, depuis les premières années soixante, il y a eu un accroissement de l'eau de basse salinité arrivant à la station Bravo en été et à la station Charlie en automne. Il semble qu'une propagation semblable d'eau de basse salinité s'effectue de India à Juliett, et ensuite à Kilo.

Aux stations Alpha, India et Juliett, les changements d'évaporation peuvent quelquefois causer des fluctuations de salinité, surtout en hiver et en automne qui sont les saisons où l'évaporation est la plus forte. La comparaison des changements de salinité avec les estimations de précipitation est peu concluante.

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INTRODUCTION

Long-term temperature changes in the North Atlantic and their relationship to climatic variations have been discussed by a number of authors (e. g. Bjerknes, 1964; Dickson *et al.*, 1975; Fieux, Stommel, 1975; Colebrook, 1976; Cushing, Dickson, 1976; Kukla *et al.*, 1977; Pocklington, 1978). Trends in sea temperature at the nine North Atlantic Ocean Weather Stations (OWS's, see Fig. 1) have been described by Rodewald (1972*a*, *b*), and also by Colebrook and Taylor (1979), and Taylor (1978). This paper discusses the surface salinity changes at these stations during the last two decades, in relation to these temperature changes and in the context of the seasonal cycles of salinity and temperature in the North Atlantic. The relative importance of evaporation changes and water mass movements in causing the year-to-year salinity changes is considered. Trends in the marine ecosystem are often compared to the simultaneous salinity changes. Therefore, as year-to-year salinity changes can be caused by several processes, it is necessary, when attempting to relate a planktonic change to a salinity change, to understand the origin of the latter. A fall of salinity due to an increased flux of low salinity water will have different biological consequences from those of a fall of salinity due to decreased evaporation or increased precipitation.

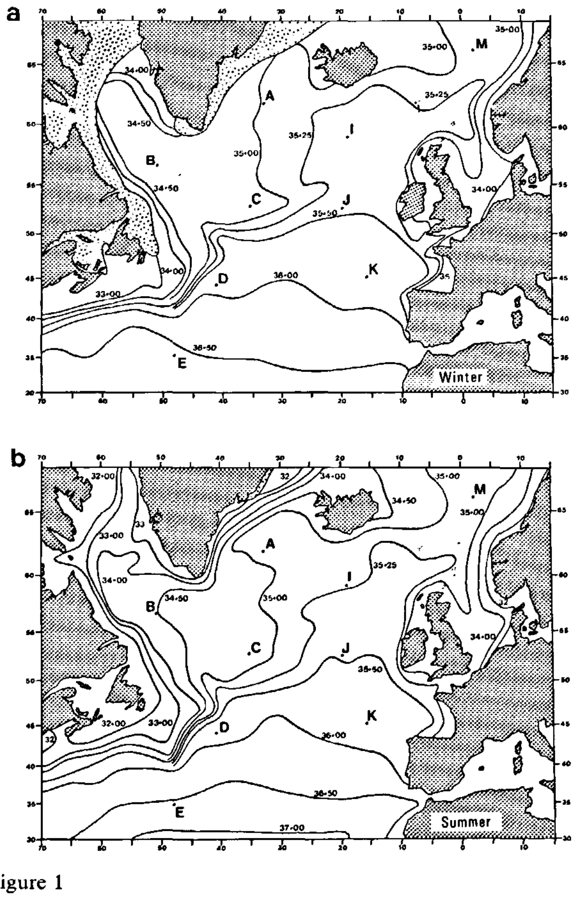

Figure 1

Nine Ocean Weather Stations and the salinity distribution of the North Atlantic, (a) winter (January to March) and (b) summer (July to September). Re-drawn from US Naval Oceanographic Office, 1967.

DATA

The data used in this study were obtained mainly from J. Smed of the International Council for the Exploration of the Sea, but additional data were assembled from copies of weather ship log-sheets, which were supplied by the U.K. Meteorological Office.

Tabulated oceanographic data for the North Atlantic Ocean Weather Stations, and the methods by which they were obtained, have been published in McGary and Morse (1964), Morse and McGary (1964), McGary (1965), Husby (1966, 1967, 1968*a*, *b*, 1969), Shuhy (1969*a*, *b*, 1974), Hannon (1974, 1976), Hammond (1973), Rosebrook (1971) and Mosby (1963, 1964, 1965, 1971). Oceanographic measurements have been carried out at the five eastern stations, Alpha, India, Juliett, Kilo and Mike, since the early 1950's and at the western stations Bravo, Charlie, Delta and Echo, from the mid-1960's.

Evaporation rates were estimated using the data of Pflugbeil and Steinborn (1963), with additional data for later years provided by the U.K. Meteorological Office.

RESULTS

Figure 1 shows the position of the nine OWS's (Alpha: 62°N 33°W; Bravo: 56°30'N 51°W; Charlie: 52°45'N 35°30'W; Delta: 44°N 41°W; Echo: 35°N 48°W; India: 59°N 19°W; Juliett: 52°30'N 20°W; Kilo: 45°N 16°W; Mike: 66°N 2°E) superimposed on charts of the winter (*a*) and summer (*b*) salinity in the North Atlantic.

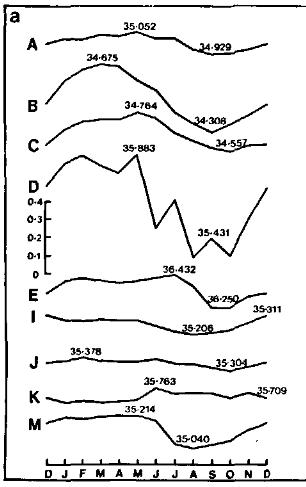

Figure 2 *a*

Long-term monthly mean sea surface salinities and temperatures at the nine Ocean Weather Stations.

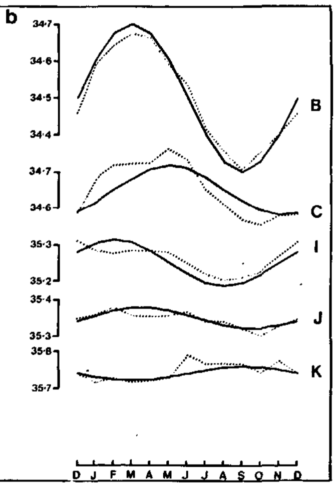

Figure 2 *b*

Predicted (unbroken line) and observed (dotted line) seasonal salinity variations at (B) Bravo, (C) Charlie, (I) India, (J) Juliett and (K) Kilo.

