J. mar. biol. Ass. India, 1972, **14** (1): 300-309

ASPECTS OF STATISTICAL METHODS IN OCEANOGRAPHY*

J. D. KERR

CSIRO, Division of Mathematical Statistics, Long Pocket Laboratories, Indooroopilly, Queensland, Australia

ABSTRACT

Statistical methods comprise design and analysis which together provide a sound scientific approach to the collection and analysis of the data and the scrutiny of hypotheses. Modern theory and techniques grew out of agricultural research and has spread to all branches of science. This paper looks at examples in which statistical methods have been applied to oceanographic problems, chiefly from the Indian Ocean. These have initially enabled a more objective but nevertheless still descriptive approach to the consideration of data by distinguishing between systematic and 'random' variation. Here 'random' variation is that which cannot be related to such factors as latitude, depth and season. Some of this results from measurement and estimation errors and small-scale sampling variation. Other variation is a systematic deviation from the simple model which a more adequate model based on causative factors would explain. While the descriptive approach does little to increase the understanding of basic causes and mechanisms, it aids the recognition of the important features of the data and reduces the likelihood of inferences based on unreliable data.

The great potential value of statistics lies in the development of methods for model building and testing, and in the suggestion of new hypotheses. The analysis essentially becomes a multivariate examination of the relations between factors because of the complex relationships between the physical, chemical and biological attributes. Such methods, whether new or adapted from other ecological studies, need to take account of the three-dimensional structure of the ocean and of the dependence on time. Examples are given of some preliminary work in this field.

Design is of prime importance in the collection of data since it determines the inferences that may be drawn from it. In oceanography, sampling is essential and work in adapting suitable methods has hardly begun. Existing theory is well designed for land based problems such as economic surveys, but is of little use in oceanic work due to at least three major problems :

(1) the properties being measured may change markedly during the course of the survey ;
(2) the sampling must be conducted from one or at most a few ships, slow moving in relation to ocean size ;
(3) special problems resulting from ocean movement which make almost impossible many time and space studies quite practicable on land.

Approaches to this problem are tentatively explored. Since ship time is expensive and in short supply, the potential gains are great. However, an imaginative and intensive investigation is required.

INTRODUCTION

OCEANOGRAPHY is one branch of science where statistical methods have not been extensively employed. This despite the fact that modern statistical theory and methodology was developed principally for a parallel branch of science—agricultural research—to meet the needs for a reliable method for the appraisal of variable data.

* Presented at the Symposium on 'Indian Ocean and Adjacent Seas—Their Origin, Science and Resources' held by the Marine Biological Association of India at Cochin from January 12 to 18, 1971.

Major advances were made however, not only in the analysis of data and the testing of scientific hypotheses, but also in the design and planning. Methods in design both of experiments and sample surveys have been developed to facilitate the collection of data which is both amenable to analysis and which provide a powerful test of the proposed hypothesis in relation to reasonable alternatives.

All this development has revolutionized agricultural or land science but has made a relatively small impact on ocean science. Special problems arise which make it difficult or impossible to apply statistical methods without modification.

This paper does not produce definitive answers nor does it survey the whole field. Also the use of statistics in fishery studies is not considered. It is simply an examination of certain approaches that I have used, and a consideration of their defects and the progress that has been made. Quoting my own work enables criticism to be made freely. I welcome both criticism and alternative proposals. It is, however, relevant to note that the use of statistics in oceanographic papers is not well established.

Components of Variation

Statistical analysis is concerned basically with the analysis of variation. Variability may be assigned to factors that are of interest and measured, or assigned to causes that cannot be determined and may be regarded as random. The initial step in any analysis, however simple, involves the setting up of a model, whether implicit or explicit.

Consider for example, a sample of water taken for an oxygen measurement. A subsample of this is used for the actual determination. Then, writing C for oxygen concentration, oxygen C estimated=C subsample+e_3 where e_3 is the error in measurement due to instrument and observer ; oxygen C subsample=C sample+e_2 where e_2 is the difference between Subsample value and the average for the sample ; and C sample=C at required place and depth +e_1 where e_1 is the difference in concentration in sample from that at the spot required since the sample cannot be located exactly ; or $C=\bar{C}+e_1+e_2+e_3$ in symbols.

