Latitudinal displacements of the Gulf Stream (1966 to 1977) and their relation to changes in temperature and zooplankton abundance in the NE Atlantic

Zooplankton abundance
Surface temperature
Gulf Stream
Climatic trends
North Atlantic

Abondance du zooplankton
Température superficielle
Gulf Stream
Tendances climatiques
Atlantique Nord

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ABSTRACT

It is shown that the north wall of the Gulf Stream was displaced southward during 1966 to 1971 and returned northward after 1973. While there was no clear relation with any of several relevant wind and pressure indices, there were similar trends in sea-surface temperature, salinity and abundance of zooplankton in the NE Atlantic. The displacements of the Gulf Stream are therefore part of a large-scale change encompassing most of the North Atlantic. These changes are either separate manifestations of variations in the global atmospheric circulation, or the changes in the NE Atlantic are the indirect result of variations in the Gulf Stream.

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RÉSUMÉ

Déplacements en latitude du Gulf Stream de 1966 à 1977
et relation avec les variations de la température
et l'abondance du zooplancton dans l'Atlantique Nord-Est.

De 1966 à 1971 le Gulf Stream s'est déplacé vers le Sud, puis est remonté vers le Nord, ainsi que le suggère l'analyse de la position de sa bordure septentrionale. Bien qu'il ne semble pas y avoir de relations nettes avec les variations parallèles des principales caractéristiques atmosphériques (vent, pression), on note toutefois une certaine similitude avec les variations de la température de surface, la salinité et l'abondance du zooplancton dans l'Atlantique Nord-Est. Ces évolutions sont soit des conséquences distinctes résultant de variations dans la circulation atmosphérique planétaire, soit le résultat indirect des variations du Gulf Stream.

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INTRODUCTION

The Gulf Stream separates from the coast of North America near Cape Hatteras (33°N, 75°W) and then travels eastwards across the North Atlantic (Fig. 1),

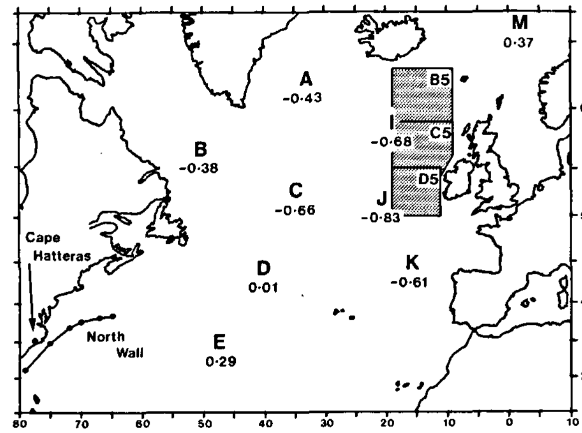


Figure 1

Chart of the North Atlantic Ocean showing: the region of the north wall of the Gulf Stream studied (the line with dots), indicating the longitudes where the latitude of the North Wall was estimated: the eigenvector pattern (as correlation coefficients) of the first temperature principal component of sea surface temperature at the nine ocean weather stations (shown by the letters, A, B, C, D, E, I, J, K and M); and the standard areas B 5, C 5 and D 5 for which plankton were averaged.

becoming the North Atlantic Current at about 55°W. In the region between 75°W and 55°W, it is subject to large meanders and is frequently accompanied by eddies (Mann, 1972; Neumann, 1968; Robinson, 1975). The present paper shows that, underlying this variability, the position of the Gulf Stream has undergone long-term changes of latitude during the period 1966 to 1977 (Fig. 2 *a*), shifting southward during 1966 to 1971 and returning northward after 1973. The changes are compared with several climatological and biological time-series from the North Atlantic region.