Descriptions of the water masses and currents at the stations are included in the data reports listed in the previous section and also in Rodewald (1972*a*), Ellett and Martin (1973) and Mosby (1972) (note that in all figures and tables, the weather stations are represented by their initial letters).

Figure 2*a* shows, the seasonal cycles of sea surface salinity, based on long-term means, at each of the nine stations. The number of observations averaged in calculating each of the mean values varies between stations: Alpha, 320; Bravo, 174; Charlie, 149; Delta, 143; Echo, 157; India, 596; Juliett, 492; Kilo, 86 and Mike, 588; and the number of years covered were: Alpha, 19; Bravo, 10; Charlie, 8; Delta, 8; Echo, 7; India, 26; Juliett, 27; Kilo, 14; and Mike, 28. Both the amplitude and phase of the salinity cycle vary considerably from station to station, in marked contrast to the seasonal cycle of sea-surface temperature in which there is no variation in phase, and the peak temperature occurs in August at all the stations (cf. Colebrook, Taylor, 1979).

Time-series of annual means, and means for each season of salinity and temperature are plotted in Figures 4 to 7 respectively. The seasons used correspond to the oceanic heating cycle, namely, winter: January to March; spring: April to June; summer: July to September; and autumn: October to December. The average number of records used in calculating a seasonal mean at each of the stations was: Alpha, 42; Bravo, 50; Charlie, 50; Delta, 45; Echo, 61; India, 97; Juliett, 80; Kilo, 33 and Mike, 42. The relative magnitude of the seasonal and the interannual variations can be seen by comparing Figures 4 to 7 with Figure 2. The variance between years was between one tenth and one half of the variance within the seasonal cycle at all stations, except for Juliett and Kilo at which the interannual fluctuations and the seasonal cycle had variances of approximately equal magnitude.

Table 1 expresses the persistence, from season to season, of both salinity and temperature at stations Alpha, India, Juliett and Mike. In general, at these stations, persistence of salinity is at least as high as that of temperature. Although this persistence extends over several seasons, the correlation coefficients between the means from non-adjacent seasons are smaller, and decline as the separation of the seasons increases. The similarity of the salinity trends in adjacent seasons supports the view that these are real, and not just the result of inadequate observations.

The fluctuations in temperature shown in Figures 4 to 7 agree with those presented in previous studies. For example, the decline in annual mean temperature at Charlie (Fig. 5*b*) agrees with that reported by Kukla *et al.* (1977) for this station. The trend at stations Alpha, India and Juliett (Figs. 4 and 6), which peaked in the middle of the 1960's, has been presented in the context of the temperature changes during the last century by Colebrook (1976). The time-series of winter temperatures at Echo (Fig. 5*d*) agree with the series of March temperatures at this station shown by Fieux and Stommel (1975). The discrepancy noticed by Fieux and Stommel between temperatures at Echo and those obtained from ship-reports was much less marked during the period covered by this study (1966 to 1973). Finally, both the time-series of seasonal temperature anomalies and that of seasonal salinity anomalies at Kilo have power spectra which clearly show the biennial oscillation obtained by Servain (1980) from a longer data set. The seasonal anomalies at Alpha, India, Juliett and Mike are dominated by trend and do not show clear peaks.

Included with each of the graphs of Figures 4 to 7, is the corresponding correlation coefficient between the time series of salinity and temperature, nearly all of them are positive. The similarity of salinity and temperature trends, which is discussed in a subsequent section, provides further evidence for the reality of the year-to-year variations in salinity.

In the following sections, some of the processes causing these interannual variations are inferred by examining

Table 1

Correlation coefficients between mean values in adjacent seasons.

	Salinity				Temperature			
	A	I	J	M	A	I	J	M
Winter/spring	0.73 (***)	0.74 (***)	0.65 (***)	0.71 (***)	0.37	0.63 (***)	0.59 (**)	0.28
Spring/summer	0.74 (***)	0.82 (***)	0.55 (***)	0.42 (*)	0.48 (*)	0.55 (**)	0.44 (*)	0.48 (*)
Summer/autumn	0.76 (***)	0.88 (***)	0.60 (***)	0.50 (**)	0.65 (**)	0.56 (**)	0.66 (***)	0.48 (*)
Autumn/winter	0.42	0.79 (***)	0.56 (**)	0.72 (***)	0.56 (*)	0.62 (***)	0.72 (***)	0.33
No. of years	18	26	27	26	18	26	27	26

(*) $P<0.05$; (**) $P<0.01$; (***) $P<0.001$.

these time series in the context of seasonal change. For the eastern stations, correlation coefficients can be used to express relationships, but for the stations Bravo, Charlie, Delta and Echo, the time-series are relatively short and the correlation coefficients are less useful.

Evaporation and precipitation

Part of the variability of the seasonal salinity cycle will result from variations of the cycles of evaporation and precipitation between stations. Figure 3 *a* shows the mean seasonal cycle of evaporation at the nine OWS's for the period 1951-1960, calculated using the method of Bunker (1976). These curves are in agreement with those given by Malkus (1962) and Bunker (1976). It is clear from Figure 3 *a* that the shapes, if not the amplitudes, of all the curves are similar, and the timings of the periods of maximum and minimum evaporation show little variation between stations. As periods of high and low salinity correspond to the periods of high and low evaporation at most stations, seasonal fluctuations in evaporation appear to contribute to the seasonal cycle of salinity.

Assessing rainfall over ocean areas is difficult (World Meteorological Organization, 1976). However, Britton (World Meteorological Organization, 1976) has estimated mean monthly precipitation for the period 1962-1973, for the three eastern stations, India, Juliett and Kilo, and combining these results with the data from Figure 3 *a*, the mean seasonal cycle of evaporation minus precipitation can be estimated (Fig. 3 *b*). Note that there is a net loss of water from the surface throughout the year, especially at Kilo, and this water must be replaced by advection. A comparison of the salinity curves (Fig. 2) with the graphs of Figure 3 *b* shows that the periods of high and low salinity broadly correspond to those of high and low evaporation minus precipitation, but the agreement is not close and differences in phase and amplitude between the salinity cycles at India and Juliett cannot be accounted for. The closest agreements are for stations India and Kilo, where the amplitude of the cycles of salinity would require annual average mixing from the surface to a depth of about 65 m. An annual sinusoidal surface loss of water $E_0 \cos \omega t$ produces a salinity cycle in a mixed layer of constant depth (h) of $S = S_0 \sin \omega t$, the amplitude of this cycle being $S_0 = 35 E_0/(\omega h)$. With E_0 (the amplitude of the evaporation minus precipitation cycle) equal to 60 cm year^{-1}, ω equal to 1 cycle year^{-1} and S_0 equal to $0.05^0/_{00}$, h is $\sim$65 m.

