

Significant time scales of long-term variability in the plankton and the environment

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High resolution methods of spectral and cross-spectral analysis are used to provide information in the frequency domain about year-to-year fluctuations in the plankton of the Northeast Atlantic and the North Sea, compared with changes in temperature, salinity, and atmospheric climate. Most of the data refer to the period from 1948 to the present.

Characteristic time scales are involved in many relationships within the plankton and between the plankton and environmental variables. The longest wavelengths appear to be associated with the major ocean current systems, and fluctuations with wavelengths of 3–4 years may be associated with surface-heat exchange phenomena. Other characteristic periodicities with wavelengths of 10–12 years and 5–6 years have not, as yet, been identified with particular processes.

Introduction

This paper presents analyses of time series of the abundance of plankton and variations in sea surface temperature and climate for the Northeast Atlantic and the North Sea for the last three decades. Patterns of relationship within and between most of these variables have been studied using correlation methods by Colebrook (1978), Colebrook and Taylor (1979), and Taylor and Stephens (1980 a). Recently, high resolution methods of spectral and cross-spectral analysis have become available that permit a more detailed examination of these relationships through a study of frequency structures.

Structure in the spectrum of a time series can arise in a number of ways. The most interesting in the context of this study is that due to external forcing operating over limited time scales. Structure can also result from internal associations between variables, usually in the form of persistence, where the value at a given time is influenced by preceding values.

In addition, there are a number of ways in which frequencies can be echoed at wavelengths differing considerably from that of the prime forcing.

It is inherent in the methods of analysis that any non-sinusoidal periodic variability will generate harmonics. In the series involved in this study, however, the only clear examples of harmonics that have been detected have periods of less than a year and are associated with the seasonal cycle. The time series have been derived from the original data in ways which avoid aliasing as far as possible. There may, however, be beat frequencies in the series due to interactions between the seasonal cy-

cle, which is the major mode of variability of most of the series, and variability at frequencies close to the seasonal cycle.

The spectra of many of the variables included in this study show a clear structure, and there are a number of characteristic frequencies in the fluctuations in the abundance of the plankton, in the sea surface temperatures, and in the climate variables. These will be discussed in the results in relation to the possible sources of structure outlined above.

Data

A routine, monthly, synoptic survey of the plankton of the North Atlantic and the North Sea has been carried out each year since 1948, using Continuous Plankton Recorders (Glover, 1967). The data from the survey provide information about year-to-year changes in the abundance of zooplankton for each of a standard set of areas shown in Figure 1. In this paper data for the years 1948 to 1980 are used, a period of 33 years.

For comparison with the plankton, time series of data for a number of environmental variables have been acquired. Sea surface temperatures (data supplied by ICES and the U.K. Meteorological Office) have been processed to give monthly and annual means for each of the areas shown in Figure 1. Annual means of sea-level atmospheric pressure for the North Atlantic between 20° and 80°N have been calculated from the data in Namias (1975). Indices of the main weather patterns over the United Kingdom have been derived from a classification of daily weather maps (Lamb, 1972) and

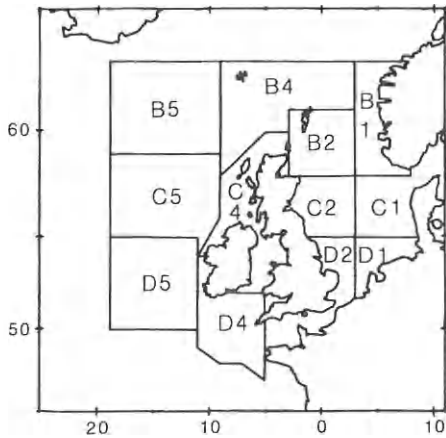


Figure 1. Chart of standard areas used in the presentation of annual means in the abundance of plankton and of sea surface temperature.

expressed as variations in the frequency (days per year) of anticyclonic, cyclonic, westerly, easterly, and northerly weather.

