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Plankton in the North Atlantic—An Example of the Problems of Analysing Variability in the Environment

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Le plancton dans l'Atlantique Nord: un exemple des problèmes posés par l'analyse de la variabilité du milieu

On peut détecter et mesurer la variabilité résultant de l'action de la pollution sur le milieu par comparaison avec le spectre de variation naturelle. Il convient d'intensifier la recherche sur la variabilité dans les mers et de la rattacher plus étroitement aux études atmosphériques.

Un exemple des problèmes qui se posent nous est donné par l'enquête effectuée dans l'Atlantique Nord et la mer du Nord par collecte permanente du plancton. Au cours des 22 dernières années, on a constaté que dans une partie de la région de nombreuses espèces accusaient progressivement une diminution quantitative alors que la biomasse du zooplancton se contractait; la saison d'activité biologique, à en juger par les stocks permanents à une profondeur d'échantillonnage de 10 m, semble s'être réduite.

Il est difficile d'établir un rapport entre ces modifications et certains facteurs causatifs par suite de l'insuffisance des observations sur le milieu. On ne sait pas exactement si les modifications de la température de l'eau de mer, ou les tendances du climat et des radiations solaires sont de caractère cyclique ou continu, si elles résultent de la turbidité croissante de l'atmosphère ou des variations de l'activité solaire. Des travaux expérimentaux ont montré que les résidus de pesticides peuvent faire baisser le taux de photo-

El plancton en el Atlántico Norte: un ejemplo de los problemas que plantea el análisis de la variabilidad del medio ambiente

La variabilidad inducida por la contaminación debe ser descubierta y medida comparándola con el espectro de la variación natural. Será necesario intensificar las investigaciones sobre variabilidad en los mares y correlacionarla más estrechamente con los estudios de la atmósfera.

Los problemas de que se trata resultan manifestos por el estudio realizado en el Atlántico Norte y Mar del Norte con el registrador continuo de plancton. Durante los 22 últimos años, en una parte de esta zona ha habido una disminución progresiva de la abundancia de muchas especies y de la biomasa del zooplancton; a juzgar por los efectivos de la población a la profundidad de 10 m en que se tomaban las muestras, la temporada anual de actividad biológica resulta acortada.

Es difícil relacionar estos cambios con los factores causantes dada la insuficiencia de observaciones ambientales. No está claro si los cambios de la temperatura del agua o de las tendencias en cuanto a clima y radiación solar, son cíclicos o constantes, ni si son el resultado de la mayor turbidez de la atmósfera o de variaciones en la energía radiada por el sol. Los trabajos experimentales han demostrado que los residuos de plaguicidas pueden reducir el ritmo

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synthèse, mais on ne dispose pas de données à long terme concernant la présence de pesticides dans la haute mer. On ignore s'il y a eu des modifications de la répartition verticale du plancton, ou si ses taux de production et de remplacement ont changé. En l'absence d'enquêtes permettant la comparaison entre les régions benthiques et côtières, on ignore si l'évolution constatée dans le plancton reflète une tendance générale des peuplements marins.

Le progrès technique, par exemple dans le domaine des ordinateurs et des instruments de terrain, nous donnera la possibilité de résoudre nombre de ces difficultés.

de la fotosíntesis pero no se dispone de datos de un período prolongado en lo que se refiere a los plaguicidas en el mar abierto. No se sabe si se producen cambios en la distribución vertical del plancton o en las tasas de producción y de reposición. A falta de estudios comparables del bentos y de las regiones costeras, no es posible inferir, si lo que ocurre en el plancton, refleja una tendencia general en las comunidades marinas.

Los adelantos técnicos en lo que se refiere, por ejemplo, a calculadoras electrónicas e instrumentos utilizados en el mar, ofrecen la oportunidad de resolver muchas de estas dificultades.

THE immediate effects of pollution can often be recognized in the field and studies in the laboratory when the precise nature of the pollutant and its source are known; for example in oil spills and localized industrial effluents.

But it will always be difficult to detect and assess the effects of pollutants whose temporal and spatial gradients are not sharply defined and localized. These include those by-products of society and industry which may be dispersed via the atmosphere or drained into the sea at numerous points through river systems; for example, fertilizers, pesticides, dusts, carbon dioxide and heavy metals from vehicle exhausts and fungicides. Most of these substances are likely to be diluted quickly to sublethal levels in the natural environment, so that it will not only be difficult to detect their concentration gradients but, also, there may not be any dramatic and easily recognizable symptoms. Nevertheless, they may give rise to subtle effects in natural ecosystems which are exposed to them over very long periods of time. Moreover, pollution at a sublethal level may interact with "normal" natural stresses and so create effects which are out of all proportion to the component risks.

In dramatic pollution incidents as well as the long-term accumulation of "trace-pollutants", there is a possibility that populations and communities which are not themselves exposed to pollution may be affected by disturbance of the ecosystem; for example, by lethal effects or changes in productivity in a distant part of the food chain. Difficulties in extrapolating and predicting from experimental studies will arise because the effects of a given pollutant, as determined in the laboratory, will apply with varying force in different natural communities and in different locations; the effects may be more critical during some seasons or phases of life cycles than at others. These ecological problems are complicated by the dependence of equilibrium, in an ecosystem, on the interrelations of migratory as well as non-migratory animals. The effects of all but the most dramatic of pollution incidents will probably be small in relation to the scale of natural variations. However, natural changes tend to be cyclic whereas many pollutants are likely to have linear and cumulative effects. The superimposition of a small, but systematic, change on the natural cycles could have major effects on the productivity or composition of an ecosystem in the course of, say, a decade or two.

Because of these and similar difficulties in detecting and assessing the effects of pollution, it has been argued that there is an urgent need to advance our understanding of variability, and its causes, in natural ecosystems. In particular, it will be essential to establish ecological "base-lines" so that the effect of pollutants can be identified against natural variation.

But there has been relatively little research on ecosystems. Fisheries research provides many examples of such studies but the data reflect the direct activities of man to such a large extent that natural sources of variability are often obscured. What is needed are assessments of variability in natural populations and communities which are not directly exploited by man.

The Continuous Plankton Recorder Survey provides an example of a long-term study of a small part of the marine ecosystem. Some of the data from this survey have been selected to illustrate just one of the kinds of variability which occur in unexploited populations and to suggest some of the problems that must be faced if the background of natural variability is to be studied as the basis for detecting, assessing and predicting the effects of pollutants.

It must be emphasized (a) that this is not a paper about pollution and (b) that the examples of environmental variation shown here are not to be interpreted as the sources of the changes in the plankton; they are given only to illustrate the problems of monitoring and analysing field data.

The Continuous Plankton Recorder Survey

Continuous Plankton Recorders (Hardy, 1939) are towed by merchant ships and ocean weather ships in the North Atlantic Ocean and the North Sea. They sample at a standard depth of 10 m; the material is analysed to provide numerical estimates of the abundance of the common species in alternate ten-mile sections of each tow. Sampling is repeated at monthly intervals along more than twenty standard routes. Details of the survey are given by Glover (1967).

The survey has formed the basis of analyses of many aspects of variation in the distribution, abundance and composition of the plankton. Colebrook (1965, 1969) has discussed the problems of such analyses and has explored the use of multi-variate statistics in dealing with the complex of interactions between the variability due to species, regions, months, years and parameters of the environment. In this paper we shall ignore all aspects of this complex except annual variation; indeed we shall deal with only a limited aspect of this, to demonstrate some selected long-term trends, without attempting the intensive statistical analysis which will be required if these trends are to be understood in the context of all the other sources of variation. This paper deals only with the eastern part of the survey which has been sampled consistently since 1948 (extension into the western North Atlantic was not started until 1961).

It is not necessary here to describe the standard methods of analysis of Plankton Recorder samples, except to say that the numbers of each organism in each ten-mile sample are transformed logarithmically [$y = \log 10 (x + 1.0)$]. These transformed estimates are then averaged to give an expression of the abundance of solar activity. Superimposed on these long-term cycles are shorter period fluctuations of which the sun-spot cycle of 11 years is the best known.