GULF STREAM POSITION DATA

Monthly charts of the north wall of the Gulf Stream were published from 1966 until 1974 in *The Gulf Stream Monthly Summary* and from 1975 to 1977 by the US National Oceanic and Atmospheric Administration in *Gulf Stream.* These charts were derived from aircraft and satellite observations. The latitude of the north wall was read from each chart at six longitudes (Fig. 1) : 79°W, 75°W, 72°W, 70°W, 67°W and 65°W (the charts were incomplete east of 65°W). Simple averaging of these latitude measurements would emphasise the eastern longitudes for which the north-south movements of the Stream are largest, possibly obscuring smaller but coherent north-south shifts further west. Interpretation of the data is also complicated by seasonal movements of the Gulf Stream, the north wall was further north in Autumn and Winter than in Spring and Summer along all of its length, except at 79°W and 67°W where the reverse is true (the variance between years was, however, more than an order of magnitude greater than the variance within the seasonal cycle). Therefore, the six estimated latitudes for each month (January 1966 to December 1977) were expressed as anomalies from their 12-year means for that month. The time-series at each of the six longitudes were then correlated and principal components (Kendall, Stuart, 1966; Colebrook, Taylor, 1979; Colebrook, 1978) calculated from the resulting correlation matrix. The monthly values of the first principal component were then averaged to produce the time-series of annual values plotted in Figure 2 *a*.

RESULTS

The first principal component of the position of the north wall (Fig. 2 *a*) has positive correlation coefficients of 0.71, 0.71, 0.57, 0.01, 0.50, 0.09 with the latitude anomalies of the north wall at the six longitudes from 65°W to 79°W respectively and can therefore be regarded as representing coherent variations from month to month in the position of this section of the Gulf Stream. The eigenvalue corresponding to this component has a value of 1.6 (principal components with eigenvalues greater than unity are usually considered significant and Bartlett's test (Kendall, Stuart, 1966) showed significance at the 1% level). The component, therefore, accounts for 26% of the total variance of the six variables, a percentage that has undoubtedly been reduced by the short-period meandering of the Gulf Stream, for there is little correlation between meanders that are widely separated in longitude. The correlation coefficients show that the north-south shifts described by the component are evident from the data as far west as the vicinity of Cape Hatteras (75°W), although the latitudinal range of the annual means at this longitude was only about 0.2 degrees, compared with about 1 degree at 65°W.