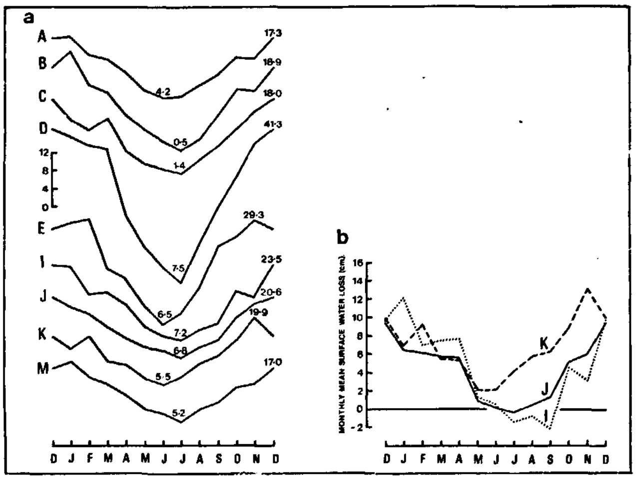

Figure 3 *a*

Mean monthly evaporation (cm) at the nine Ocean Weather Stations.

Figure 3 *b*

Mean monthly evaporation minus precipitation (cm) at stations India, Juliett and Kilo.

For stations India and Juliett (1951-1974), Alpha (1951-1970) and Mike (1951-1970), time series of monthly mean evaporation rates were calculated from monthly mean meteorological data. A comparison with evaporation rates calculated from six hourly meteorological data at India and Juliett for 1972-1974 showed that the estimates from monthly data gave reliable month to month variations, even after the seasonal variations had been removed. Table 2 contains the results of correlating the seasonal mean evaporation rates with the seasonal means of salinity and temperature. None of the correlation coefficients calculated for station Mike approached significance. At each of the remaining stations, the highest correlation coefficient between salinity and evaporation occurred in the winter and autumn, the seasons of highest evaporation rates. Table 2 shows sea surface temperature and evaporation to be positively related although often only weakly, at all stations except Mike. This might be expected from the use of sea-surface temperature in the calculation of evaporation rates, but whether there is a real relationship between year-to-year changes in sea temperature and evaporation or whether the relation results from a systematic inaccuracy in the evaporation estimates is uncertain.

Stations Alpha and India, which are adjacent, have high correlations between salinity and evaporation in the winter. This particular importance of evaporation in the winter may be the reason why the winter salinities at these stations show a strong correlation (0.84***), which is not shown in the spring, summer and autumn

Table 2

Correlation coefficients between salinity and evaporation, and temperature and evaporation, during different seasons at stations Alpha, India, Juliett and Mike.

	Salinity				Temperature			
	A	I	J	M	A	I	J	M
Winter	0.62 (**)	0.61 (**)	0.37	0.08	0.07	0.24	0.27	−0.20
Spring	0.33	0.60 (**)	0.27	−0.29	0.09	0.50 (*)	0.27	−0.20
Summer	0.17	0.23	0.35	−0.27	0.13	0.46 (*)	0.12	0.34
Autumn	0.18	0.79 (***)	0.52 (**)	−0.12	0.27	0.37	0.19	0.00
No. of years	16	23	24	17	16	23	24	17

(correlation coefficients: 0.26, 0.38 and 0.03, respectively).

The salinity variations at stations India and Juliett were also compared with Britton's estimated monthly precipitation rates (1962 to 1973) for these stations. Although there is generally a slight inverse relation (correlation coefficients as large as −0.4) between the salinity time series at these stations and seasonal means of this precipitation data, none of the correlation coefficients reached significance. However, the precipitation estimates may not be sufficiently accurate to reveal a relationship with salinity.

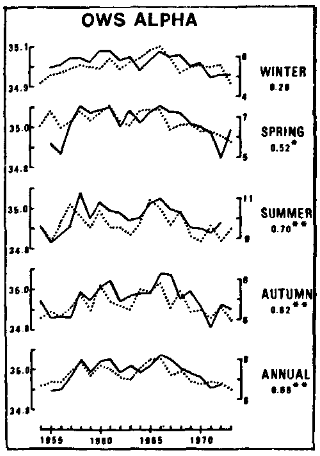

Figure 4

Station Alpha: interannual variation of salinity (unbroken line) and temperature (dotted line) by season. The correlation coefficients between the salinity and temperature time-series are included ($P < 0.05$; ** $P < 0.01$; *** $P < 0.001$).*

Seasonal low salinity flux

In this section, the seasonal and interannual variations in the surface salinity at the Ocean Weather Stations is discussed in relation to the salinity changes in the northern and coastal regions of the North Atlantic. Seasonal salinity fluctuations can be traced from the Grand Banks area eastward (Neumann, 1940; Smed, 1943; Defant, 1961). It is likely that these changes are the result of periodic salinity fluctuations in the Labrador Current, which injects low salinity water into the North-Atlantic Current; this is spread by mixing and turbulent diffusion in north-easterly and south-easterly directions. This flux of low salinity water is strongest in the summer, causing a large drop in the salinity at Bravo (Figs. 1 and 2 *a*), and may be responsible for the smaller fall in the salinity at Charlie about two months later (Fig. 2 *a*). At each station the fall in salinity is confined, approximately, to the upper 100 m. The spreading of this low salinity layer during summer can be seen in sections for 1958 published by Dietrich (1969).