Data for temperature and salinity at Ocean Weather Station India have been assembled from several sources (Pflugbeil and Steinborn (1963); ICES; and the U.K. Meteorological Office). Heat fluxes and evaporation rates at OWS India were compiled by the late Andrew Bunker of the Woods Hole Oceanographic Institution, using bulk formulae.

Methods

Spectral analysis subdivides the variability of a time series of observations among frequency bands. Cross-spectral analysis produces two spectra, a coherence spectrum, which, in this context, behaves as a set of correlation coefficients, one for each frequency band, and a phase spectrum, which shows how the timings of the sets of observations are related at each frequency band.

The techniques used in this study are Maximum Entropy Spectral and Cross-Spectral analyses, in which the derivation of a spectrum is a two-stage process. First, a filter is derived which will reduce the original time series to white noise, and then the spectrum is calculated as the response of the filter to sine waves over the relevant range of frequencies.

It was convenient, given the available computing facilities, to calculate the spectra and cross-spectra for the longer series of monthly data using a method developed by Strand (1977); for the annual series the cross-spectra were derived using a method by Nuttall (1976) and the individual spectra using a method by Barrodale and Erickson (1980). There is an element of trial and error in choosing the number of coefficients in

the filters; with too few the spectra are highly smoothed, while too many produce spurious detail. In all the analyses described here filter lengths of about 20 % of the length of the series have been used.

Results

By the standards of time-series analysis, a period of 33 years is relatively short, and the results of the spectral and cross-spectral analyses have to be treated with some caution. Nevertheless, in the large number of analyses that have been performed there are recurrent peaks in the spectra at a number of wavelengths. Figure 2 is a histogram of the frequency of peaks in 120 spectra for 10 zooplankton taxa in each of the 12 areas shown in Figure 1. The results are similar to those shown in a previously published diagram (Colebrook, 1979) which was based on power spectra for data up to 1975. Compared with the earlier diagram, the Maximum Entropy method, combined with the longer data series, has resulted in the resolution of a single peak at the longest wavelengths into two, associated with periods longer than 40 years and between 10 and 20 years. The remaining peaks at 5-6.5 years, 3-3.5 years, and 2-2.2 years are common to both presentations.

With the exception of the peak at 5-6.5 years, the peaks at the other wavelengths occur in either the sea surface temperatures or in the climatic variables or both. These relationships have been studied in some detail.

Colebrook (1978) showed that the annual fluctuations in the abundance of zooplankton were correlated with the changes in the frequency of westerly weather. Figure 3 shows the coherence and phase spectra for westerly weather against the first principal component

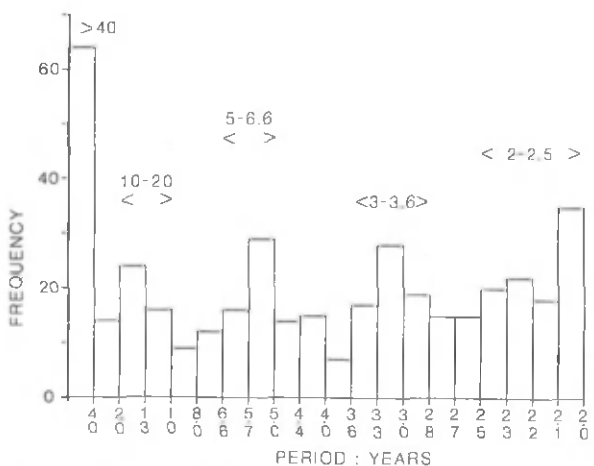


Figure 2. Histogram of the frequency at different wavelengths of peaks in 120 maximum entropy spectra of the annual fluctuations in the abundance for 1948 to 1980, of 10 zooplankton taxa in each of the 12 areas shown in Figure 1.