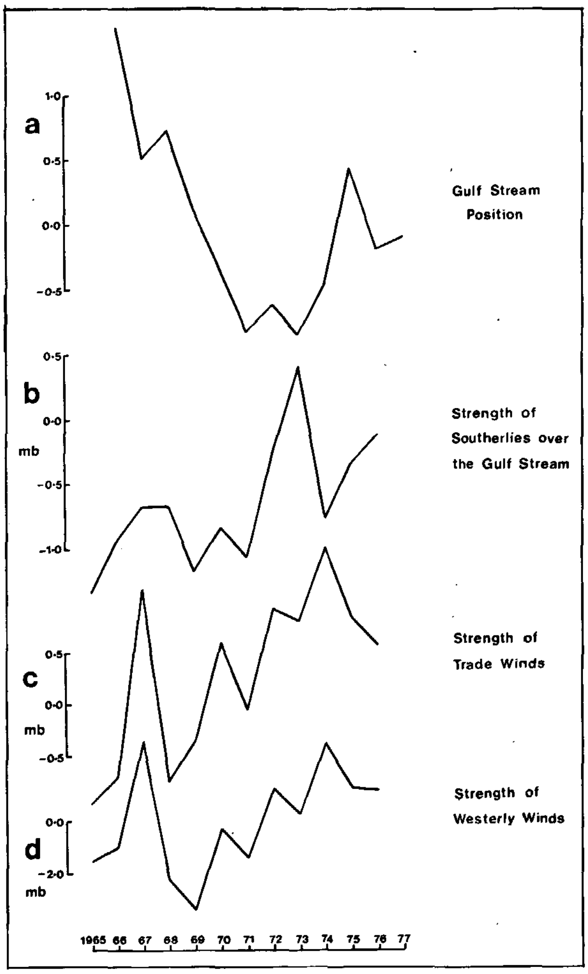


Figure 2

Annual means, 1966-1977, of: (a) First principal component of the position of the north wall of the Gulf Stream standardised so that the variance of the monthly means is the latent root; (b) Index of strength of southerly winds over the Gulf Stream (pressure difference over the stream between 60° W and 80° W); (c) Index of strength of North Atlantic Trade Winds (pressure difference between 35°N and 20°N); (d) Index of strength of North Atlantic Westerlies (pressure difference between 35°N and 60°N).

The origin of the trend in Figure 2 *a* is as yet unclear. The explanation must be sought, however, in the processes driving the Gulf Stream and causing it to separate from the North American coast. The Stream is driven by the combined stress of the Trade and Westerly winds and also by outbreaks of could air from the American continent (Worthington, 1976, 1977). In Figures 2 and 3 the position of the Gulf Stream is compared with some relevant indices of the atmospheric circulation, calculated from the tables presented by Namias (1975). Following Colebrook and Taylor (1979), the pressure difference over the Atlantic between 35°N and 20°N is used as an index of Trade Wind strength (Fig. 2 *c*) and

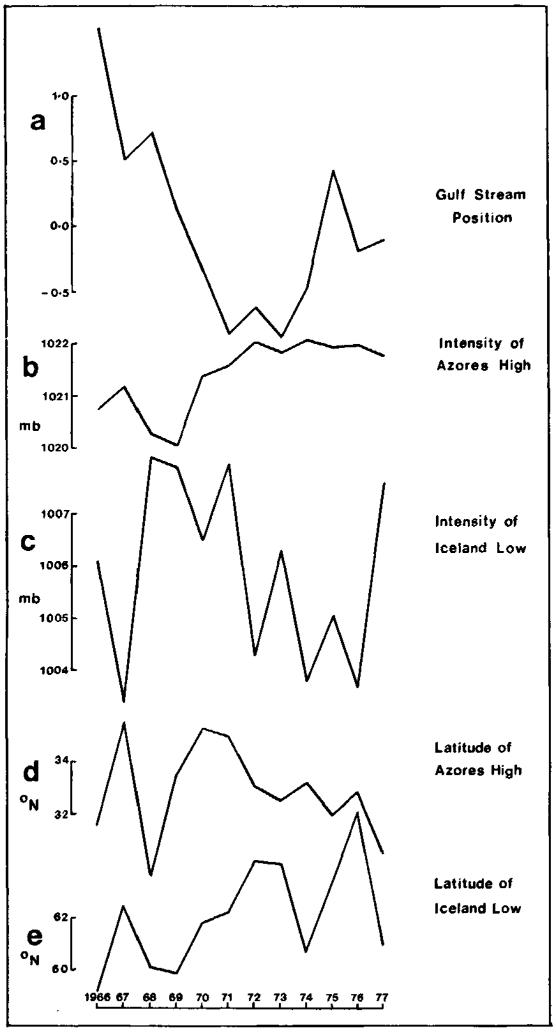


Figure 3

Annual means for 1966-1977, *of: (a) Position of the north wall of the Gulf Stream (as Fig. 2 a); (b) Intensity of the Azores High; (c) Intensity of the Iceland Low; (d) Latitude of the Azores High; (e) Latitude of the Iceland Low. Time series b, c, d, and e were calculated using the definition of Lamb and Johnson* (1965).

the pressure difference over the Atlantic between 35°N and 60°N as an index of Westerly Wind strength (Fig. 2 *d*). The strength of southerly winds over the Gulf Stream is estimated by the pressure difference between 60°W and 80°W (Fig. 2 *b*). The latitude and intensity of the Iceland Low are estimated by approximating its latitudinal pressure variation from 50°N to 70°N by a parabola at each of the longitudes 40°W, 30°W, 20°W, 10°W (Fig. 3 *c* and *e*), and averaging the results. The latitude and intensity of the Azores High are estimated by a similar treatment using the pressures from 20°N to 40°N at the longitudes 60°W, 50°W, 40°W, 30°W, 20°W (Fig. 3 *b* and *d*). These definitions are essentially those of Lamb and Johnson (1965).