To illustrate this process, consider the Labrador Current as a periodically varying source of low salinity water, $\bar{S} + S_0 \sin \omega t$ (where $\bar{S}$ is its mean salinity and S_0 is its seasonal amplitude), which is diffusing in one dimension from $x=0$ to a sink at $x=X$. By solving the diffusion equation:

$$\frac{\partial S}{\partial t} = A \frac{\partial^2 S}{\partial x^2}, \qquad (1)$$

where A is a constant diffusion coefficient, the salinity variation at any point x is approximately:

$$S = \bar{S}\left(\frac{X-x}{X}\right) + S_0 e^{-kx} \sin(\omega t - kx), \qquad (2)$$

providing $X \gg k^{-1}$ (with $k = \sqrt{\omega/2A}$). Equation (2) shows that the annual mean salinity increases linearly from $x=0$ to $x=X$, while the seasonal cycle is damped and phase-shifted with increasing x. Figure 2 *b* applies this result to the seasonal variations of salinity at five of the nine weather stations. As the appropriate value of X is not known and the first term of equation (2) merely determines the spatial variation of the annual mean salinity, this term has been neglected in the calculations, the curves of predicted values being plotted, so that their annual means correspond with the observed values. The top graph (B) shows the seasonal salinity curve at Bravo together with a fitted sine curve, this station being taken as $x=0$. Curve C shows the predicted salinity variation at Charlie ($x = 1\,079$ km), when ω has the value 1 cycle year^{-1} and $A = 10^5$ m^2 sec^{-1} (therefore $k = 9.98 \times 10^{-4}$ km^{-1}), together with the observed salinity variation. This simple calculation reflects the change in the amplitude and phase of the seasonal cycle between Bravo and Charlie. This value of A was found to give a reasonable estimate of the phase shift between the stations, and to be compatible with published values; for example Stommel (1949) estimated a value of 2.3×10^4 m^2 sec^{-1} in the Gulf Stream region; Neumann (1940) obtained 5×10^4 m^2 sec^{-1} from a study of surface salinities to the east of the Grand Banks, and Adem (1970) has used 3×10^4 m^2 sec^{-1} in model calculations. The value represents the dispersion of the turbulent surface layers.

At any instant, the rate of flow of low salinity water can be estimated by using equation (2) to calculate $A(\partial S/\partial x)$. The seasonal term of the equation corresponds to a salinity flux which, at Bravo, oscillates seasonally between $\pm 2.82 \times 10^{-2}$ ‰ m sec^{-1}. Taking this salinity flux to be a flow of freshwater which is mixing with a 100 m thick layer of 35‰ saline water, the flux of freshwater per unit width varies over a range $(2 \times 2.82 \times 10^{-2}) \times 100/35 = 0.161$ m^2 sec^{-1}, and if this freshwater flow leaves the Davis Strait as a band 1 000 km wide then this total flow of water has a seasonal range of 161 000 m^3 sec^{-1}.

The year-to-year salinity variations at Bravo and Charlie are consistent with this interpretation of their seasonal

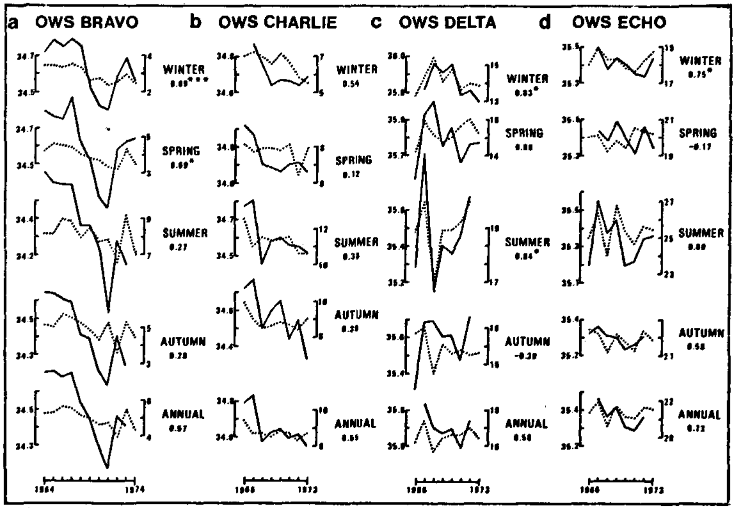

Figure 5 *a*

Station Bravo: see legend of Figure 4.

Figure 5 *b*

Station Charlie: see legend of Figure 4

Figure 5 *c*

Station Delta: see legend of Figure 4.

Figure 5 *d*

Station Echo: see legend of Figure 4.

changes. The most striking feature of the time-series from station Bravo (Fig. 5 *a*) is the decline of mean summer salinity between 1964 and 1971, the resulting low salinity values being maintained to 1973. There has been no corresponding trend in summer temperatures at Bravo, and the data of Shuhy (1974) shows that for the period up to 1969 (the period covered by Shuhy), the trend was confined to the upper 100 m. Therefore, there appears to have been an increase in the melt-water and runoff reaching station Bravo *via* the Labrador Current. The charts of Dickson *et al.* (1975) show that between the late 1960's and the early 1970's, there was a general reduction of atmospheric pressure in winter over the Hudson Bay – Baffin Bay area, with an increasing tendency for winds to blow out of the Davis Straits during this period. If this is so then it is to be expected that the decline of summer salinity at Bravo should be followed by a decline of the autumn salinities at Charlie. This is seen to be the case (Fig. 5 *b*), the correlation coefficient between the time-series being 0.83 ($P<0.01$), and the decline of salinity at Charlie is much more marked in the autumn than in any other season. The autumn salinity trend at Charlie is half the summer salinity trend at Bravo, which lies between the ratio predicted by the model calculations of the last section (0.3) and the observed ratio of the seasonal salinity cycles at Charlie and Bravo (0.6).

Figure 2 *a* suggests that the calculation leading to Figure 2 *b* curves B and C, can be applied to stations India and Juliett, for the season of low salinity at Juliett occurs later, and has a smaller amplitude than at India. In this case, the salinity at India is determined by the seasonal variation in the East Iceland Current, the additional low salinity water in the summer spreading southwards towards Juliett (compare Fig. 1 *a* and *b*). If a sine curve is fitted to the seasonal cycle at India (Fig. 2 *b*, Curve I), the predicted curve for Juliett ($x=780$ km) using the same values for ω, A, k, as above, is that shown in Figure 2 *b*, Curve J. These results are consistent with a seasonal southward dispersion of low salinity water, and Ellett and Martin (1973) inferred a similar southward dispersion in the Rockall Channel. Dispersion from India to Juliett is against the prevailing winds. However, winds are very variable in this area, and July and August, the months in which the southward dispersion effect would be strongest, are the months with the weakest southerly wind components (e. g. Lamb, 1972, p. 180).