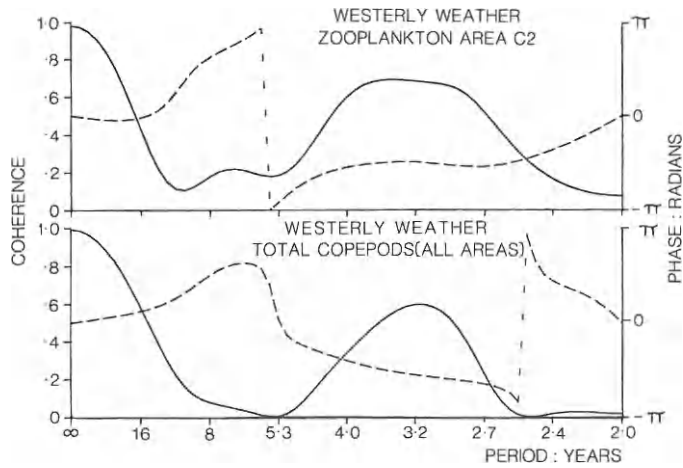


Figure 3. Plots of coherence (solid lines) and phase (dashed lines) spectra of the frequency of westerly weather over the U.K. for 1948 to 1980 against the first principal component of the annual fluctuations in abundance of 17 zooplankton taxa for area C2 (see Fig. 1) and the first principal component of the annual fluctuations in the abundance of copepods in all the areas shown in Figure 1.

of the annual fluctuations in the abundance of 17 zooplankton taxa in area C2 (see Fig. 1) and also against the first principal component of the abundance of total copepods in all 12 areas shown in Figure 1.

These are typical of a number of spectra which indicate that the relationship between the westerly weather and the zooplankton tends to be confined to two frequency bands, at the longest wavelengths and at 3–4 years, corresponding with two of the peaks in Figure 2. The fluctuations at the longest wavelengths are in phase, while those at 3–4 years are best regarded as being out of phase with the westerly weather.

The element of virtually linear trend in the westerly

weather appears to be of considerable importance in relation to the plankton. Both the westerly and easterly weather are related (but with opposite phases) to fluctuations in sea-level atmospheric pressure associated with a geographical pattern shown in Figure 4, but, rather surprisingly, the easterly weather shows a higher coherence at the longest wavelengths.

Figure 5 shows plots of the time series of westerly and easterly weather. These indicate that on the whole the two variables are negatively related, as would be expected, except for a period from 1970 to about 1975 when the negative relationship breaks down. This corresponds to a period of fairly consistent high frequen-

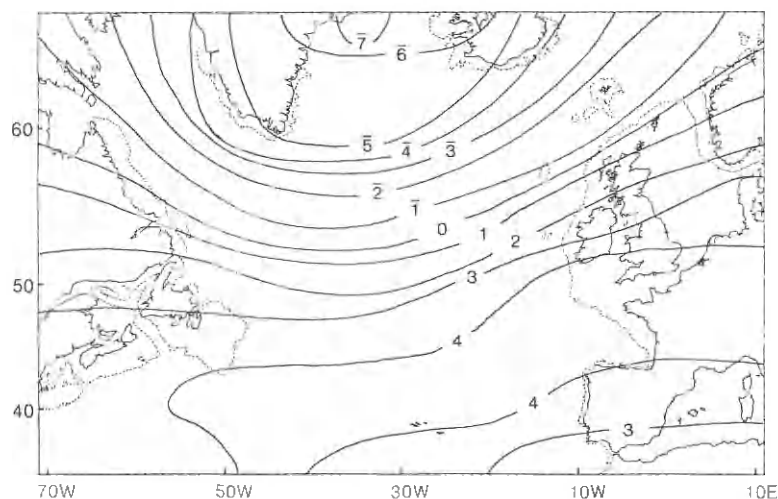


Figure 4. Chart of the first principal component of annual means of sea-level atmospheric pressure for 1948 to 1975 with observations on a staggered 5° grid at 35°N (10° 65°N, 65°W (-10°) 10°E and 40°N (10°) 60°N, 70°W (-10°) 10°E.