Despite the conflicts in the evidence and its interpretation, there appear to have been changes in solar radiation that could, conceivably, contribute towards patterns of variation in the plankton of the kind described in this paper. However, it is far from clear whether the atmospheric changes are parts of cycles or continuing trends, and whether they are generated from outside the earth's atmosphere or are the products of man's activities. There has been very little research into the possible relationships, partly because there is a gross shortage of observations made with the required resolution and accuracy over a sufficient period of time; most observational programmes in the atmosphere have been directed largely towards the solution of purely meteorological problems.

The same inconclusive comments could be made, with varying force, with regard to all the other aspects of the marine environment which we have not considered here. For example, there is little understanding of the biogeographical effects of observed variations of sea temperature, although Rodewald (1967) has demonstrated some major trends in sea surface temperature during the past few decades (which, incidentally, he attributes partly to changes in the atmospheric pressure system over the North Atlantic). Although more research could be done, it will be severely restricted by the availability of past records which consist largely of surface temperatures taken by merchant ships and reported to the Meteorological Office with a low degree of resolution.

The situation is even worse if we consider variables that are not included in weather monitoring programmes. It would be quite impossible, for example, to compile a record of fluctuations of nutrients in time and space, during the past twenty years in the North Atlantic. The failure to make such records reflects the shortage of funds and man-power for research but it also arises from the technical difficulty of making measurements in the field on the required scale. However, the absence of such field records has the effect of sterilizing knowledge gained from laboratory experiments which have shown, for example, that light, temperature and nutrients are, indeed, critical to the fundamental biological processes of marine organisms.

The same argument applies to a consideration of pollutants. For example, in laboratory experiments, Wurster (1968) found that DDT reduced the rate of photosynthesis in four species of phytoplankton. Menzel, Anderson and Randtke (1970) showed that the effect varied considerably between species; thus, although "chlorinated hydrocarbons may not be universally toxic to all species, they may exert a dramatic effect on the succession and dominance of individual forms". Valuable laboratory studies of this kind are wasted unless we know whether there are chlorinated hydrocarbons in the seas and, if so, whether their concentration has varied in time and space. Moreover the results of short-term laboratory experiments (whether they be studies of fundamental physiology or of pollutants) cannot be extrapolated simply to conditions in the field. In this particular example, the depression of photosynthesis occurred at concentrations near or above the limit of solubility of DDT in water. But the experiment was not designed to measure the effects of long-term exposure to lower concentrations (and we wonder whether sufficient attention is being paid to regional and temporal variations in lipids which might hold pesticide residues in the sea water?).

Variations in the plankton of the open sea were used as the starting point in this paper but, because of the lack of comparable surveys of the coasts and inshore regions, we do not know whether there have been similar variations in the abundance, biomass or seasonal cycles of benthic organisms. Indeed, the validity of the apparent trends in the plankton is in question. Continuous Plankton Recorders sample at only one depth, 10 m, and we do not know whether there have been systematic changes in the vertical distribution of the plankton. It must be conceded, also, that the results described here refer only to standing stocks; we do not know whether there have been changes in the rate of production and turnover. In an attempt to overcome a few of these problems, the Edinburgh Oceanographic Laboratory is now engaged on an ambitious programme of design of a new Oceanographic Recorder which will undulate vertically as it is towed by merchant ships. In addition to sampling the plankton in the upper 75 or 100 m, it will contain a data logger and sensors for various physical and biophysical parameters (Glover, 1967, 1970).

Concluding remarks

We have used very simple examples, in this paper, designed to make what should be a simple and obvious point. The present state of knowledge of variability in the field and the present level of monitoring the natural environment are inadequate for the detection and identification of the sources of variation and, especially, for the separation of natural processes from all but the most obvious consequences of pollution incidents.

It follows from the arguments advanced in this paper that it is essential to implement field monitoring programmes designed to provide the basic data for environmental research as a whole; the problems of pollution cannot be considered in isolation from those of ecology in general. Theoretical and laboratory studies have shown the kinds of variables that should be measured but these are often ignored. For example, as Professor R. A. Bryson pointed out (at the 1968 National Meeting of the American Association for the Advancement of Science), although it has been established theoretically that the atmospheric dust load could affect many aspects of climate, "there are no systematic observations of dust densities and distribution, and apparently no plans for such observations contained in the Global Atmospheric Research Program of the World Weather Watch!"

It ought not to be necessary to emphasize the need to integrate environmental monitoring programmes so that, for example, atmospheric observations are designed to meet the requirements, not only of meteorologists, but also of biologists and, conversely, to ensure that plans for oceanographic monitoring should consider the needs of meteorologists. Indeed, as the examples in this paper have shown, the need to share monitoring programmes is only one aspect of the need to achieve a truly multi-disciplinary approach to marine science. Dickson and Lee (1969) made the same point when they said, "It is clear therefore that changes in the atmospheric circulation

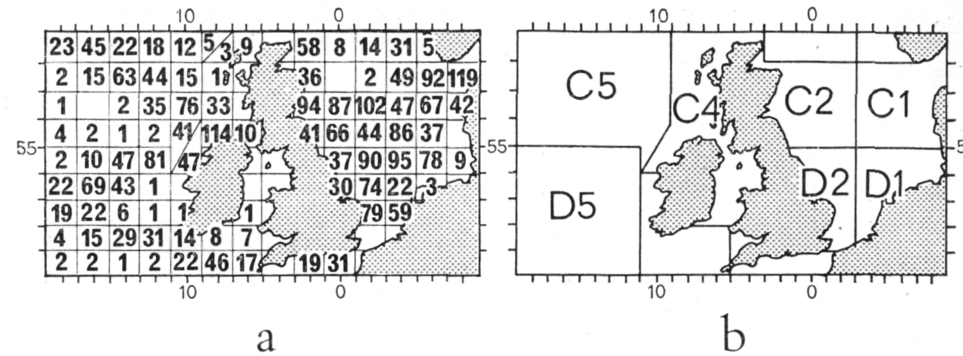

Fig. 1. The Continuous Plankton Recorder Survey 1948–1969
(a) Total numbers of analysed samples ($\times 10^{-1}$) *in the standard rectangles of the eastern part of the survey*
(b) The seven sub-areas for which data are presented in this paper

each organism in each standard rectangle (1° latitude by 2° longitude). For most purposes the rectangle means are averaged again to give the results for larger sub-areas which are designed to correspond, approximately, with the regional sub-division of fishery statistics. Although the logarithmic transformation has many merits in statistical analysis of the results (Colebrook, 1960), this standard treatment has the disadvantage that back-transformation of the processed data does not restore the rectangle or sub-area estimates to the original numbers per sample. For most purposes, therefore, the results must be considered as indices of abundance.

Figure 1a gives the numbers of analysed samples ($\times 10^{-1}$) in each of the rectangles of the area around the British Isles. Figure 1b shows the seven sub-areas which are the basis of all the results expressed in this paper. There was an observation for every month from January 1948 to December 1969 in all of these seven sub-areas.

Annual fluctuations in the plankton

Previous papers describing annual variations of plankton in the Recorder Survey have dealt with relatively short periods of about 12 years; see, for example, Colebrook and Robinson (1964). Glover (1967a, 1970), showed graphs of the abundance of 19 species of zooplankton during a period of 18 years; there appeared to have been a progressive decline in the abundance of many of these organisms. Robinson (1969) described trends in the phytoplankton and, especially, an apparently progressive delay in the date at which the phytoplankton blooms in the spring of each year.

It is now possible to bring these results up to date (figs 2 and 3), incorporating results for the last 22 years.

Figure 2 shows the annual fluctuations in abundance of eleven zooplankton organisms, selected to typify the range of variation. The results for each sub-area were standardized (with a mean of zero and variance of one) so that (a) results from sub-areas with different levels of abundance could be combined and (b) results for species with different levels of abundance can be compared directly. In this way, the pattern of the fluctuations in abundance can be observed by eliminating differences in abundance between areas and species. Figure 2 serves to illustrate the wide range of variation, within and between species, but it is also apparent that there are certain consistent trends.