The calculation for India and Juliett implies that summer salinity anomalies at station India should spread southwards to Juliett, and there are indications of this occurring. The summer salinity at Juliett has correlation coefficients of 0.40*, 0.63*** and 0.75*** with the winter, spring and autumn salinities at India, but 0.83*** with the summer salinity at India. The other seasonal comparisons show much lower correlations. The time lag expected between the arrival of low salinity water at India and Juliett is of the order of one month. When the time series of June salinity at India is correlated with those for June, July and August at Juliett, the correlation coefficients are 0.58**, 0.72*** and 0.55**, showing the expected lag (the June-July correlation coefficient with the stations reversed is only 0.43*), and a similar but less marked effect can be seen with correlation coefficients based on July salinity at India. None of these lagged relations are found among the correlations for temperature.

The distributions in Figures 1 *a* and *b* suggest that low salinity water could spread as far as station Kilo, both from the North and also from the Labrador Sea. Figure 2 *b*, Curve K shows the seasonal cycle at Kilo predicted by summing the contributions from Bravo (with $x=2\,463$ km) and from India (with $x=1\,568$ km). Neither contribution alone gives such good agreement as shown in Figure 2 *b*. However, this interpretation of the salinity cycle at Kilo must be considered speculative because comparison of Figures 3 *b* and 2 *b* shows that seasonal variations of evaporation and precipitation are also contributing factors at this station. Table 3, which is described in the next section, shows that winter salinity anomalies at Juliett tend to reappear further South at Kilo later in the year, which is the opposite of the motion of temperature anomalies. This is in keeping with the above interpretation of the salinity cycle at Kilo, for the lowest salinities at this station occur in the spring. There is, however, no sign of the autumn trend at Charlie reappearing at Kilo.

Figures 1 and 2 *a* indicate that the salinity cycles at Alpha and Mike may be interpreted in the same way as the seasonal variations at Bravo and India, the low salinities in summer being caused by low salinity water from the East Greenland, East Iceland and Norwegian Currents. There is no indication of the passage of salinity anomalies from either Alpha or Mike to India, which is reasonable as the salinity cycles at these three stations are nearly in phase (Fig. 2 *a*). A particularly noticeable feature at station Mike (Fig. 7 *b*) is the very low salinities during the summers of 1956 and 1965, which persisted to the following springs. There were no associated temperature changes so that the curves appear to represent an increase in the flux of coastal runoff or northern melt-water to the station.

Station Delta appears to resemble Bravo in that its seasonal salinity cycle has a similar amplitude (Fig. 2 *a*) and the largest interannual salinity changes at each station occurred during the summer. Further, the seasonal salinity cycles at Delta and Echo appear to be related in the same way as Bravo and Charlie (Fig. 2). However, Delta is in a region of sharp salinity and temperature gradients where the North Atlantic Current meanders (McGary and Morse, 1964; Husby, 1969; Hammond, 1973; Hannon, 1976), and the seasonal cycle of salinity at Delta is much less smooth than at the other stations. It therefore seems likely that the large amplitude of the salinity cycle at Delta is caused by the sharpness of the salinity gradients in this region, and has its origin in the seasonal movements of the Labrador and North Atlantic Currents, and perhaps also the evaporation – precipitation cycle. This inference is supported by the interannual variations of summer salinity for, unlike those at Bravo, the summer salinity changes at Delta are very similar to the summer temperature changes, and the trend does not resemble that of Figure 5 *a*. In addition, there is no indication that the changes in summer salinity at Delta propagated to any of the neighbouring stations; the summer changes at Echo do show slight similarities to

Table 3
Inter-season correlation coefficients between pairs of weather stations S: salinity and T: temperature.

	OWS I					OWS J		
	Winter	Spring	Summer	Autumn		Spring	Summer	Autumn
Winter S	0.62 (***)	0.77 (***)	0.73 (***)	0.69 (***)	Winter S	0.49 (**)	0.40 (*)	0.47 (*)
OWS J T	0.72 (***)	0.62 (***)	0.32	0.48 (*)	OWS I T	0.32	0.09	0.26
Number of years: 26								

	OWS A					OWS I		
	Winter	Spring	Summer	Autumn		Spring	Summer	Autumn
Winter S	0.84 (***)	0.67 (**)	0.65 (**)	0.61 (**)	Winter S	0.37	0.28	0.11
OWS I T	0.29	0.42	0.46	0.33	OWS A T	0.12	−0.18	−0.12
Number of years: 18								

	OWS M					OWS I		
	Spring	Summer	Autumn	Foll. wint.		Summer	Autumn	Foll. wint.
Spring T OWS I	−0.28	0.31	0.54 (**)	−0.04	Spring OWS M	−0.43 (*)	−0.37	−0.33
Number of years: 22								

	OWS K					OWS J		
	Winter	Spring	Summer	Autumn		Spring	Summer	Autumn
Winter S	0.10	0.55 (*)	0.23	0.53 (*)	Winter S	0.02	0.14	−0.02
OWS J T	0.62 (*)	0.20	0.29	0.39	OWS K T	0.53 (*)	0.71 (**)	0.53 (*)
Number of years: 14								

those at Delta, but this is not reflected in the autumn which Figure 2 *a* suggests should be the case. Therefore, the interpretation of these changes as being due to water mass displacement seems to be a more likely possibility.

Salinity and temperature trends

The correlation coefficients displayed in Figures 4 to 7 show that year-to-year changes of salinity and temperature have tended to be correlated at most of the stations (cf. Taylor, Stephens, 1980). This was noted by Smed (1943) in a study of data for 1900-1940. Smed considered that the causes might be that the salinity and temperature changes had their origin in the geographical displacement of water masses, or, alternatively, that as the atmospheric circulation increased in strength, more heat was transported northwards by the atmosphere and more evaporation of the ocean occurred. However, northern North Atlantic temperatures and salinities during the last 100 years have tended to be inversely related to the strength of the atmospheric circulation (Taylor, 1978; Colebrook, Taylor, 1979). Therefore, in view of the preponderance of positive salinity and temperature correlations in Figures 4 to 7, and of the evidence of diffusion and advection effects described previously and below, the simplest explanation seems to be that the salinity and temperature changes are similar because they are caused by the displacement of water masses arising from a shift in the balance of the ocean currents. Further, in most cases it is the general trends that match rather than the changes in individual years, indicating that the underlying trend is caused by the displacements of currents and water masses. These long term water movements are either the results of changes of *in situ* forcing by local winds or are caused by large scale variations in the ocean circulation (Taylor, 1978; Colebrook, Taylor, 1979).