In the model it is chiefly e_1 that is of interest but it cannot be investigated without a knowledge of the magnitude and distribution of e_2 and e_3. The instrument and observer components of e_3 may be separated and both investigated in a simple experiment. With a little more difficulty, problems of instrumental bias and observer bias may also be studied using standard statistical procedures. The methods of variance components make possible estimation of the subsample effects by correcting for the e_3 component in variation for a number of subsamples, using finite or infinite sampling theory as appropriate.

An investigation of the e_1 component is illuminating since estimation of quantities—be it oxygen, zooplankton, or phosphate—is frequently based on one sample from one depth and position which are only nominally attained. The size of this component obviously places limits on the adequacy of fit of any model on an oceanic or large scale basis. However, there appear to be few instances where a designed pattern of sampling using a depth range to study the variation due to factors such as wire angle and ship movement, and covering an area say one or two miles square to allow for the difficulty of siting a station exactly. If σ_1^2, σ_2^2, and σ_3^2 are the variances of the three 'error' components, it will usually be found that $\sigma_1^2 >> \sigma_2^2 + \sigma_3^2$. Further no model when fitted to the data will have an error variance σ_m^2 less than $\sigma_1^2 + \sigma_2^2 + \sigma_3^2$ when fitted, if it is based on data comprising one sample per depth and one position per nominal station. σ_m^2 will normally far exceed this quantity because (as discussed below) the model is inadequate, and consequently such repeated sampling as a routine matter would be unproductive. Nevertheless absence of this information frequently means it is not possible to objectively judge the adequacy of the model fitted.

An attempt to proceed to a theoretical construction of the correct form of model runs immediately into several difficulties resulting from the inadequacy of available data, the lack of precise theory for specifying the model, and the mathematical and statistical difficulty in handling the complex model that results. Instead I shall discuss many examples, both published and unpublished that result from collaboration—chiefly in the analysis of existing data rather than design in its collection—with the staff of CSIRO Division of Fisheries and Oceanography, at Cronulla.

Experimental and Laboratory Studies of Variability

The value of sound design and statistical analysis of laboratory investigations of oceanographical methodology and the errors associated with any estimation is readily demonstrated. For example, consider a small experiment to assess the recovery of chlorophyll by Chromatography. Recoveries were made from known mixtures of Chlorophylls *a*, *b*, and *c* in pure solution. Analysis—by means of logarithmic transformation and 95% confidence limit estimation—showed that the estimates, as a percentage of the true value, almost certainly lay in the range:

Chlorophyll *a* 95-101%
b 109-126%
c 70-105%

the mean giving an estimate of bias and the width of the range being a function of variability of the method.

In another experiment to extract chlorophyll from *Nitzchia closterium* by grinding (Kerr and Subba Rao, 1966), two replicates of a 3^3 factorial in blocks of 9 samples were run. The factors investigated were grinding time, extraction time, and temperature. Analysis demonstrated that 30 seconds was adequate for grinding and that yield decreased approximately linearly with the logarithm of extraction time. Near optimum procedures were thus discovered and the lack of a significant difference according to temperature, show that cooling was not necessary.

Designed experiments have value not only in their analyses, but also when procedures fail. A design to estimate the accuracy of calcium and magnesium estimation by titration methods (Whitfield, Leyendekkers and Kerr, 1969) showed the limitation of the method in being unable to produce results for certain combinations with worthwhile reliability. This might not have been discovered had factors been varied individually. Non-orthogonal analysis of variance, weighted according to variation, showed that graphical estimation of the end point was less variable but resulted in biases absent when least squares methods were used, and that the procedure was suspect for high Mg/Ca ratios. The number of titrations that could be run was severely limited and consequently the experiment could not be repeated.