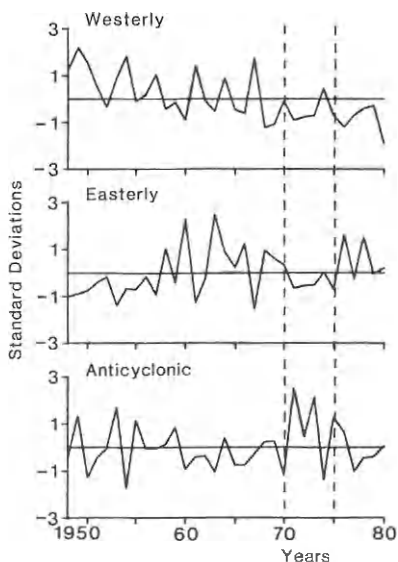


Figure 5. Plots of the frequencies of westerly, easterly, and anticyclonic weather (as days per year standardized to zero mean and unit variance) over the U.K. for the years 1948 to 1980.

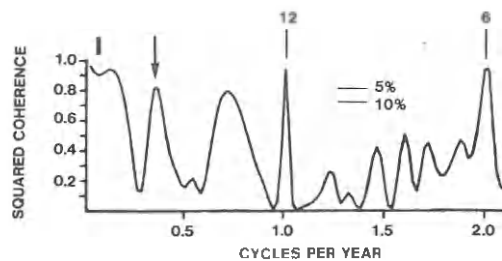
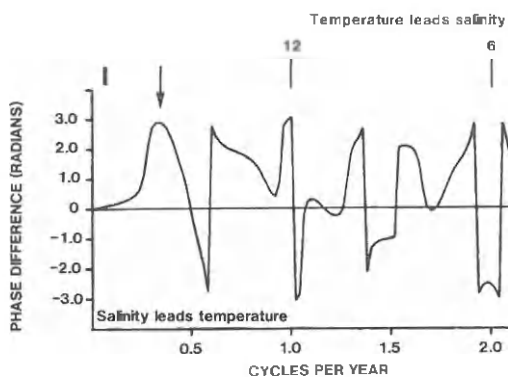
cies of anticyclonic weather (also shown in Figure 5). Thus it would appear that the apparently systematic trend in the occurrence of westerly weather may be due to processes that are not constant with time.

On the assumption that there is a causal link between the westerly weather and the plankton, it would be expected that the plankton would be more variable within the wave bands associated with the relationship. On the whole, however, the plankton show a higher proportion of long wavelength variability than does the westerly weather.

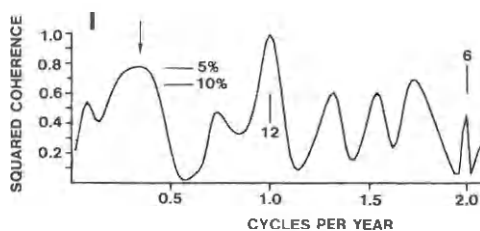
Colebrook (1981; 1982) has shown that persistence in stocks from year to year is a feature of several species of zooplankton. The extent of persistence is a function of the size of overwintering stocks and may also be related to development times. The effect of persistence is to increase the proportion of long wavelength variability in year-to-year fluctuations in abundance. It seems probable, therefore, that the high proportion of long wavelength variability in the plankton is due to a combination of forcing at these wavelengths and persistence in stocks from year to year.