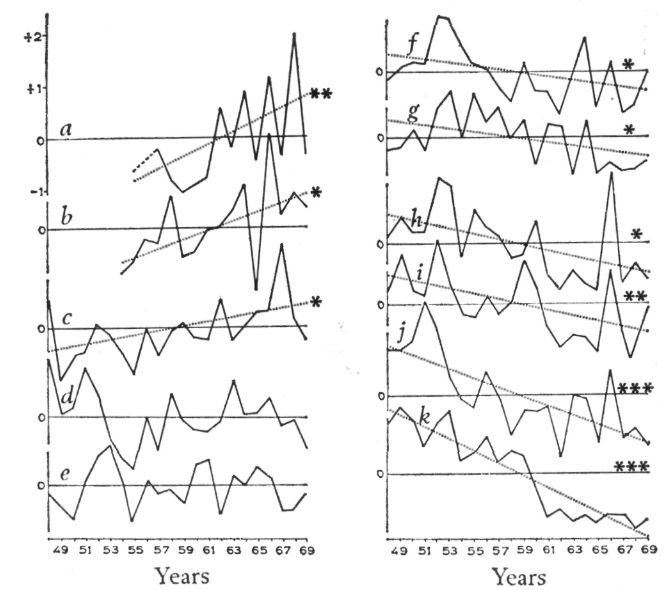

Fig 2. Fluctuations in abundance of eleven zooplankton organisms in the seven areas shown in fig 1(b)

The graphs show the average annual abundance of each species, standardized about a mean of zero; see scale, in standard deviation units, at top left. Calculated trend lines are drawn for those graphs which give a significant fit to a straight line (indicated by one, two or three asterisks for P = <5.0%, <1.0% and <0.1%, respectively).

The organisms are: a. *Pleuromamma borealis;* b. *Euchaeta norvegica;* c. *Acartia clausi;* d. *Temora longicornis;* e. *Clione limacina;* f. *Calanus helgolandicus and finmarchicus,* stages V and VI; g. *Metridia lucens;* h. *Candacia armata;* i. *Centropages typicus;* j. *Spiratella retroversa;* k. *Pseudocalanus* and *Paracalanus*, combined.

Some data for the first two organisms, *Pleuromamma borealis* and *Euchaeta norvegica*, are missing because these species were not counted and identified separately from their genera in the first six or seven years of the survey. Nevertheless, it looks as though these two, and *Acartia clausi*, have been tending to increase in abundance. The next two species (*d, Temora longicornis* and *e, Clione limacina*) do not show any marked trends unless it be the maintenance of their numbers about their long-term mean. The graph *f*, for stages V and VI of *Calanus* (*helgolandicus* and *finmarchicus* combined), shows a moderate decline in abundance. All the remaining species (*g* to *k*) give strong indications of a consistent decrease in abundance throughout the period of 22 years; this is most marked in the case of *Spiratella retroversa* and the combined genera *Pseudocalanus* and *Paracalanus*

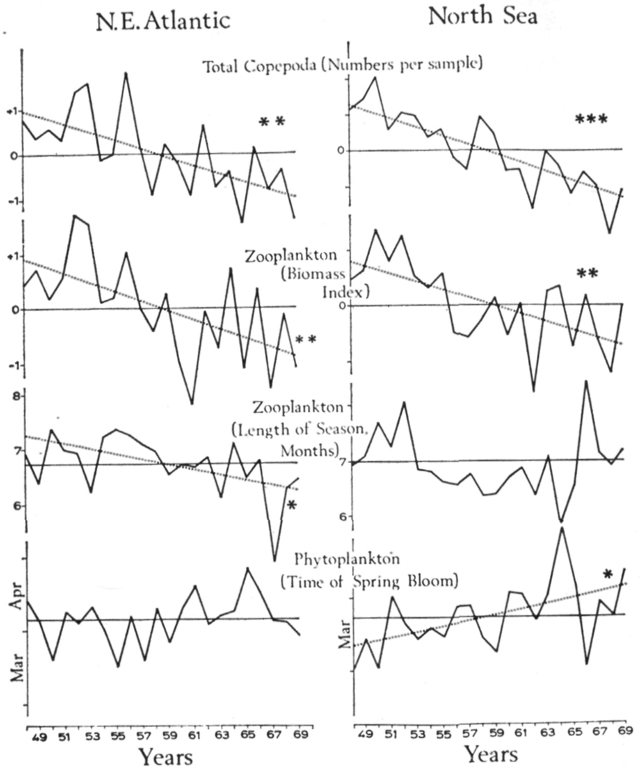

Fig. 3. Fluctuations in the plankton in the north-east Atlantic (sub-areas C4, C5 and D5 combined, see fig 1(b)) and the North Sea (sub-areas C1, C2, D1 and D2 combined) see text for detailed explanation. The results in the top two pairs of graphs are standardized about a mean of zero; the scales in standard deviation units being shown in the left-hand of each pair of graphs. The scales for the bottom two pairs of graphs are in months; plotted about the overall means for 22 years. Calculated trend lines are drawn for those graphs which give a significant fit to a straight line (indicated by one, two or three asterisks for $P = <5.0\%$, $<1.0\%$ and $<0.1\%$, respectively)

(which are not separated in routine analysis of the samples). In those cases where the fit to a straight line is significant at better than 5 per cent, the line and its significance, are indicated.

Figure 3 is an attempt to summarize these trends and to relate them to other indices of events in the plankton; the results for the three Atlantic areas (C4, C5 and D5) are shown separately from those for the North Sea (C1, C2, D1 and D2).

The numbers of copepods (all species combined) were standardized to permit the combination of data from different sub-areas. The graphs in fig 3 show a most dramatic decline with a highly significant fit to a straight line in the Atlantic as well as the North Sea.

Zooplankton biomass was calculated from the estimates of numerical abundance using the method developed by Glover (1968) to plot the geographical distribution of biomass. Briefly, the numbers of organisms in the six major groups in the zooplankton were multiplied by the net weights, using the best available estimates extracted from various published material. These were: 1.24 and 0.10 for Copepoda larger and smaller than *Calanus* stage IV, respectively, 0.8 to 14.5 for Euphausiidae (depending on the month), 3.0 for Hyperiidae, 1.3 for Chaetognatha and 0.12 for Gastropoda, Thecosomata. No attempt was made to allow for regional variations in weight nor, with the exception of Euphausiidae, for seasonal changes. Moreover, because of the logarithmic transformations and the standardization of the data for each sub-area, mentioned above, the results cannot be expressed as biomass in terms of wet weight per unit volume of water sampled: they can only be regarded as a "biomass index". Despite the crudity of the method, fig 3 gives a clear indication of a systematic decline in the biomass of the standing stock of zooplankton at the standard sampling depth of 10 m. In the north-eastern Atlantic as well as the North Sea the fit to a straight line is significant at < 1 per cent. A more detailed analysis, which is not yet complete, suggests that the greater part of the fall in biomass arose from a decline in the abundance of small copepods, chiefly *Pseudocalanus* and *Paracalanus*.

Previous work in the Recorder Survey has often emphasized the importance of variations, between years and areas, in the timing of the seasonal cycle and its duration. Colebrook and Robinson (1965) used a statistical technique to estimate the "season duration" of the phytoplankton and copepods. For this paper we have used a different technique. The beginning and end of the "season" were calculated as the dates in the spring and autumn when the graphs of zooplankton biomass crossed the mean in each sub-area for the whole year; we assumed a linear rate of change between months. In this way differences in overall abundance, between years and sub-areas, were eliminated; the dates were calculated with regard to the shape of the seasonal curve in each year and area without regard to its height (or abundance). The results in fig 3 show that there has been considerable variation, between years, in the length of the season, measured from the standing stock of zooplankton biomass. Moreover, in the north-east Atlantic at least, the duration of the season appears to have become progressively shorter, amounting to a decrease of about 4½ weeks during the past 22 years, judging from the slope of the calculated straight line.