A simple experiment to compare the persulphate method of phosphate determination with the perchloric acid method on a series of different sets of identical preparations showed clear results—standard deviations in the ratio of 19 : 1. While the superiority in this case was evident from inspection, proper design enabled estimation of confidence limits on variability. While it may be unnecessary in such cases, proper design means little extra work (sometimes less) and is a form of insurance against the contingency—quite frequent—that the differences are too small or the data too variable for meaningful conclusions otherwise.

Counting of cells or organisms may be investigated statistically to assess the amount required to produce satisfactory results, thus avoiding poor estimates or needless counting. One investigation showed the 5 complete counts of phytoplankton from all the squares from each of two duplicates could be replaced by a plan in which only the diagonal squares were counted from the 5 counts but using triplicates. Without any increase in variance, counting was reduced 70% at the expense of a little more preparation work.

In productivity determination, two small experiments, one comparing the two methods and the second comparing materials, found that perspex gave reduced readings compared with glass and probably caused the difference found between two methods then in use. A much longer series of duplicates taken on two cruises were of little value because the experimental set-up was not well controlled. As another example of the problems, an experiment was designed to test whether distilled water Carbon 14 samples gave higher production estimates. A 5% improvement was tentatively found but the analysis was rendered suspect by heterogeneous variation. This was attributed on investigation, to failure to randomize subsampling—the subsamples were taken from a sample jar which had stood for an hour after collection and was not mixed before sampling. The desirability both of randomizing wherever possible and of full consultation between statistician and scientist is apparent.

An investigation of both CSIRO and NIO phosphate determinations from a series of samples showed the two could be related

$$\text{CSIRO Value} = 0.04 + 0.96 \text{ NIO Value}.$$

A separate precision test gave much lower variability—S.D. 0.02 compared with 0.05—than obtained from the initial data. The reduction may have been partly due to the operators trying unconsciously to get good repeated values, illustrating the value of designs planned so that the operator has no opportunity to 'improve' his results. In oxygen determinations, the process was divided into sampling and addition of reagent (stage 1) and titration and calculation (stage 2), with either complete performance by one method in one laboratory or swapping between stages. Results showed no difference between CSIRO or NIO either at first or second stages but an unexpected depression of the results whenever interchange occurred irrespective of which laboratory did which stage.

Work by Stark (1968) showed the advantage of designed intercalibration studies. A design is given that provided effective between laboratory comparisons at the various stages of chemical analysis enabling the identification of the stage at which different laboratory practice produced different results.

AD HOC STATISTICAL STUDIES

In this section, I examine a number of applications of statistics with some unusual features to reflect the variety of investigations which may profit from statistical analysis.

Benthos samples were made by an ' orange peel ' grab and a sledge dredge in order to estimate the distribution of spanner crab *Lyreidus tridentatus*. Both implements were somewhat unsatisfactory in their operation, but were the best available. Catches of the grab were analysed and the numbers at 35, 40 and 45m although highly variable, were found similar but different from those at 50m. The data were over-dispersed but fitted a negative binomial distribution. Catch of the sledge dredge was found to be proportional to the number of revolutions and the efficiency of the dredge estimated as 20-25% that of the grab. Further grab samples in a restricted depth range (39-44m) showed the distribution could be regarded as random in this region, the poisson being a good fit. However, problems with the dredge such as wheel jamming and filling with material, resulted in catches being apparently unrelated to distance travelled.

Measurement of carapace length of this crab showed that the distribution was distinctly multimodal and monthly collections—separated by sex—showed a clear progression of the young crabs, produced in September each year. It was possible to estimate the mean length and standard deviation for each moult and, in addition, the time of moulting and the composition of the moult. After the third moult, in some or all months, there were crabs from two years in the same moult.

The effect of hauling speed on zooplankton catches was investigated by Kerr, Tranter, and Heron (1968). Analysis of specially collected data showed interesting dependences on speed for instance the catch of both adult and juvenile euphausiids declined as speed increased while the catch of small copepods increased to a maximum. On the other hand the numbers of intact appendicularians rose to a peak at 1.5 metres per second and then declined. Examination of the tails showed that total catch increased steadily with speed but the proportion intact dropped rapidly above 1.5 metres per second.