With respect to the variability at 3–4 years, there is some evidence that it can be linked to a definite process

TEMPERATURE - SALINITY CROSS-SPECTRA



TEMPERATURE AND HEAT FLUX



SALINITY AND EVAPORATION

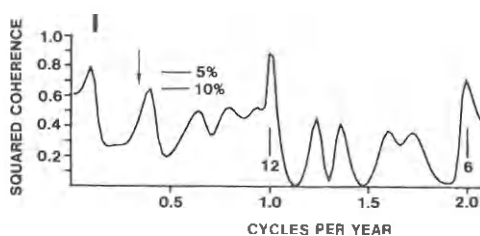


Figure 6. Cross-spectra for temperature and salinity at Ocean Weather Station India and coherence spectra for temperature and heat flux and for salinity and evaporation. Peaks at 12 and 6 months are marked, and an arrow indicates the frequency band corresponding to a wavelength of about 3 years. In the graphs of coherence, 10 % and 5 % levels of probability are indicated.

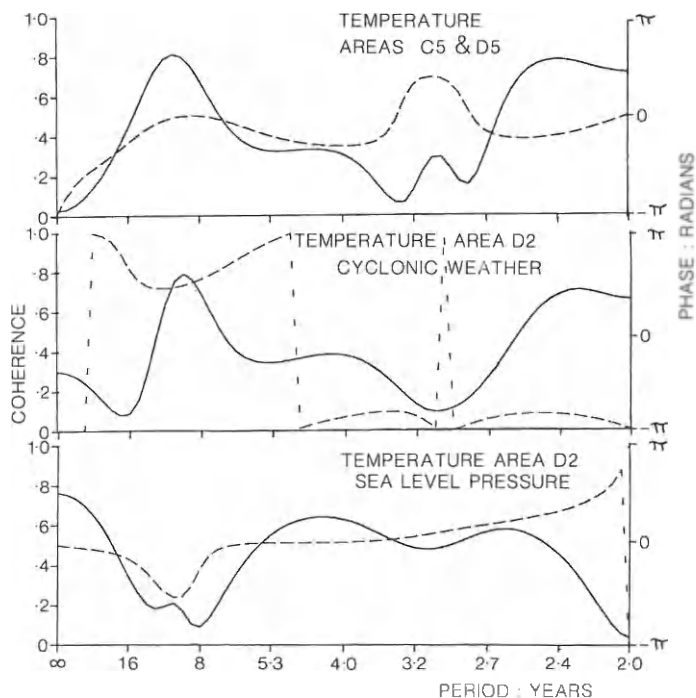


Figure 7. Plots of the coherence (solid lines) and phase (dashed lines) spectra for: (top) sea surface temperature (1948 to 1980) for areas C5 and D5 (see Fig. 1); (centre) sea surface temperature in area D2 and the frequency of cyclonic weather over the U.K.; (bottom) the same temperature data and the fluctuations in sea-level atmospheric pressure associated with the distribution pattern shown in Figure 4.

involving heat flux and evaporation. This can be illustrated using monthly data from Ocean Weather Station India. Figure 6 shows the coherence and phase spectra for temperature and salinity and the coherence spectra for temperature and heat flux, and salinity and evaporation.

The cross-spectra between salinity and temperature show a band with a wavelength of about 3 years in which there is a peak in coherence but the salinity and temperature are nearly out of phase. The other coherence spectra show that variations in surface-heat exchanges are an important source of variability in this wave band. Also, the spectra of heat flux and evaporation have peaks at about 3 years, indicating that there is forcing at this wavelength. Varying surface fluxes can be expected to cause variations in salinity and temperature that differ markedly in phase and can also be presumed to influence the vertical density structure in the surface layers, which may in turn be the source of variations in the abundance of the plankton in this frequency band.

The histogram of the frequency of peaks in the spectra of zooplankton (Fig. 2) shows a fairly high frequency of peaks relating to periods of 10 to 20 years.