This interpretation of the salinity-temperature relation is supported by the observation that the year-to-year variations of salinity and temperature have magnitudes consistent with the spatial gradients of these variables. The slopes of regressions relating annual salinity fluctuations to annual temperature fluctuations, at the stations Alpha, India and Juliett, have values of 0.086, 0.112 and 0.131°/$_{00}$ (°C)$^{-1}$ respectively. These compare favourably with the ratio of the spatial gradients of these variables, which may be estimated for this region by the ratio of the differences in mean salinity between stations Alpha and Kilo to the difference in mean temperature between the stations, this ratio being 0.093°/$_{00}$ (°C)$^{-1}$.

The direction from Alpha to Kilo is roughly that of the steepest salinity and temperature gradients in the North-East Atlantic. Thus, the salinity and temperature fluctuations have the relative magnitudes that would be expected if they were caused by the shifting of water masses. The calculation cannot be easily performed at the western stations, because the time-series are short and the gradients are harder to estimate. Nevertheless, the salinity and temperature variations seem to be similarly related to the spatial gradients; for example, at Bravo in the winter (the only season for which salinity and temperature are correlated, Fig. 5 *a*), the regression coefficient is 0.055°/$_{00}$ (°C)$^{-1}$ and the ratio of the gradients from Bravo to Charlie is 0.026°/$_{00}$ (°C)$^{-1}$. Further corroboration is provided by the correlation coefficients in Table 2. If these are compared with those in Figures 4, 6 and 7, it can be seen that whenever salinity

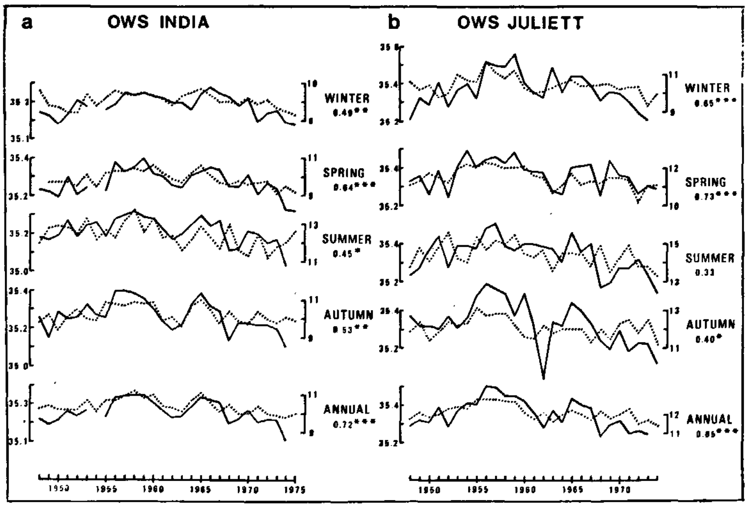

Figure 6 *a*
Station India: see legend of Figure 4.

Figure 6 *b*
Station Juliett: see legend of Figure 4.

has a large correlation with evaporation, its correlation with temperature tends to be small, and vice versa. This would be expected if evaporation and advection are separate processes independently causing year-to-year salinity fluctuations. At stations Alpha, Charlie, Echo, India, Juliett and Mike, the annual mean values of salinity and temperature are at least as highly correlated as the means for any season, which suggests that at these stations the largest salinity and temperature changes were caused by advection. However, an annual mean is the average of more observations than a seasonal mean so that the effect of random fluctuations will be reduced and this may be a partial explanation for the larger correlation coefficients between annual means.

At each of the stations Delta and Echo, salinity and temperature changes (Figs. 5 *c* and 5 *d*) are correlated in the winter, but not in the spring or autumn. Spring and autumn are the periods of onset and breakdown of the seasonal thermocline, which in this area is intense so that spring and autumn salinity and temperature averages will be sensitive to the timing of the changes.

Transport of anomalies

The time series from the eastern stations Alpha, India, Juliett, Kilo and Mike are long enough to provide evidence of the movement of salinity and temperature anomalies (i. e. transport of water with abnormally high or low salinity or temperature) by the current system of the North Atlantic. Table 3 illustrates this by showing correlation coefficients between weather stations, these being calculated from the time series of Figures 4, 6 and 7.

It is clear from Table 3 that there is a much higher correlation between the winter salinity at Juliett and the salinity during the following seasons of the year at India than there is if the seasonal lag is reversed and winter at India is compared with subsequent seasons at Juliett. This indicates that winter salinity anomalies tend to move with the North Atlantic Drift, northwards from Juliett towards India. The corresponding correlation coefficients for the temperatures at India and Juliett show, but to a lesser extent, that winter anomalies also may drift from Juliett to India. Similarly, Table 3 suggests a tendency for winter salinity (and perhaps temperature) anomalies to propagate north-westwards, presumably with the Irminger Current, from India to Alpha. Advection of temperature anomalies by the North Atlantic Drift and Irminger Current may also be inferred, starting from seasons other than winter. In the case of salinity, this is also true between India and Alpha; between Juliett and India, however, the results are confused by the southwards spread of low salinity water.

There is no indication in the time series of Figures 6 and 7 of the passage of salinity anomalies from India to Mike with the North Atlantic Drift, perhaps because, by the time the advected winter anomalies reach Mike, low salinity water is arriving there from the North and East. Table 3 shows that spring temperature anomalies may progress from India to Mike. There is also a slight indication that winter temperature anomalies at India may reappear later in the year at Mike.

Between weather stations, Juliett and Kilo conditions are complex. Table 3 suggests that winter temperature anomalies travel northwards from Kilo to Juliett, which is in keeping with the position of these stations with respect to the North Atlantic Drift, whereas salinity anomalies propagate southwards from Juliett to Kilo, this being consistent with the seasonal cycle of salinity at Kilo as described previously.