Another net problem concerned the ability to pass through the gauze, complicated by possible stretching of the gauze, and the variability of the mesh size. Heron and Kerr (1968) found by investigation with glass beads that a small expansion—as low as zero for monofilament nylon and 4-10% for silk—was adequate to explain the results. The results differed from previous estimates of high expansion because experimental control was good and variability of the mesh size was not ignored.

Information on persistence and variability of currents over time and space are difficult to obtain. For the East Australian Current, a statistical analysis was made to see what could be derived from merchant ship logs. Low precision is a major problem with such data. However, Hamon and Kerr (1968) found much of the variability resulted from the current itself. Correlation between current estimates close in time was as high as 0·6-0·8 on adjacent sections, dropping to 0·2 at about 200 km separation. Estimates of the same section a few days apart showed correlations of 0·5 which dropped off to zero as the time separation with a strong indication of negative correlation at 30-40 days which agreed with other estimates on eddy passage times. While the current was found to be predominantly southward, interesting results as to variability were found from what might have been rejected as ' hopeless data '.

INITIAL MODELLING STUDIES

In the preceding investigations, statistical analysis was mainly of value in estimating variability, distinguishing real effects from error or unaccountable variation and the analysis of problems for which statistical treatment was obviously required.

Now I consider those investigations where statistics have been used in an attempt to help the understanding of oceanographic problems. First consider the study by Newell and Kerr (1968) of suspended organic matter in the South Eastern Indian Ocean, data which results from just one cruise (Diamentina 5/64). Carbon, Nitrogen, Carbohydrate and Phosphate measurements were examined with a simple model

$$y_{ij} = \mu + l_i + d_j + f(l_i, d_j) + e_{ij}$$

where y_{ij} is the value of the dependent variable at the ith latitude and jth depth ;

μ is the overall mean ;

l_i is the effect of the ith latitude ;

d_j is the effect of the jth depth ;

$f(l_i, d_j)$ is a function of both latitude and depth ;

e_{ij} is an error term.

In order that the error e_{ij} should be approximately normally distributed as required for testing and efficient estimation, the dependent variables used were :

Log (Particulate Carbon+5)

Log (Ninhydrin—positive Nitrogen+0·5)

Log (Carbohydrate+2)

Log (Phosphate+1)

Non-orthogonal analysis of variance according to this model showed major depth differences below 150 metres (those above were evident without analysis) and, except for carbon, latitude differences were also significant. However, in no case did the interaction of latitude with depth approach significance. Estimates of latitude and depth effect were obtained and the depth values related to knowledge of the water masses.

Such an analysis does not prove that say, for Carbon, the values at any depth were the same for all latitudes, but it did show clearly that depth differences did exist below 150 metres in a sufficiently systematic manner over the entire course of an ocean cruise that it was sensible to attempt to interpret them.

In 1962-63 the CSIRO Laboratory at Cronulla undertook a series of six 'Seasonal Biological Cruises' at two monthly intervals along IIOE between 32°S and 9°S Latitude, traversing it in both directions each cruise, thus covering the whole year. Similar statistical analyses were made of Chlorophylls (Humphrey and Kerr, 1969) and Zooplankton Biomass (Tranter and Kerr, 1969) in which the data were related to Latitude, Season, Time of Day and Depth, including their two factor interactions. The models used were a natural extension of those used for carbon, with some modifications because of the large size of the non-orthogonal analyses that were needed. Column chlorophylls and vertical biomass hauls were related to latitude, season and time of day. Between 35 and 50% of the total variation was ascribable to these factors and interactions except in the case of Chlorophyll *c* for which the errors of determination are very high. Similarly analyses have since been made in an unpublished investigation of the relation of the density of major groups of zooplankton species.

Not surprisingly, a number of interactions were found significant. For chlorophyll *a* no diurnal effects were found but major seasonal variations were detected and these were shown to differ significantly with different latitudes and at different depths. Seasonal variation was shown to be less at lower depths while the change with different latitudes was of a lower order than between different depths.