The position of the Gulf Stream does not appear to be simply related to any of these variables; in particular, the latitude of the north wall does not follow either the strength of the local southerly winds (the north wall tending to be displaced in the opposite direction to the winds), or the north-south displacements of the major atmospheric circulations. Over most of the period there was a steady increase in the intensity of the Westerly and, especially, the Trade Winds. Figures 3 *a* and *b* suggest that, in general, southward displacements of the Gulf Stream have occurred when the Azores High was strong; the relationship, however, is weak. The processes by which the Gulf Stream separates from the American coast are poorly understood (e. g. Holland, 1978, p. 389) but in theoretical studies it has been proposed that the Stream leaves the coast at the point where its transport becomes too large to be geostrophically balanced (Veronis, 1978), in which case increased wind-stress should result in the point of separation being further south suggesting that Figures 3 *a* and *b* might show some similarity. It seems unlikely that variation in the winter outbreaks of cold air is the cause of the Gulf Stream displacements since examination of the monthly values of the principal component shows that no individual season dominates the trend. For instance, there was a southward displacement of the north wall during the spring following the severe winter of 1976-1977 (Worthington, 1977) but the shift was not large, being smaller than a similar change that occurred in the preceeding spring.

Physical changes further north in the Atlantic show trends that are similar to the meridional displacement of

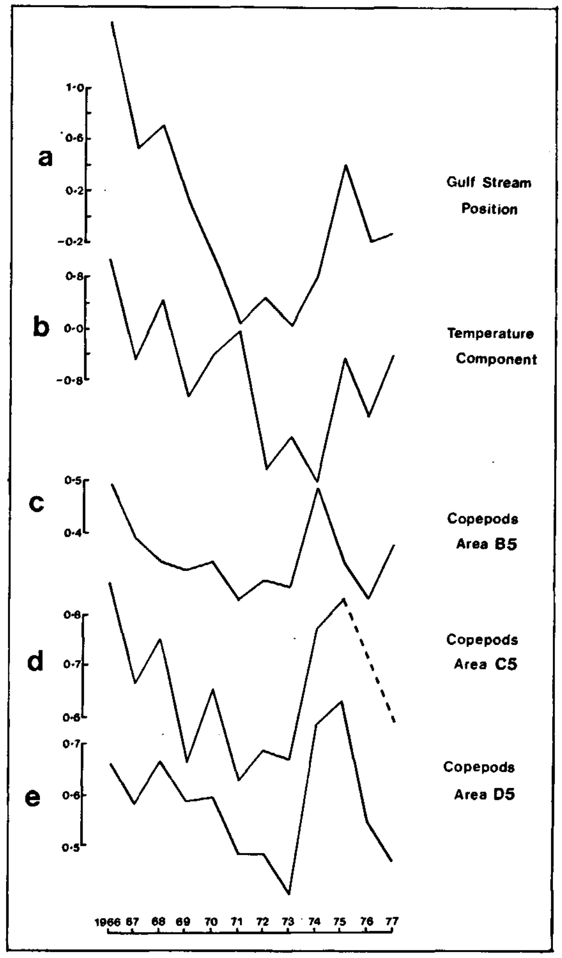
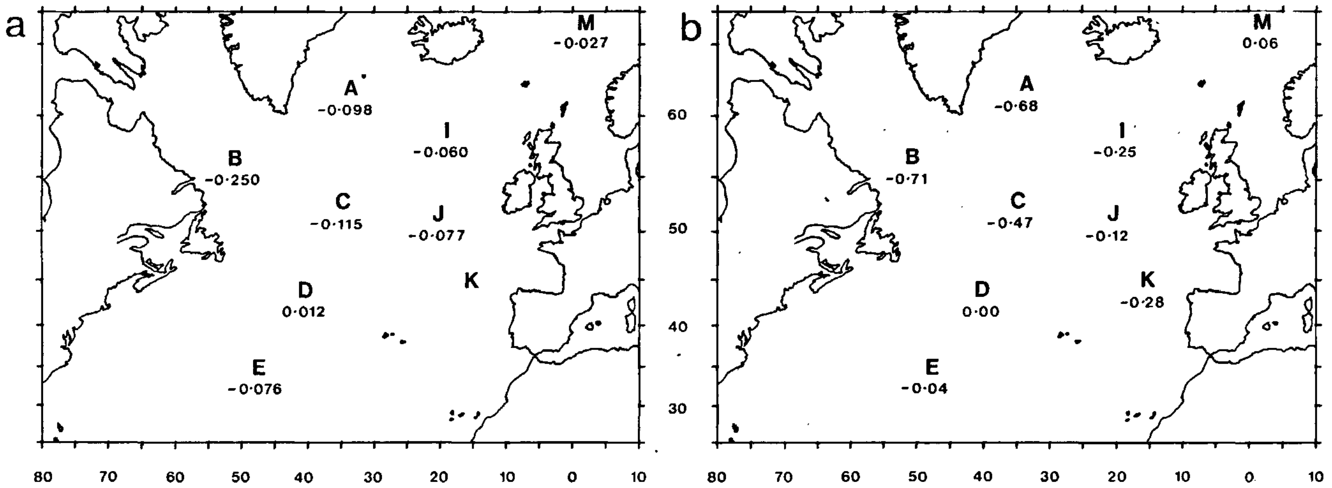