An event with major consequences for almost every aspect of the plankton is the blooming of the phytoplankton in the spring of each year. Visual estimates of the green coloration of the Recorder collecting silks can be used to provide a measure of abundance of phytoplankton (Robinson, 1970). From these estimates, the date of the spring bloom was calculated, in the same way as the season duration of the biomass; that is, the date when the seasonal graph crossed the mean in each sub-area and year. The resultant estimates, in fig 3, show a wide range of variation with a suggestion of a progressive delay in both regions, although the fit to a straight line is significant (at < 5 per cent) in the North Sea only. From these results, it might be estimated that the delay in the start of the phytoplankton bloom has amounted to about 3 weeks, judging by the slope of the calculated straight line for the North Sea data.

Obviously, further analysis of the data will be needed to define the extent and precise form of the changes in the plankton which are suggested by this limited selection from the results. The attempt to fit straight lines, for example, is probably an unjustifiable simplification and it will be necessary to investigate the variability of large numbers of species not presented here. An examination of the diatoms, which is under way, is revealing a very complicated pattern of variability but, again, there appears to have been a decline in abundance of some of

the common species in parts of the survey area—these include *Rhizosolenia styliformis*, *Chaetoceros* (especially *Phaeoceros*), *Nitzschia delicatissima*, *Rhizosolenia imbricata* var. *shrubsolei* and *Dactyliosolen mediterraneus*.

Discussion

It would be premature to try to relate these trends in the plankton to changes in physical parameters. However, in order to illustrate the scale of the problem, we conclude with some examples of variability in one of the most critical aspects of the environment—radiant energy—which is too often ignored in spite of its great importance in regard to biological processes in general and photosynthesis in particular.

It is not easy to find appropriate records of radiation over the Atlantic and North Sea and such data as are available often reveal conflicting patterns of variation. Figure 4 shows four of the various direct and indirect estimates that might be used to describe solar radiation at the surface of the sea or on land in the northern hemisphere. The estimate for the two Ocean Weather Stations was calculated (using the equation developed by Black, 1956) from tables of low cloud, published by the U.K. Meteorological Office. These two stations lie at the western edge of sub-areas C5 and D5 [fig 1(*b*)]. Although there was considerable variability, between years, there is some indication of a progressive decrease in radiation with a significant fit (< 5 per cent) to a straight line. On the other hand, there is little evidence of a systematic trend in the "hours of bright sunshine" at Lerwick in the Shetlands (from Meteorological Office records) or direct measurements of radiation at Valencia on the west coast of Ireland (from the Irish Meteorological Office).

The last graph in fig 4 is re-drawn from fig 2*a* of Pivovarova (1968). Direct measurements of solar radiation were made at eight stations in the Soviet Union, at or near mid-day when there was no trace of cloud obscuring the sun's disc. Monthly means were calculated and, from these, the annual means and the long-term average. The results in fig 4, expressed as percentages of the long-term mean, show a sharp change in the pattern of the fluctuations at about the middle of the time-series; for the last twenty years, the recorded values of solar radiation have declined steadily. Pivovarova (1968) assumes that the solar constant has not changed and points out that there has been no systematic increase in water vapour in the atmosphere. She concludes that the decrease in radiation was the result of increases in aerosols in the atmosphere; this increased turbidity could have resulted from volcanic eruptions and the gradual pollution of the atmosphere from man's activities. Since there was only one major eruption during this period (in 1963 at Mount Agung in Indonesia), the inference is that the trend of the past twenty years is explained largely as the result of man's increased industrial activity. Pivovarova estimates that the attenuation of radiation due to aerosols increased about 30 per cent in the period 1953 to 1963. This could lead to a reduction of radiation by about 5 per cent.

Workers in other parts of the world have drawn attention to the progressive increase in the turbidity of the atmosphere; see, for example, Petersen and Bryson (1968) who based their conclusions on calculations of

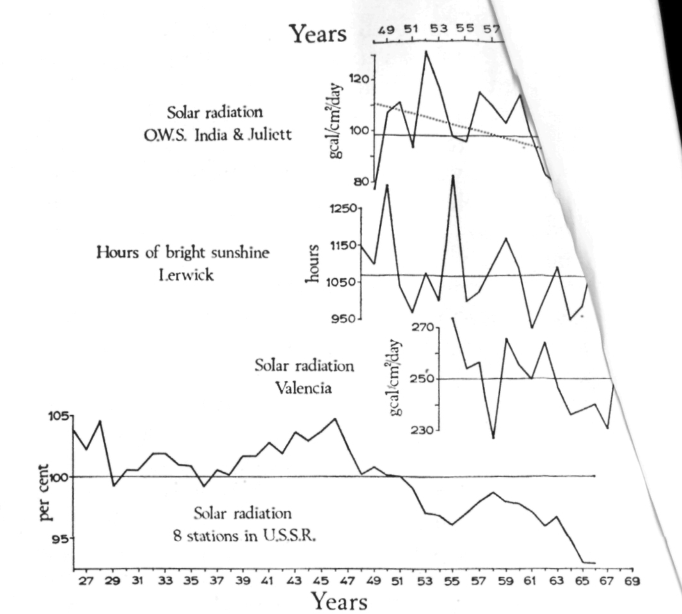

Fig 4. Selected estimates of solar radiation at the surface of the sea and land in the northern hemisphere; see text for detailed explanation. The calculated trend line for solar radiation at the two Ocean Weather Stations fits a straight line ($P < 1.0\%$). The observations at Lerwick, in the Shetland Isles, and Valencia, on the west coast of Ireland, do not fit a straight line at $P = 5.0\%$. No attempt was made to calculate a linear trend line for the observations in the U.S.S.R. (redrawn from Pivovarova, 1968) because of the obvious change in the pattern of variation after 1946

turbidity from measurements of solar radiation in Hawaii. They quote other workers who have measured major increases in the amount of atmospheric particulate matter over the U.S.A. and the Caucasus. McCormick and Ludwig (1967) report increases of 57 per cent and 88 per cent in the turbidity of the air above Washington and Davos, respectively, since the early part of this century; they suggest that global increases in turbidity during the past few decades may be responsible for the decrease in world-wide air temperatures, in spite of the apparent increase of CO_2 which would have the opposite effect. Professor R. A. Bryson, in a paper delivered at the 1968 National Meeting of the American Association for the Advancement of Science, argued that changes in air temperature in this century are related to the observed changes of CO_2 and atmospheric dusts. On the other hand, the Annual Report for 1969 of the Chief Inspector of Alkali Works in the U.K., as reported in *Nature*, vol. 227 (5261), dismisses these theories as mere speculation; he argues that there is no sign that those physical features of the earth which "undergo regular long-term periodicity in fluctuation" are being disturbed by man's efforts "which are puny compared with nature's".

Clearly, there are strong differences of opinion. Lamb (1969) sees the recent global decrease of air temperature as part of a much longer series of climatic oscillations and cycles with their origin in the fluctuating energy output of the sun. He estimates that the reduction of temperature over central England, since 1680, amounts to about 1°C but he points out that this is sufficient to shorten the average growing season, on the land, by about two weeks. Johnson *et al.* (1970) suggest that the fluctuations in temperature are cyclical, compounded of oscillations with periods of 78 and 181 years, related to over the North Atlantic have a dramatic response in the sea itself and that there are possible feedback effects since the ocean is seen to be actively transporting heat from one place to another and not acting merely as a reservoir. But the standard oceanographic observations made in the past only indicate the sort of things which might be happening: they are inadequate for use in any detailed analysis of the coupling between atmosphere and ocean".

Even if satisfactory monitoring can be achieved, there remain many problems in the development of methods for analysing the data. The calculation of a simple average is unlikely to reveal the complexities of environmental interaction; the data for the plankton, in this paper, have been subjected to several transformations (not described in full, for reasons of brevity). Data processing and analysis is another field in which meteorologists, oceanographers and biologists have much to gain from each other.

Until recently, arguments of this kind were no more than idealistic platitudes. However, during the past two or three decades, the problems of environmental science have assumed a new order of dimension and, at the same time, the developments of instrument technology have provided solutions to what, previously, were intractable problems on grounds of intellectual difficulty alone. Technology is now providing instruments to make observations, the data loggers to record them and the computers with which to analyse them.