As expected, the time of day effect was highly significant for zooplankton biomass and interacted only with depth. The day night differences were shown to diminish with depth ; mean biomass also diminished but not as rapidly. Seasonal effects were significant and interacted with latitude but these factors did not interact with diurnal and depth effects. Thus a large body of data were replaced by four figures which showed all the major features of the data and distinguished them from random variation. As an example from the zooplankton study, (Fig. 1) shows the estimated relation of Euphausiacea counts to latitude and season.

In fact, statistical analysis by concentrating on the main features may appear too simple. Nevertheless all the information is used in the estimation of the major features. Aspects of the data attributed to 'error variation' may in fact be interesting real differences important in a particular area, and may be investigated by looking at the residual variation. However, non-statistical examination runs into the major problem of a lack of ability to distinguish what is real, from what results from chance sampling. One station may give quite different results from another only a few miles—or even sometimes a few yards—away.

Nevertheless, Rochford (1969) shows from the same cruises and using the less variable physical and chemical data, a great complexity of interesting features that would have been lost in a purely statistical analysis of the data. Further it should be appreciated that the above analyses do not relate biomass or chlorophyll to factors that directly influence them i.e. they do not elucidate structure. While they have been helpful, the analyses are only a guide to understanding and in no sense an easy substitute for reasoned consideration of ocean structure and its interrelationships. It is only with such an understanding that the value of statistical analyses is enhanced and also rightly remains the servant of the investigation and not its master.

FURTHER MODELLING

Encouraged by the usefulness of the above and conscious of its limitations, a continued study of statistical methods in conjunction with an appreciation of oceanographical problems is desirable so that the two disciplines may be of mutual benefit. Below I outline some of the exploratory steps towards an understanding of mechanisms. They are limited in value partly because the underlying theory is not much developed and the nature of the ocean makes any realistic theory a complex one.

In a simple attempt to examine relationships, zooplankton biomass data for the seasonal Biological Cruises—were analysed as a function of mixed layer depth (defined by temperature gradient) separated into northern and southern (below 19°S) sections.