Figure 4

Annual means for 1966-1977, *of: (a) Position of the north wall of the Gulf Stream (as Fig. 2 a); (b) the first principal component of sea surface temperature anomalies at the ocean weather stations (see Fig. 1) standardised so that the variance of the monthly means is the latent root; (c), (d), (e) numbers of copepods in areas B 5, C 5 and D 5 respectively (see Fig. 1) of the Continuous Plankton Recorder Survey. The value for area C 5 for* 1976 *is missing (units: logarithm of the mean numbers per 3 m³).*



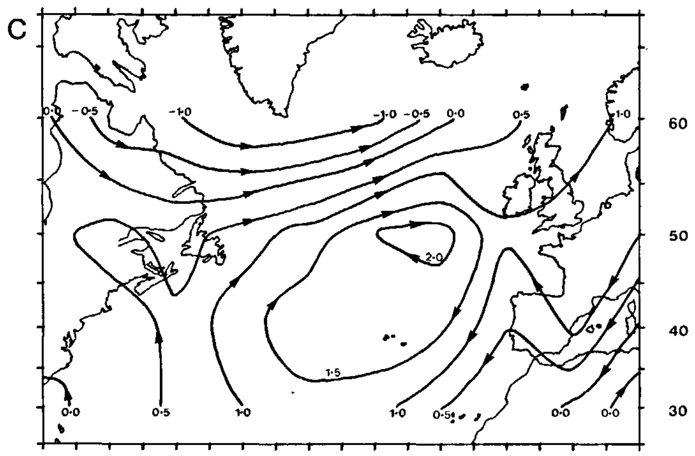


Figure 5
(a) Difference in surface salinity ($^0/_{00}$) at the North Atlantic Ocean Weather stations between 1966-1969 *and* 1970-1974. *(No data are available for station K); (b) Difference in sea surface temperature (°C) at the North Atlantic Ocean Weather stations between* 1966-1969 *and* 1970-1974; *(c) Difference in sea level pressure (mb) between* 1966-1969, 1975. *and* 1970-1974 *(Data from Namias* 1975 *).*