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Plankton in the North Atlantic—An Example of the Problems of Analysing Variability in the Environment

*R. S. Glover, G. A. Robinson and J. M. Colebrook**

Le plancton dans l'Atlantique Nord: un exemple des problèmes posés par l'analyse de la variabilité du milieu

On peut détecter et mesurer la variabilité résultant de l'action de la pollution sur le milieu par comparaison avec le spectre de variation naturelle. Il convient d'intensifier la recherche sur la variabilité dans les mers et de la rattacher plus étroitement aux études atmosphériques.

Un exemple des problèmes qui se posent nous est donné par l'enquête effectuée dans l'Atlantique Nord et la mer du Nord par collecte permanente du plancton. Au cours des 22 dernières années, on a constaté que dans une partie de la région de nombreuses espèces accusaient progressivement une diminution quantitative alors que la biomasse du zooplancton se contractait; la saison d'activité biologique, à en juger par les stocks permanents à une profondeur d'échantillonnage de 10 m, semble s'être réduite.

Il est difficile d'établir un rapport entre ces modifications et certains facteurs causatifs par suite de l'insuffisance des observations sur le milieu. On ne sait pas exactement si les modifications de la température de l'eau de mer, ou les tendances du climat et des radiations solaires sont de caractère cyclique ou continu, si elles résultent de la turbidité croissante de l'atmosphère ou des variations de l'activité solaire. Des travaux expérimentaux ont montré que les résidus de pesticides peuvent faire baisser le taux de photo-

El plancton en el Atlántico Norte: un ejemplo de los problemas que plantea el análisis de la variabilidad del medio ambiente

La variabilidad inducida por la contaminación debe ser descubierta y medida comparándola con el espectro de la variación natural. Será necesario intensificar las investigaciones sobre variabilidad en los mares y correlacionarla más estrechamente con los estudios de la atmósfera.

Los problemas de que se trata resultan manifestos por el estudio realizado en el Atlántico Norte y Mar del Norte con el registrador continuo de plancton. Durante los 22 últimos años, en una parte de esta zona ha habido una disminución progresiva de la abundancia de muchas especies y de la biomasa del zooplancton; a juzgar por los efectivos de la población a la profundidad de 10 m en que se tomaban las muestras, la temporada anual de actividad biológica resulta acortada.

Es difícil relacionar estos cambios con los factores causantes dada la insuficiencia de observaciones ambientales. No está claro si los cambios de la temperatura del agua o de las tendencias en cuanto a clima y radiación solar, son cíclicos o constantes, ni si son el resultado de la mayor turbidez de la atmósfera o de variaciones en la energía radiada por el sol. Los trabajos experimentales han demostrado que los residuos de plaguicidas pueden reducir el ritmo

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synthèse, mais on ne dispose pas de données à long terme concernant la présence de pesticides dans la haute mer. On ignore s'il y a eu des modifications de la répartition verticale du plancton, ou si ses taux de production et de remplacement ont changé. En l'absence d'enquêtes permettant la comparaison entre les régions benthiques et côtières, on ignore si l'évolution constatée dans le plancton reflète une tendance générale des peuplements marins.

Le progrès technique, par exemple dans le domaine des ordinateurs et des instruments de terrain, nous donnera la possibilité de résoudre nombre de ces difficultés.

de la fotosíntesis pero no se dispone de datos de un período prolongado en lo que se refiere a los plaguicidas en el mar abierto. No se sabe si se producen cambios en la distribución vertical del plancton o en las tasas de producción y de reposición. A falta de estudios comparables del bentos y de las regiones costeras, no es posible inferir, si lo que ocurre en el plancton, refleja una tendencia general en las comunidades marinas.

Los adelantos técnicos en lo que se refiere, por ejemplo, a calculadoras electrónicas e instrumentos utilizados en el mar, ofrecen la oportunidad de resolver muchas de estas dificultades.

THE immediate effects of pollution can often be recognized in the field and studies in the laboratory when the precise nature of the pollutant and its source are known; for example in oil spills and localized industrial effluents.

But it will always be difficult to detect and assess the effects of pollutants whose temporal and spatial gradients are not sharply defined and localized. These include those by-products of society and industry which may be dispersed via the atmosphere or drained into the sea at numerous points through river systems; for example, fertilizers, pesticides, dusts, carbon dioxide and heavy metals from vehicle exhausts and fungicides. Most of these substances are likely to be diluted quickly to sublethal levels in the natural environment, so that it will not only be difficult to detect their concentration gradients but, also, there may not be any dramatic and easily recognizable symptoms. Nevertheless, they may give rise to subtle effects in natural ecosystems which are exposed to them over very long periods of time. Moreover, pollution at a sublethal level may interact with "normal" natural stresses and so create effects which are out of all proportion to the component risks.

In dramatic pollution incidents as well as the long-term accumulation of "trace-pollutants", there is a possibility that populations and communities which are not themselves exposed to pollution may be affected by disturbance of the ecosystem; for example, by lethal effects or changes in productivity in a distant part of the food chain. Difficulties in extrapolating and predicting from experimental studies will arise because the effects of a given pollutant, as determined in the laboratory, will apply with varying force in different natural communities and in different locations; the effects may be more critical during some seasons or phases of life cycles than at others. These ecological problems are complicated by the dependence of equilibrium, in an ecosystem, on the interrelations of migratory as well as non-migratory animals. The effects of all but the most dramatic of pollution incidents will probably be small in relation to the scale of natural variations. However, natural changes tend to be cyclic whereas many pollutants are likely to have linear and cumulative effects. The superimposition of a small, but systematic, change on the natural cycles could have major effects on the productivity or composition of an ecosystem in the course of, say, a decade or two.

Because of these and similar difficulties in detecting and assessing the effects of pollution, it has been argued that there is an urgent need to advance our understanding of variability, and its causes, in natural ecosystems. In particular, it will be essential to establish ecological "base-lines" so that the effect of pollutants can be identified against natural variation.

But there has been relatively little research on ecosystems. Fisheries research provides many examples of such studies but the data reflect the direct activities of man to such a large extent that natural sources of variability are often obscured. What is needed are assessments of variability in natural populations and communities which are not directly exploited by man.

The Continuous Plankton Recorder Survey provides an example of a long-term study of a small part of the marine ecosystem. Some of the data from this survey have been selected to illustrate just one of the kinds of variability which occur in unexploited populations and to suggest some of the problems that must be faced if the background of natural variability is to be studied as the basis for detecting, assessing and predicting the effects of pollutants.

It must be emphasized (a) that this is not a paper about pollution and (b) that the examples of environmental variation shown here are not to be interpreted as the sources of the changes in the plankton; they are given only to illustrate the problems of monitoring and analysing field data.

The Continuous Plankton Recorder Survey

Continuous Plankton Recorders (Hardy, 1939) are towed by merchant ships and ocean weather ships in the North Atlantic Ocean and the North Sea. They sample at a standard depth of 10 m; the material is analysed to provide numerical estimates of the abundance of the common species in alternate ten-mile sections of each tow. Sampling is repeated at monthly intervals along more than twenty standard routes. Details of the survey are given by Glover (1967).

The survey has formed the basis of analyses of many aspects of variation in the distribution, abundance and composition of the plankton. Colebrook (1965, 1969) has discussed the problems of such analyses and has explored the use of multi-variate statistics in dealing with the complex of interactions between the variability due to species, regions, months, years and parameters of the environment. In this paper we shall ignore all aspects of this complex except annual variation; indeed we shall deal with only a limited aspect of this, to demonstrate some selected long-term trends, without attempting the intensive statistical analysis which will be required if these trends are to be understood in the context of all the other sources of variation. This paper deals only with the eastern part of the survey which has been sampled consistently since 1948 (extension into the western North Atlantic was not started until 1961).