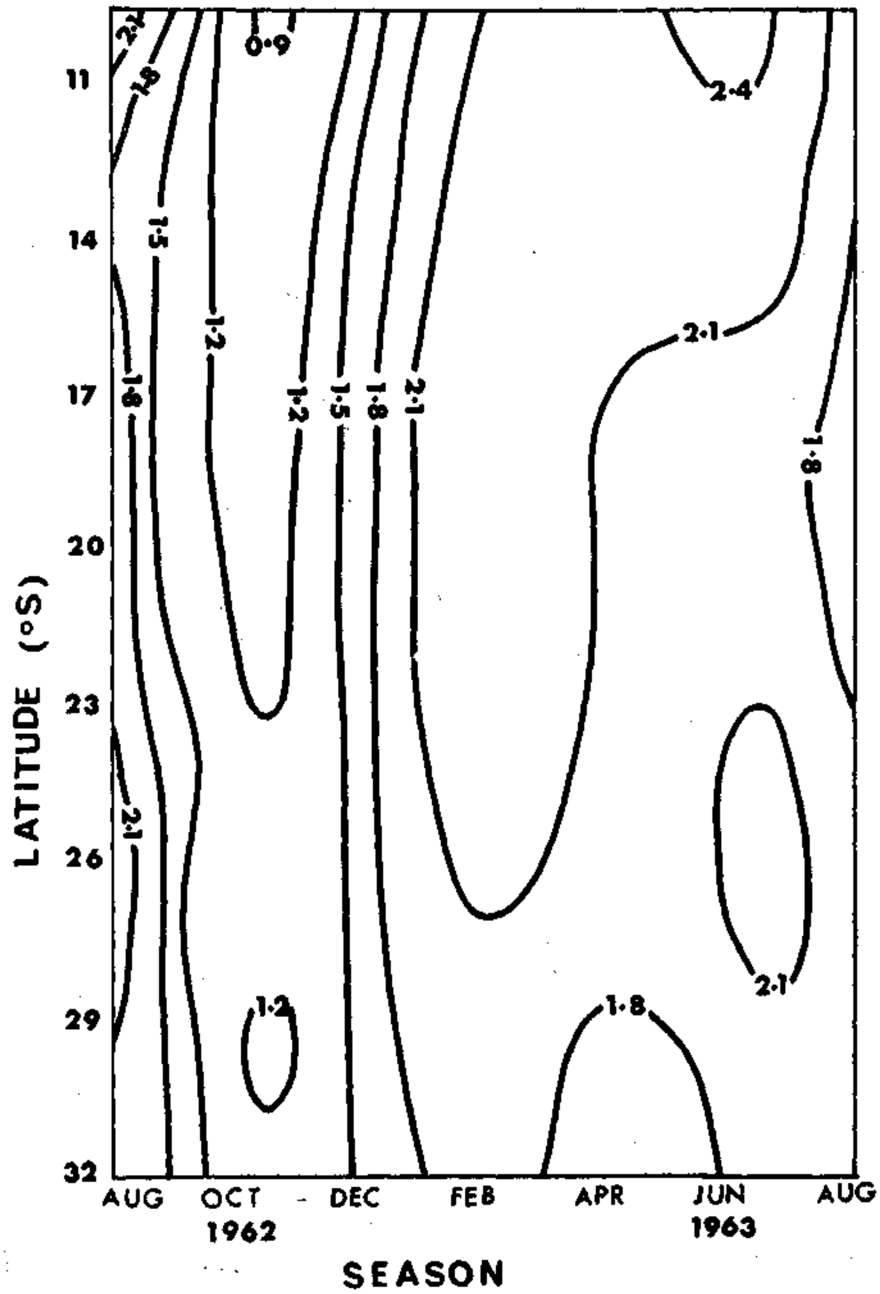

Fig. 1. Estimated relation of Euphausiacea Counts along longitude 110°E, Indian Ocean, to Latitude and Time of Year. Contours, $\log_{10}$ (Counts/m^3+1).

Little or perhaps an inverse relation was expected in the north. In the south, increased mixed layer depth was expected to be associated with an increased nutrient supply due to upwelling, resulting in higher biomass. The day night effect was eliminated but the dependence on mixed layer depth, while just significant indicated a drop in biomass when depth increased. A similar analysis was made with chlorophyll *a* data—one step closer to nutrient in the food chain but with an equally naive model—and again the main result was that most variation remained unexplained with no clear relation emerging. Consequently an analysis was made of the distribution of both phosphate and nitrate immediately above and below the mixed layer, while also eliminating season and latitude effects. For phosphate 50-60% of the variation could be accounted for, but again these are descriptive effects and largely do not explain why the variation occurs. Mixed layer depth was highly significant. Nitrate was only poorly predicted by any of these factors so this is another aspect requiring exploration.

A major reason for the failure to find the expected relation to biomass was the failure to take time between upwelling and biomass response into account. This failure was due to the lack of data but it should be emphasized that a serious study of cruise sampling design should improve this situation in the future. One simple analysis (Newell, 1966) illustrating the possible improvement was the fitting of the simple model relating Organic Nitrate Concn. at Time t weeks, o_t to nitrate concentration n_t,

$$o_t = k\, n_{t-c} + e_t.$$

Only weekly data were available and correlations were calculated:

Same Week	0·09
Preceding Week	0·44**
Two weeks before	0·43**
Three weeks before	0·13
Four weeks before	0·16
**Probability	0·01

thus indicating a value between 1 and 2 for c. Even this has the defect that no account was taken of water mass movement but it suggests this was much less serious than the failure to allow for time delay.