Peaks at wavelengths of 10 to 12 years occur regularly in the spectra and cross-spectra of year-to-year variations in sea surface temperature, particularly in the areas in Figure 1 south of 59°N (that is, all the C and D

areas). As an example, Figure 7 (top) shows the spectra and cross-spectra for areas C5 and D5. A peak at about the same wavelength also occurs in the spectrum for the frequency of cyclonic weather over the United Kingdom which is generally in phase with the variability in the temperatures. As an example, Figure 7 (centre) shows the cross-spectra for cyclonic weather and temperature in area D2. Figure 7 (bottom) shows the cross-spectra for temperature in area D2 and the fluctuations in atmospheric pressure associated with the geographical pattern shown in Figure 4. The coherence shows a marked dip corresponding to the peak in the coherence with the cyclonic weather.

Although peaks corresponding to this wavelength occur occasionally for some species of zooplankton, the most systematic relationship is, however, with five species of phytoplankton, all belonging to the genus *Ceratium*. Figure 8 shows the first principal components of the annual fluctuations in abundance of each of these species for the 12 areas shown in Figure 1, together with plots of sea surface temperature and the frequency of cyclonic weather. Data for the *Ceratium* species are available only since 1958 and, given the short time series, coherence spectra have not been calculated. In Figure 8, fitted polynomial curves emphasize the long-term variations and suggest that the five species are negatively related to both temperature and cyclonic weather.

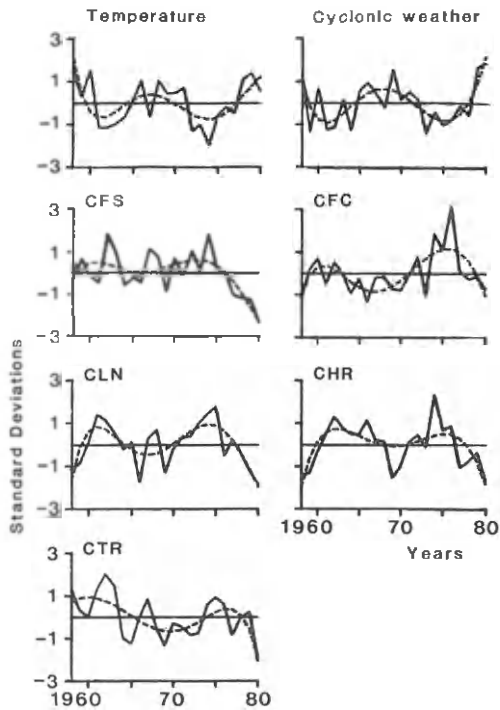


Figure 8. Plots of sea surface temperature, frequency of cyclonic weather, and the first principal components of *Ceratium fusus* (CFS), *Ceratium furca* (CFC), *Ceratium lineatum* (CLN), *Ceratium horridum* (CHR) and *Ceratium tripos* (CTR) in all the areas shown in Figure 1. All the plots refer to the period 1958 to 1980, and all are standardized to zero mean and unit variance; superimposed (dashed lines) are fitted fourth-order polynomial curves.

Most of the variables considered in this study show clear seasonal cycles and, in the plankton and the sea surface temperatures, the amplitude of the seasonal changes is far larger than the year-to-year changes. There is, therefore, the possibility of interaction between the seasonal cycle and periodic variability at longer wavelengths producing beat frequencies with wavelengths of less than a year and between 1 and 2 years. Since the Nyquist frequency of the annual data series is 0.5 cycles per year, beat frequencies can only be detected in the monthly series. Figure 9 shows a portion of the spectrum of temperature in area C5 and the coherence spectrum for areas C5 and B5 (see Figure 1). In addition to the clear peak of the seasonal cycle both spectra show peaks at about 2.3 to 2.7 years and also at 1.6 years, which is the expected wavelength of the beat frequency. There should also be a second beat frequency at about 0.7 years, but this does not occur in either of the spectra. Figure 9 also contains a portion of the spectrum of an artificial random variable containing a seasonal cycle modulated by a cycle of 2.8 years corresponding with the peak in the temperature data. In

this spectrum both of the expected beat frequencies, with wavelengths of 1.8 and 0.7 years, occur and these also appear in the coherence spectrum of a pair of such variables. The phase relationships in the temperature cross-spectrum for areas C5 and B5 are in agreement with those of the simulated data confirming the identification of the beat frequencies.