It is not necessary here to describe the standard methods of analysis of Plankton Recorder samples, except to say that the numbers of each organism in each ten-mile sample are transformed logarithmically [$y = \log 10 (x + 1.0)$]. These transformed estimates are then averaged to give an expression of the abundance of

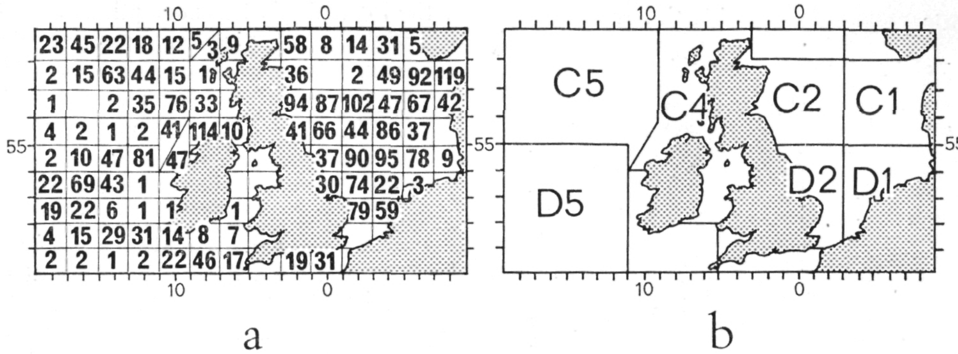

Fig. 1. The Continuous Plankton Recorder Survey 1948–1969

(a) Total numbers of analysed samples ($\times 10^{-1}$) *in the standard rectangles of the eastern part of the survey*

(b) The seven sub-areas for which data are presented in this paper

each organism in each standard rectangle (1° latitude by 2° longitude). For most purposes the rectangle means are averaged again to give the results for larger sub-areas which are designed to correspond, approximately, with the regional sub-division of fishery statistics. Although the logarithmic transformation has many merits in statistical analysis of the results (Colebrook, 1960), this standard treatment has the disadvantage that back-transformation of the processed data does not restore the rectangle or sub-area estimates to the original numbers per sample. For most purposes, therefore, the results must be considered as indices of abundance.

Figure 1a gives the numbers of analysed samples ($\times 10^{-1}$) in each of the rectangles of the area around the British Isles. Figure 1b shows the seven sub-areas which are the basis of all the results expressed in this paper. There was an observation for every month from January 1948 to December 1969 in all of these seven sub-areas.

Annual fluctuations in the plankton

Previous papers describing annual variations of plankton in the Recorder Survey have dealt with relatively short periods of about 12 years; see, for example, Colebrook and Robinson (1964). Glover (1967a, 1970), showed graphs of the abundance of 19 species of zooplankton during a period of 18 years; there appeared to have been a progressive decline in the abundance of many of these organisms. Robinson (1969) described trends in the phytoplankton and, especially, an apparently progressive delay in the date at which the phytoplankton blooms in the spring of each year.

It is now possible to bring these results up to date (figs 2 and 3), incorporating results for the last 22 years.

Figure 2 shows the annual fluctuations in abundance of eleven zooplankton organisms, selected to typify the range of variation. The results for each sub-area were standardized (with a mean of zero and variance of one) so that (a) results from sub-areas with different levels of abundance could be combined and (b) results for species with different levels of abundance can be compared directly. In this way, the pattern of the fluctuations in abundance can be observed by eliminating differences in abundance between areas and species. Figure 2 serves to illustrate the wide range of variation, within and between species, but it is also apparent that there are certain consistent trends.

Some data for the first two organisms, *Pleuromamma*

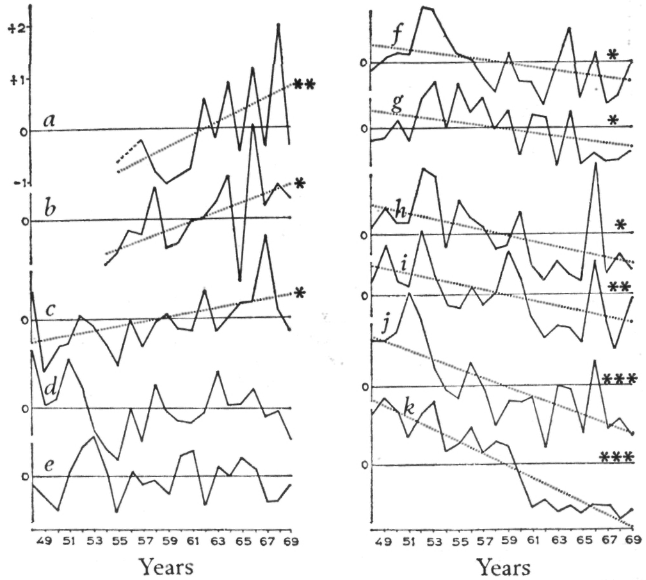

Fig 2. Fluctuations in abundance of eleven zooplankton organisms in the seven areas shown in fig 1(b)

The graphs show the average annual abundance of each species, standardized about a mean of zero; see scale, in standard deviation units, at top left. Calculated trend lines are drawn for those graphs which give a significant fit to a straight line (indicated by one, two or three asterisks for $P = <5.0\%$, $<1.0\%$ and $<0.1\%$, respectively).

The organisms are: a. *Pleuromamma borealis;* b. *Euchaeta norvegica;* c. *Acartia clausi;* d. *Temora longicornis;* e. *Clione limacina;* f. *Calanus helgolandicus and finmarchicus*, stages V and VI; g. *Metridia lucens;* h. *Candacia armata;* i. *Centropages typicus;* j. *Spiratella retroversa;* k. *Pseudocalanus* and *Paracalanus*, combined.

borealis and *Euchaeta norvegica*, are missing because these species were not counted and identified separately from their genera in the first six or seven years of the survey. Nevertheless, it looks as though these two, and *Acartia clausi*, have been tending to increase in abundance. The next two species (*d, Temora longicornis* and *e, Clione limacina*) do not show any marked trends unless it be the maintenance of their numbers about their long-term mean. The graph *f*, for stages V and VI of *Calanus* (*helgolandicus* and *finmarchicus* combined), shows a moderate decline in abundance. All the remaining species (*g* to *k*) give strong indications of a consistent decrease in abundance throughout the period of 22 years; this is most marked in the case of *Spiratella retroversa* and the combined genera *Pseudocalanus* and *Paracalanus*

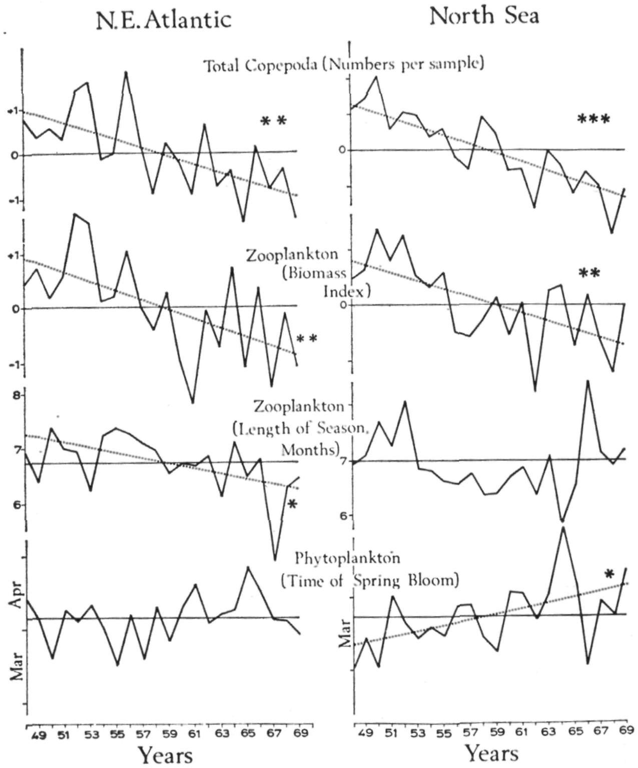

Fig. 3. Fluctuations in the plankton in the north-east Atlantic (sub-areas C4, C5 and D5 combined, see fig 1(b)) and the North Sea (sub-areas C1, C2, D1 and D2 combined) see text for detailed explanation. The results in the top two pairs of graphs are standardized about a mean of zero; the scales in standard deviation units being shown in the left-hand of each pair of graphs. The scales for the bottom two pairs of graphs are in months; plotted about the overall means for 22 years. Calculated trend lines are drawn for those graphs which give a significant fit to a straight line (indicated by one, two or three asterisks for $P = <5.0\%$, $<1.0\%$ and $<0.1\%$, respectively)

(which are not separated in routine analysis of the samples). In those cases where the fit to a straight line is significant at better than 5 per cent, the line and its significance, are indicated.