The interpretation of the results in Table 3 as representing the advection of salinity and temperature anomalies is open to the criticism that the large lag-correlations may have been caused by drifting of atmospheric anomalies between the stations over a period of months. In order to examine this possibility, 21 years of measured monthly values of wind velocity and speed, cloud cover, and estimated evaporation rates from the eastern stations Alpha, India, Juliett and Mike were each subjected to the same lag-correlation study as in Table 3. The correlation coefficients revealed no evidence of the drifting of anomalies of any of these variables on a time-scale of months; the correlation coefficients with lags were considerably smaller than those for zero-lag and in most cases were well below the conventional level of statistical significance.

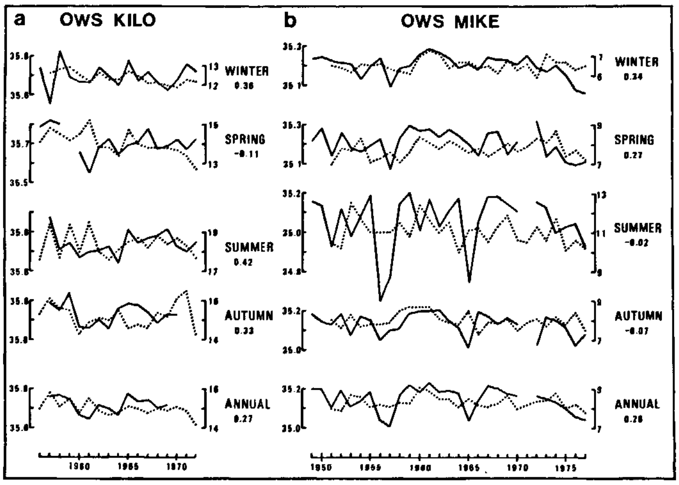

Figure 7 *a*
Station Kilo: see legend of Figure 4.

Figure 7 *b*
Station Mike: see legend of Figure 4.

CONCLUSIONS

The general conclusion of this study is that anomalous current flows resulting in the displacement of water masses are an important cause of interannual surface salinity changes at all the nine stations. However, on occasions the processes of evaporation and precipitation, and the seasonal spread of low salinity water, can also be significant. This agrees with the results of Daly (1978) who concluded, from several case studies with a simple temperature model of the North-East Atlantic, that the separate contributions of anomalous surface cooling and anomalous advection to the sea temperature change gave agreements of varying closeness, the best results being achieved by a combination of these processes. Although there is no published evidence of the movement of salinity and temperature anomalies across the North Atlantic, the movement of temperature anomalies across the North Pacific has been proposed by Favourite and McLain (1973), is suggested by the results of Davis (1976), and was included in the calculations of Clark (1972).

This study implicitly assumes that the changes observed at the nine Ocean Weather Stations provide a representative picture of the changes that occurred in the whole region. For temperature changes, the assumption is reasonable. It has been demonstrated in the previous sections that the temperature variations agree with those of other authors who used data which was not restricted to the fixed stations. Further, by applying the technique of principal components analysis to monthly temperature anomalies from the North Atlantic, Colebrook and Taylor (1979) have shown that the nine stations reflect the dominant geographical patterns of change without distortion, these dominant patterns accounting for at least 50% of the variance of the temperature changes. The assumption is harder to corroborate for the surface salinity measurements, as the coverage of salinity data is much poorer and inadequate for principal component analysis to be applied. However, the seasonal salinity cycles at the Ocean Weather Stations are consistent with the interpretation of the seasonal cycles of salinity in the North Atlantic that has emerged from previous studies. In addition, the general similarity of salinity and temperature trends at most stations, which was found by Colebrook and Taylor (1979) in data from different areas, indicates that the salinity changes observed at the nine stations may also be representative of those between the stations. Finally, the relationships between the time-series at neighbouring stations are in agreement with the current system of the region, and this provides further support for the assumption.

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REFERENCES

Adem J., 1970. On the prediction of monthly mean ocean temperatures, *Tellus*, **22**, 410-430.

Bjerknes J., 1964. Atlantic air-sea interaction, *Adv. Geophys.*, **10**, 1-82.

Bunker A. F., 1976. Computations of surface energy flux and annual air-sea interaction cycles of the North Atlantic Ocean, *Mon. Weath. Rev.*, **104**, 1122-1140.

Clark N. E., 1972. Specification of sea surface temperature anomaly patterns in the Eastern North Pacific, *J. Phys. Oceanogr.*, **2**, 391-404.

Colebrook J. M., 1976. Trends in the climate of the North Atlantic Ocean over the past century, *Nature* (*London*), **263**, 576-577.

Colebrook J. M., Taylor A. H., 1979. Year-to-year changes in sea surface temperature, North Atlantic and North Sea, 1948-1974, *Deep-Sea Res.*, **26 A**, 825-850.

Cushing D. H., Dickson R. R., 1976. The biological response in the sea to climatic changes, *Adv. Mar. Biol.*, **14**, 2-122.

Daly A. W., 1978. The response of North Atlantic sea surface temperature to atmospheric forcing processes, *Q.J.R. Meteorol. Soc.*, **104**, 363-382.

Davis R. E., 1976. Predictability of sea surface temperature and sea level pressure anomalies over the North Pacific Ocean, *J. Phys. Oceanogr.*, **6**, 249-265.

Defant A., 1961. *Physical Oceanography*, **1**, Pergamon Press, Oxford, New York, London, Paris, 729 p.

Dickson R. R., Lamb H. H., Malmberg S. A., Colebrook J. M., 1975. Climatic reversal in the Northern North Atlantic, *Nature* (*London*), **256**, 479-482.

Dietrich G., 1969. *Atlas of hydrography of the northern North Atlantic Ocean based on the polar front survey during the international geophysical year winter and summer* 1958, edited by Cons. Int. Explor. Mer, Service Hydrographique, Copenhagen.

Ellett D. J., Martin J. H. A., 1973. The physical and chemical oceanography of the Rockall Channel, *Deep-Sea Res.*, **20**, 585-625.

Favourite F., McLain D. R., 1973. Coherence in transpacific movements of positive and negative anomalies of sea surface temperature, 1953-1960, *Nature* (*London*), **244**, 139-143.

Fieux M., Stommel H., 1975. Preliminary look at feasibility of using marine reports of sea surface temperature for documenting climatic change in the Western North Atlantic, *J. Mar. Res.*, **33**, 83-95.

Hammond R. F., 1973. Oceanographic observations at North Atlantic Ocean Station Delta, August 1967-August 1968, *US Coast Guard Oceanogr. Rep.*, CG 373-58.