Further, analysis of phytoplankton numbers and water mass properties off Port Hacking (Grant and Kerr, 1970) showed interesting dependence on phosphorous, oxygen, temperature, salinity and nitrate. Examination of data one and two weeks previously showed that correlation with phosphates values increased giving a 1-2 week time delay for the response but no simple relation to nitrate which tended to be significant in conjunction with oxygen. It is certainly desirable to relate biomass or counts simultaneously to these factors rather than by series of simple correlations as has been done, and it is also advantageous to consider possible interactions which are likely to occur because of complex dependence on the nature of the environment. However, it is difficult to obtain adequate data to elucidate such relations. Classification methods—such as those of Lance and Williams (1967) are useful as a preliminary procedure for investigating similarity of species behaviour as a preparation for determining the different factors affecting the different groups. It was found that grouping the observations on the basis of species observed, gave groups contiguous in time and with similar water mass properties. Another phytoplankton examination showed significant relationships between chlorophyll *a*, phytoplankton, and production measurements, even though only simultaneous measurements were available.

An investigation now being undertaken as a result of these previous studies, involves the assembly of data from all over the Indian Ocean, with the aim of investigating the relation between zooplankton, chlorophyll, production, nutrient and physical properties of the water mass. The major problem again will be the difficulty of allowing for time effects. Nevertheless it is expected to yield interesting results.

Design

In most of the work already considered, the data were obtained before any thought was given to statistical analysis, or the form of theoretical model (such as time delays) that might be investigated. To a large degree this was inevitable, firstly because no statistical advice was readily available, and secondly because the existing sampling theory (for example Cochran, 1963), while well adapted for land based problems such as economic surveys and soil surveys, is of little use in oceanic work due to at least three major problems :

(1) the properties being measured may change markedly during the course of the survey ;

(2) the sampling must be conducted from one or at most a few ships, slow moving in relation to ocean size ;

(3) special problems of navigation and of returning to the same point resulting from ocean movement which make almost impossible many time and space studies quite practicable on land.

None of these problems are insurmountable—compromise is required that will make possible the type of analysis required. In the time available to prepare this paper I have been unable to make any systematic attack on this problem. Mathematically the theory may be intractable and simulation studies may be required to investigate sampling properties. It may prove impossible to conduct properly a design survey on the whole ocean with the ships available but a well designed survey on a smaller area would be expected to yield more useful data than an ill-conceived large scale one.

To give an example of what might be possible, I have produced a small simple survey, randomly selected subject to the restriction above. The plan was made as far as possible to balance latitude, longitude and time effects without an unreasonable increase in cruising time to enable the kind of analysis required. The design is by no means optimum but it does illustrate the possibilities. Compare a conventional cruise order (left) with the proposed one (right, exhibited before randomization) for a simple 4×4 grid.

1	8	9	16		1	16	8	9
2	7	10	15		15	2	10	7
3	6	11	14		14	3	11	6
4	5	12	13		4	13	5	12

I have been consulted in only two practical cases of non-experimental sampling design. One was elementary involving sampling water at intervals in a small estuary (Crosset, Giles and Kerr, 1969). Intervals of 3, 4 and 5 hours were selected randomly to adequately sample all times of day with no intervals too short (to allow time for the chemical analysis) and allowing for the limitations of one boat. Two neighbouring positions were sampled to give a check on variation and the whole procedure was replicated three months later. Depth effects were found and in addition time trends on which as superimposed a cyclic effect which was similar in both replications.

The other case involved the selection of a cruise plan for the collection of prawn larvae in the eastern Indian Ocean by surface hauls at night. The availability of only one ship, the time required for hauls and the need to call into port halfway, imposed several limitations. Below are shown both the original and my suggested plan with the numbers of the nights on which hauls were to be made on the various sections

Old	New
—13— —15— —11— —17—	—14— — 3— — 7— —10—
— 4— — 6— — 2— — 8—	— 4— —15— — 2— —17—
—14— —12— —16— —10—	—13— — 6— —11— — 8—
— 5— — 3— — 7— — 1—	— 5— —12— —16— — 1—

The new plan was selected ' randomly ' and provided for balancing of time and latitude effects and a better coverage in time. Although feasible, it was not proceeded with for the simple reason that it was considered unwise to ask the supplier of the ship to agree to a plan which would involve a number of hours cruising at only half speed. The plan had distinct advantages over the original one and its rejection was unlikely to encourage the development of plans. Research work into oceanographic survey design would be of immense aid in planning cruises to provide data which will enable the testing adequately of realistic models.

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