Figure 3 is an attempt to summarize these trends and to relate them to other indices of events in the plankton; the results for the three Atlantic areas (C4, C5 and D5) are shown separately from those for the North Sea (C1, C2, D1 and D2).

The numbers of copepods (all species combined) were standardized to permit the combination of data from different sub-areas. The graphs in fig 3 show a most dramatic decline with a highly significant fit to a straight line in the Atlantic as well as the North Sea.

Zooplankton biomass was calculated from the estimates of numerical abundance using the method developed by Glover (1968) to plot the geographical distribution of biomass. Briefly, the numbers of organisms in the six major groups in the zooplankton were multiplied by the net weights, using the best available estimates extracted from various published material. These were: 1.24 and 0.10 for Copepoda larger and smaller than *Calanus* stage IV, respectively, 0.8 to 14.5 for Euphausiidae (depending on the month), 3.0 for Hyperiidae, 1.3 for Chaetognatha and 0.12 for Gastropoda, Thecosomata. No attempt was made to allow for regional variations in weight nor, with the exception of Euphausiidae, for seasonal changes. Moreover, because of the logarithmic transformations and the standardization of the data for each sub-area, mentioned above, the results cannot be expressed as biomass in terms of wet weight per unit volume of water sampled: they can only be regarded as a "biomass index". Despite the crudity of the method, fig 3 gives a clear indication of a systematic decline in the biomass of the standing stock of zooplankton at the standard sampling depth of 10 m. In the north-eastern Atlantic as well as the North Sea the fit to a straight line is significant at < 1 per cent. A more detailed analysis, which is not yet complete, suggests that the greater part of the fall in biomass arose from a decline in the abundance of small copepods, chiefly *Pseudocalanus* and *Paracalanus*.

Previous work in the Recorder Survey has often emphasized the importance of variations, between years and areas, in the timing of the seasonal cycle and its duration. Colebrook and Robinson (1965) used a statistical technique to estimate the "season duration" of the phytoplankton and copepods. For this paper we have used a different technique. The beginning and end of the "season" were calculated as the dates in the spring and autumn when the graphs of zooplankton biomass crossed the mean in each sub-area for the whole year; we assumed a linear rate of change between months. In this way differences in overall abundance, between years and sub-areas, were eliminated; the dates were calculated with regard to the shape of the seasonal curve in each year and area without regard to its height (or abundance). The results in fig 3 show that there has been considerable variation, between years, in the length of the season, measured from the standing stock of zooplankton biomass. Moreover, in the north-east Atlantic at least, the duration of the season appears to have become progressively shorter, amounting to a decrease of about 4½ weeks during the past 22 years, judging from the slope of the calculated straight line.

An event with major consequences for almost every aspect of the plankton is the blooming of the phytoplankton in the spring of each year. Visual estimates of the green coloration of the Recorder collecting silks can be used to provide a measure of abundance of phytoplankton (Robinson, 1970). From these estimates, the date of the spring bloom was calculated, in the same way as the season duration of the biomass; that is, the date when the seasonal graph crossed the mean in each sub-area and year. The resultant estimates, in fig 3, show a wide range of variation with a suggestion of a progressive delay in both regions, although the fit to a straight line is significant (at < 5 per cent) in the North Sea only. From these results, it might be estimated that the delay in the start of the phytoplankton bloom has amounted to about 3 weeks, judging by the slope of the calculated straight line for the North Sea data.

Obviously, further analysis of the data will be needed to define the extent and precise form of the changes in the plankton which are suggested by this limited selection from the results. The attempt to fit straight lines, for example, is probably an unjustifiable simplification and it will be necessary to investigate the variability of large numbers of species not presented here. An examination of the diatoms, which is under way, is revealing a very complicated pattern of variability but, again, there appears to have been a decline in abundance of some of the common species in parts of the survey area—these include *Rhizosolenia styliformis*, *Chaetoceros* (especially *Phaeoceros*), *Nitzschia delicatissima*, *Rhizosolenia imbricata* var. *shrubsolei* and *Dactyliosolen mediterraneus*.

Discussion

It would be premature to try to relate these trends in the plankton to changes in physical parameters. However, in order to illustrate the scale of the problem, we conclude with some examples of variability in one of the most critical aspects of the environment—radiant energy—which is too often ignored in spite of its great importance in regard to biological processes in general and photosynthesis in particular.

It is not easy to find appropriate records of radiation over the Atlantic and North Sea and such data as are available often reveal conflicting patterns of variation. Figure 4 shows four of the various direct and indirect estimates that might be used to describe solar radiation at the surface of the sea or on land in the northern hemisphere. The estimate for the two Ocean Weather Stations was calculated (using the equation developed by Black, 1956) from tables of low cloud, published by the U.K. Meteorological Office. These two stations lie at the western edge of sub-areas C5 and D5 [fig 1(*b*)]. Although there was considerable variability, between years, there is some indication of a progressive decrease in radiation with a significant fit (< 5 per cent) to a straight line. On the other hand, there is little evidence of a systematic trend in the "hours of bright sunshine" at Lerwick in the Shetlands (from Meteorological Office records) or direct measurements of radiation at Valencia on the west coast of Ireland (from the Irish Meteorological Office).

The last graph in fig 4 is re-drawn from fig 2*a* of Pivovarova (1968). Direct measurements of solar radiation were made at eight stations in the Soviet Union, at or near mid-day when there was no trace of cloud obscuring the sun's disc. Monthly means were calculated and, from these, the annual means and the long-term average. The results in fig 4, expressed as percentages of the long-term mean, show a sharp change in the pattern of the fluctuations at about the middle of the time-series; for the last twenty years, the recorded values of solar radiation have declined steadily. Pivovarova (1968) assumes that the solar constant has not changed and points out that there has been no systematic increase in water vapour in the atmosphere. She concludes that the decrease in radiation was the result of increases in aerosols in the atmosphere; this increased turbidity could have resulted from volcanic eruptions and the gradual pollution of the atmosphere from man's activities. Since there was only one major eruption during this period (in 1963 at Mount Agung in Indonesia), the inference is that the trend of the past twenty years is explained largely as the result of man's increased industrial activity. Pivovarova estimates that the attenuation of radiation due to aerosols increased about 30 per cent in the period 1953 to 1963. This could lead to a reduction of radiation by about 5 per cent.

Workers in other parts of the world have drawn attention to the progressive increase in the turbidity of the atmosphere; see, for example, Petersen and Bryson (1968) who based their conclusions on calculations of