In the annual series it is possible that such beat frequencies may be aliased to produce peaks at wavelengths of just over 2 years, and this may account for at least some of the peaks in the plankton data in this wave band (see Fig. 2).

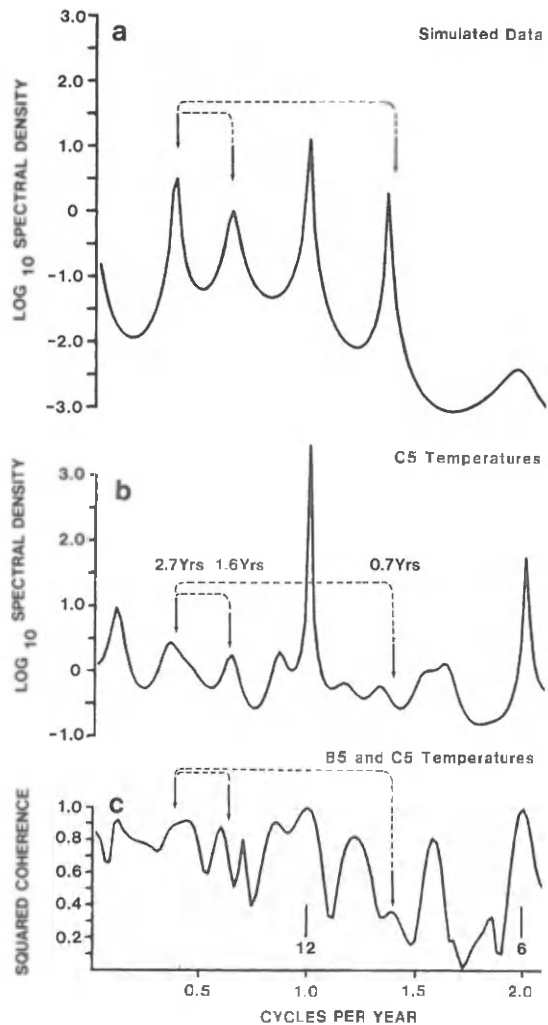


Figure 9. Spectra showing beat frequencies from interactions with the seasonal cycle. (a) Simulated data. (b) Temperature for 1948 to 1980 for area C5 (see Fig. 1). (c) Coherence spectra for temperatures for areas B5 and C5. The peaks at 33 months and 12 months are indicated together with the beat frequencies.

Conclusions

The presentation of spectra of time series raises the question of the existence of real cyclical fluctuations. All the time series considered in this study represent small samples from series that are probably stationary over very much longer periods, and none of the characteristic frequencies can be regarded as proof of real cyclical behaviour.

The spectra are, nevertheless, useful in a number of ways. Clearly the number of possible combinations of variables is very much larger than the number of variables and their spectra provide "finger prints" useful in the search for relationships between variables.

The cross-spectra provide valuable information about the nature of relationships and, in particular, how the extent of relationship varies with wavelength.

It would appear that characteristic time scales are involved in most of the relationships and some of these can be associated with particular processes. It has been shown that the peaks in the spectra at wavelengths of 3–4 years may be associated with surface heat exchange phenomena, and it seems likely that the longest wavelengths are associated with variations in the major current systems (Colebrook and Taylor, 1979; Taylor and Stephens, 1980 b). In the plankton the long wavelength variations are probably enhanced by persistence.

The 10–12-year peaks in sea surface temperature and climate and the 5–6-year peaks in the plankton have not, as yet, been identified with any process.

There are still problems in the interpretation of the nature of relationships as displayed by coherence and phase spectra. What has been presented here is based on the clearest and simplest patterns in the spectra and is far from being a complete study of the available information.

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