Hannon L. J., 1974. Oceanographic observations at North Atlantic Ocean Station Charlie, April 1967-April 1968, *US Coast Guard Oceanogr. Rep.*, CG 373-61.

Hannon L. J., 1976. Oceanographic observations at North Atlantic Ocean Station Delta, August 1968-August 1969, *US Coast Guard Oceanogr. Rep.*, CG 373-69.

Husby D. M., 1966. Oceanographic observations at North Atlantic Ocean Station Charlie, June 1964-January 1965, *US Coast Guard Oceanogr. Rep.*, CG 373-8.

Husby D. M., 1967. Oceanographic observations at North Atlantic Ocean Station Bravo, August 1964-November 1965, *US Coast Guard Oceanogr. Rep.*, CG 373-9.

Husby D. M., 1968 *a*. Oceanographic observations at North Atlantic Ocean Station Bravo, October 1965-1966, *US Coast Guard Oceanogr. Rep.*, CG 373-14.

Husby D. M., 1968 *b*. Oceanographic observations at North Atlantic Ocean, Station Charlie, May 1966-March 1967, *US Coast Guard Oceanogr. Rep.*, CG 373-17.

Husby D. M., 1969. Oceanographic observations at North Atlantic

Ocean Station Delta, July 1966-August 1967, *US Coast Guard Oceanogr. Rep.*, CG 373-23.

Kukla G. J., Angell J. K., Korshover J., Dronia H., Hoskai M., Namias J., Rodewald M., Yamamoto R., Iwashima T., 1977. New data on climatic trends, *Nature (London)*, **270**, 573-580.

Lamb H. H., 1972. *Climate: present, past and future*, **1**, edited by Methuen and Co Ltd, London, 613 p.

Malkus J. S., 1962. Large-scale interactions, in: *The Sea*, edited by M. N. Hill, Interscience Publishers, New York-London, **1**, 88-285.

McGary J. W., 1965. Oceanographic observations at North Atlantic Ocean Station Bravo, January to April 1964, *US Coast Guard Oceanogr. Rep.*, CG 373-7.

McGary J. W., Morse R. M., 1964. Oceanographic observations at North Atlantic Ocean Station Delta, March-April 1963, *US Coast Guard Oceanogr. Rep.*, CG 373-3.

Morse R. M., McGary J. W., 1964. Oceanographic observations at North Atlantic Ocean Station Echo, January-February 1963, *US Coast Guard Oceanogr. Rep.*, CG 373-2.

Mosby H., 1963. Oceanographical tables from Weather Ship Station M (66°N, 2°E), 1948-1958, Univ. Bergen, Geof. Inst., Bergen.

Mosby H., 1964. Oceanographical tables from Weather Ship Station M (66°N, 2°E), 1959-1963, Univ. Bergen, Geof. Inst., Bergen.

Mosby H., 1965. Oceanographical tables from Weather Ship Station A (62°N, 33°W), 1954-1965, Univ. Bergen, Geof. Inst., Bergen.

Mosby H., 1971. Oceanographical tables from Weather Ship Station M (66°N, 2°E), 1964-1968, Univ. Bergen, Geof. Inst., Bergen.

Mosby H., 1972. Basic problems in the Norwegian Sea, in: The Norwegian Sea region: its hydrography, glacial and biological history, Royal Swedish Academy of Sciences, Universitetsforlaget, *Arct. Spec. Rep.*, **2**, 7-11.

Neumann G., 1940. Die ozeanographischen Verhältnisse an der Meeresoberfläche in Golfstromsektor nördlich und norwestlich der Azoren, *Ann. Hydr. Mont. Meteorol.*, **68**, Juni, Beiheft, 87 p.

Pflugbeil C., Steinborn E., 1963. Einzelveroffentlichungen des Seewetteramtes, in: *Zur klimatologie des Nordatlantischen Ozeans*, Dtsch. Wetterdienste, no. **39**, 114 p.

Pocklington R., 1978. Climatic trends in the North Atlantic, *Nature (London)*, **273**, 407.

Rodewald M., 1972 *a*. Long-term variations of sea surface temperatures in the areas of the nine North Atlantic Ocean Weather Stations during the period 1951-1968, *Rapp. Cons. Int. Explor. Mer*, **162**, 139-153.

Rodewald M., 1972 *b*. Temperature conditions in the North and Northwest Atlantic during the decade 1959-1970, *Spec. Publ. Int. Comm. N. W. Atl. Fish.*, **8**, 9-34.

Rosebrook A. D., 1971. Oceanographic observations at North Atlantic Ocean Station Echo, November 1967-December 1968, *US Coast Guard Oceanogr. Rep.*, CG 373-49.

Servain J., 1980. Analyse corrélative des températures de surface sur le Proche Atlantique, *Oceanol. Acta*, **3**, 1, 3-6.

Shuhy J. L., 1969 *a*. Oceanographic observations at North Atlantic Ocean Station Bravo, October 1966-October 1967, *US Coast Guard Oceanogr. Rep.*, CG 373-20.

Shuhy J. L., 1969 *b*. Oceanographic observations at North Atlantic Ocean Station Echo, September 1966-October 1967, *US Coast Guard Oceanogr. Rep.*, CG 373-21.

Shuhy J. L., 1974. Oceanographic observations at North Atlantic Ocean Station Bravo, November 1967-November 1969, *US Coast Guard Oceanogr. Rep.*, CG 373-63.

Smed J., 1943. Annual and seasonal variations in the salinity of North Atlantic surface water, *Rapp. Cons. Int. Explor. Mer*, **112**, 79-94.

Stommel H., 1949. Horizontal diffusion due to oceanic turbulence, *J. Mar. Res.* **8**, 199-225.

Taylor A. H., 1978. Long-term changes in the North Atlantic current system and their biological implications, *Proc. R. Soc. Edinburgh, Sect. B*, **76**, 223-243.

Taylor A. H., Stephens J. A., 1980. Latidudinal displacements of the Gulf Stream (1966 to 1967) and their relation to changes in temperature and zooplankton abundance in the NE Atlantic, *Oceanol. Acta*, **3**, 2, 145-149.

US Naval Oceanographic Office, 1967. Oceanographic atlas of the North Atlantic Ocean, Section II, physical properties, *US Nav. Oceanogr. Off. Publ.*, **700**, 300 p.

World Meteorological Organisation, 1976. *Oceanic Water Balance*, WMO no. 442, 112 p.