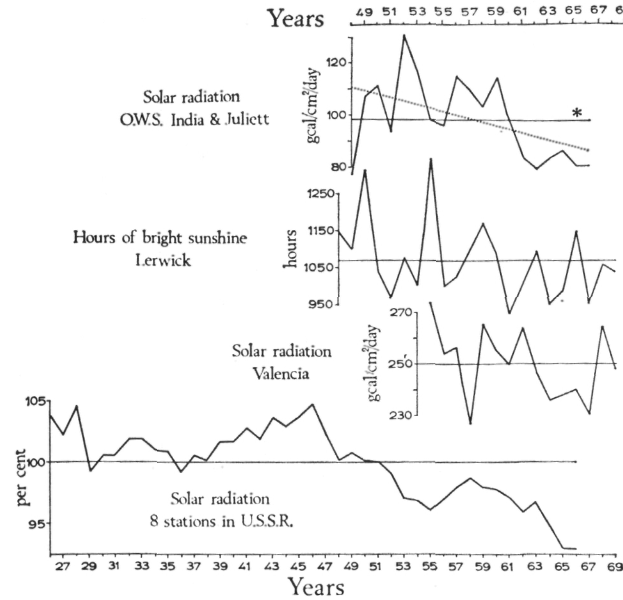

Fig 4. Selected estimates of solar radiation at the surface of the sea and land in the northern hemisphere; see text for detailed explanation. The calculated trend line for solar radiation at the two Ocean Weather Stations fits a straight line ($P < 1.0\%$). The observations at Lerwick, in the Shetland Isles, and Valencia, on the west coast of Ireland, do not fit a straight line at $P = 5.0\%$. No attempt was made to calculate a linear trend line for the observations in the U.S.S.R. (redrawn from Pivovarova, 1968) because of the obvious change in the pattern of variation after 1946

turbidity from measurements of solar radiation in Hawaii. They quote other workers who have measured major increases in the amount of atmospheric particulate matter over the U.S.A. and the Caucasus. McCormick and Ludwig (1967) report increases of 57 per cent and 88 per cent in the turbidity of the air above Washington and Davos, respectively, since the early part of this century; they suggest that global increases in turbidity during the past few decades may be responsible for the decrease in world-wide air temperatures, in spite of the apparent increase of CO_2 which would have the opposite effect. Professor R. A. Bryson, in a paper delivered at the 1968 National Meeting of the American Association for the Advancement of Science, argued that changes in air temperature in this century are related to the observed changes of CO_2 and atmospheric dusts. On the other hand, the Annual Report for 1969 of the Chief Inspector of Alkali Works in the U.K., as reported in *Nature*, vol. 227 (5261), dismisses these theories as mere speculation; he argues that there is no sign that those physical features of the earth which "undergo regular long-term periodicity in fluctuation" are being disturbed by man's efforts "which are puny compared with nature's".

Clearly, there are strong differences of opinion. Lamb (1969) sees the recent global decrease of air temperature as part of a much longer series of climatic oscillations and cycles with their origin in the fluctuating energy output of the sun. He estimates that the reduction of temperature over central England, since 1680, amounts to about 1°C but he points out that this is sufficient to shorten the average growing season, on the land, by about two weeks. Johnson *et al.* (1970) suggest that the fluctuations in temperature are cyclical, compounded of oscillations with periods of 78 and 181 years, related to solar activity. Superimposed on these long-term cycles are shorter period fluctuations of which the sun-spot cycle of 11 years is the best known.

Despite the conflicts in the evidence and its interpretation, there appear to have been changes in solar radiation that could, conceivably, contribute towards patterns of variation in the plankton of the kind described in this paper. However, it is far from clear whether the atmospheric changes are parts of cycles or continuing trends, and whether they are generated from outside the earth's atmosphere or are the products of man's activities. There has been very little research into the possible relationships, partly because there is a gross shortage of observations made with the required resolution and accuracy over a sufficient period of time; most observational programmes in the atmosphere have been directed largely towards the solution of purely meteorological problems.

The same inconclusive comments could be made, with varying force, with regard to all the other aspects of the marine environment which we have not considered here. For example, there is little understanding of the biogeographical effects of observed variations of sea temperature, although Rodewald (1967) has demonstrated some major trends in sea surface temperature during the past few decades (which, incidentally, he attributes partly to changes in the atmospheric pressure system over the North Atlantic). Although more research could be done, it will be severely restricted by the availability of past records which consist largely of surface temperatures taken by merchant ships and reported to the Meteorological Office with a low degree of resolution.

The situation is even worse if we consider variables that are not included in weather monitoring programmes. It would be quite impossible, for example, to compile a record of fluctuations of nutrients in time and space, during the past twenty years in the North Atlantic. The failure to make such records reflects the shortage of funds and man-power for research but it also arises from the technical difficulty of making measurements in the field on the required scale. However, the absence of such field records has the effect of sterilizing knowledge gained from laboratory experiments which have shown, for example, that light, temperature and nutrients are, indeed, critical to the fundamental biological processes of marine organisms.

The same argument applies to a consideration of pollutants. For example, in laboratory experiments, Wurster (1968) found that DDT reduced the rate of photosynthesis in four species of phytoplankton. Menzel, Anderson and Randtke (1970) showed that the effect varied considerably between species; thus, although "chlorinated hydrocarbons may not be universally toxic to all species, they may exert a dramatic effect on the succession and dominance of individual forms". Valuable laboratory studies of this kind are wasted unless we know whether there are chlorinated hydrocarbons in the seas and, if so, whether their concentration has varied in time and space. Moreover the results of short-term laboratory experiments (whether they be studies of fundamental physiology or of pollutants) cannot be extrapolated simply to conditions in the field. In this particular example, the depression of photosynthesis occurred at concentrations near or above the limit of solubility of DDT in water. But the experiment was not designed to measure the effects of long-term exposure to lower concentrations (and we wonder whether sufficient attention is being paid to regional and temporal variations in lipids which might hold pesticide residues in the sea water?).

Variations in the plankton of the open sea were used as the starting point in this paper but, because of the lack of comparable surveys of the coasts and inshore regions, we do not know whether there have been similar variations in the abundance, biomass or seasonal cycles of benthic organisms. Indeed, the validity of the apparent trends in the plankton is in question. Continuous Plankton Recorders sample at only one depth, 10 m, and we do not know whether there have been systematic changes in the vertical distribution of the plankton. It must be conceded, also, that the results described here refer only to standing stocks; we do not know whether there have been changes in the rate of production and turnover. In an attempt to overcome a few of these problems, the Edinburgh Oceanographic Laboratory is now engaged on an ambitious programme of design of a new Oceanographic Recorder which will undulate vertically as it is towed by merchant ships. In addition to sampling the plankton in the upper 75 or 100 m, it will contain a data logger and sensors for various physical and biophysical parameters (Glover, 1967, 1970).

Concluding remarks

We have used very simple examples, in this paper, designed to make what should be a simple and obvious point. The present state of knowledge of variability in the field and the present level of monitoring the natural environment are inadequate for the detection and identification of the sources of variation and, especially, for the separation of natural processes from all but the most obvious consequences of pollution incidents.

It follows from the arguments advanced in this paper that it is essential to implement field monitoring programmes designed to provide the basic data for environmental research as a whole; the problems of pollution cannot be considered in isolation from those of ecology in general. Theoretical and laboratory studies have shown the kinds of variables that should be measured but these are often ignored. For example, as Professor R. A. Bryson pointed out (at the 1968 National Meeting of the American Association for the Advancement of Science), although it has been established theoretically that the atmospheric dust load could affect many aspects of climate, "there are no systematic observations of dust densities and distribution, and apparently no plans for such observations contained in the Global Atmospheric Research Program of the World Weather Watch!"

It ought not to be necessary to emphasize the need to integrate environmental monitoring programmes so that, for example, atmospheric observations are designed to meet the requirements, not only of meteorologists, but also of biologists and, conversely, to ensure that plans for oceanographic monitoring should consider the needs of meteorologists. Indeed, as the examples in this paper have shown, the need to share monitoring programmes is only one aspect of the need to achieve a truly multidisciplinary approach to marine science. Dickson and Lee (1969) made the same point when they said, "It is clear therefore that changes in the atmospheric circulation over the North Atlantic have a dramatic response in the sea itself and that there are possible feedback effects since the ocean is seen to be actively transporting heat from one place to another and not acting merely as a reservoir. But the standard oceanographic observations made in the past only indicate the sort of things which might be happening: they are inadequate for use in any detailed analysis of the coupling between atmosphere and ocean".

Even if satisfactory monitoring can be achieved, there remain many problems in the development of methods for analysing the data. The calculation of a simple average is unlikely to reveal the complexities of environmental interaction; the data for the plankton, in this paper, have been subjected to several transformations (not described in full, for reasons of brevity). Data processing and analysis is another field in which meteorologists, oceanographers and biologists have much to gain from each other.

Until recently, arguments of this kind were no more than idealistic platitudes. However, during the past two or three decades, the problems of environmental science have assumed a new order of dimension and, at the same time, the developments of instrument technology have provided solutions to what, previously, were intractable problems on grounds of intellectual difficulty alone. Technology is now providing instruments to make observations, the data loggers to record them and the computers with which to analyse them.

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