the Gulf Stream. For instance, Figure 4 *b* shows annual means of the first principal component (Taylor, 1978) of monthly temperature anomalies for the period 1951-1977 at the nine North Atlantic ocean weather stations (the time series from the weather stations have been extended in time using temperatures reported by merchant ships). This component represents the dominant mode of temperature change in the North Atlantic. The geographical pattern associated with the component is illustrated in Figure 1 by its correlation coefficients with the temperature anomalies at the individual stations. This mode of temperature change, which recurs throughout at least the last 28 years, extends down to 250 m, and has been accompanied by similar long-term changes in salinity (Taylor, 1978; Colebrook, Taylor, 1979), represents a tendency for temperature anomalies around the southern stations D and E to be opposite in sign to those at the more northerly stations A, B, C, I, J and K. It is clear that the temperature component shows a long-term trend that is similar to that of the Gulf Stream position.

There are indications that biological changes in the North Atlantic have been similar to the changes in Gulf Stream position. Figures 4 *c*, *d* and *e* show the annual fluctuations in the numbers of copepods estimated from the samples of the Continuous Plankton Recorder Survey (Edinburgh Oceanographic Laboratory, 1973) from the NE Atlantic areas B5, C5, and D5 (Fig. 1) for the years 1966 to 1977. The pattern of the fluctuations in the plankton shows some similarities with the variability in the displacement of the Gulf Stream and with the trend in the weather station temperature component. Further, Colebrook (1978) has reported that several species of zooplankton in the eastern North Atlantic showed trends of abundance similar to that of the ocean weather station temperature component during the 24-year period 1951 to 1974.

DISCUSSION

The long-term fluctuations in the north wall of the Gulf Stream during 1966 to 1977 are associated with widespread changes over the whole of the North Atlantic. These associated changes are summarised in Figure 5 which shows the differences in surface salinity, surface temperature and sea level pressure between a group of years (1970-1974) of southerly Gulf Stream position and a group of years (1966-1969, 1975) of northerly Gulf Stream position. Apart from the station M in the Norwegian Sea the pattern of the differences in salinity and temperature between the two periods (Fig. 5 *a* and *b*) are similar, the pattern of the temperature differences also resembling that of the principal component of temperature in Figure 1. Figure 5 *c* shows that the more southerly Gulf Stream position was accompanied by a generally stronger atmospheric circulation with more southerly winds blowing across the north wall, i. e. winds in the opposite direction to its displacement. Possibly the changes in Figures 4 and 5 are separate manifestations of variations in the general atmospheric circulation as described by Dickson *et al.* (1975) and, in the Pacific, by White *et al.* (1978). The temperature variations of

Figure 4 *b* would then be the result of local atmospheric forcing under the same large-scale circulation patterns which give rise to changes in the Gulf Stream system. The plankton changes would be caused by local changes in wind-speed and wind-direction which would be associated with variations in insolation and depth of mixing. Alternatively, in view of the fact that the Gulf Stream shifts show greater similarity to the physical and biological changes further north than any of these do to the atmospheric circulation indices, it is conceivable that the oceanographic changes in the North Atlantic are the indirect result of the latitudinal displacements of the Gulf Stream, a suggestion that has been made previously (Martin, 1972; Colebrook, 1976). The similarity of temperature and salinity changes in the NE Atlantic indicates that variation in advection is an important source of the changes (Colebrook, Taylor, 1979). This is to be expected since polewards of about 45°N there is a net loss of heat across the ocean surface through the year (Malkus, 1962; Bunker, 1976) against which the ocean temperature is maintained by the heat advection of the ocean currents. However, the means by which advection changes could cause changes in zooplankton abundance are less clear. Possibly overwintering stocks play an important role, small advected changes in winter populations being magnified into marked differences the following summer (Colebrook, 1979). This study emphasises that the plankton trends are part of a series of changes spread across the North Atlantic.

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