Sea Level Data and Techniques for Detecting Vertical Crustal Movements

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Abstract. In accordance with the wishes of the Panel Chairman an attempt is made to survey "problems, requirements, and the outlook for the future" in the study of sea level time series so as to determine the relative movement of land and sea levels. The basic aim is to eliminate from the record the contributions from whatever marine dynamic phenomena respond to treatment, allowing the secular element to be identified with optimum clarity. Nevertheless the concept of sea level perturbation varies according to regional experience. The recent work of the Permanent Service for Mean Sea Level helps to eliminate geodetic noise from the series and makes it possible, perhaps, to treat the global mean sea level data bank so as to define eustatic changes in ocean volume which, in the present context, may be regarded as the final goal, allowing the identification of vertical crustal motion itself.

Scale Lengths

This survey is not concerned with geological time scales, although sea level evidence for crustal motion can be relevant in this sense. Neither is it intended to discuss archaeological time scales since interpretation here is limited to locations, such as are found in the Mediterranean or in Scandinavia, which experience a small tidal range combined with low rates of accretion and erosion. The aim is to consider the period of instrumental history where continuous or near-continuous observed time series of sea level are available for interpretation. The interest is therefore focussed upon recent time, within the last hundred years, and often upon the last two decades. With regard to spatial scales it should be noted that observed sea levels are ideally referred to a fixed mark local to the instrumental site. Although attempts are invariably made to select a stable bench mark, it is clearly a matter for survey procedures to determine whether a particular bench mark is regionally representative. Again, if any attempts are to be made to determine absolute sea level or sea level topography, rather than variations at a point, then much greater reliance must be placed upon survey evidence and the well-known controversy over apparent sea level slopes becomes a matter of anxiety. However, where secular variations of level, determined at a number of points, have the appearance of spatial coherency then these reinforce each other and in some cases justify interpolation within the observing network.

Limitations

The restrictions of the exercise are numerous, not least being the obvious lack of control over the data. The material is historic and in large measure obtained by instruments designed and installed for operational rather than scientific purposes and somewhat inadequately maintained. Location, in harbours or estuaries, is often inconvenient and in another context [e.g. Lennon, 1971] reference is made to the several imperfections of the standard instrument. In fact it is in many ways surprising that the search for a secular signal which may be as small as one mm per year can be pursued with success.

In the context of this Symposium it is relevant to address a particular problem which does not appear in the associated literature. It is only during the last decade that satellite orbital analysis and laser altimetry have been combined with gravimetric surveys to determine the variations of the gravitational field with longitude. As experience has been gained with these techniques and as they have become more precise, there has been developed within the last few years a detailed determination of the geoid. However as yet we have no conception of the stability of the geoid in time and space. What we do know is that the geoid demonstrates significant relief ranging through almost 200m from a depression south of India to a peak in the vicinity of Papua New Guinea. By definition the geoid describes an equipotential surface and we can expect the ocean surface to conform with the geoid relief. The point which must be made however is that if one bears in mind the above-mentioned apparent gradient over 200m, it will require only a small time variation of the geoid at a point to seriously perturb the observed secular variations of sea level at such a station. The nature of the problem is such that little can be stated at this time although some thought has been given to geoid stability. In a personal communication Kaula considers that the most likely source of change lies in the phenomenon of glacial rebound in the higher latitudes and figures of approximately 0.3mm per year have been postulated. Though small, such a change nevertheless is significant in terms of secular variations of sea level.

Techniques

The common procedure is first to apply a tidal filter so as to remove tides of diurnal and higher species. Tides of fortnightly, monthly, semi-diurnal, annual and longer period tend to be more intricately entangled with contributions from atmosphere and other sources and require sophisticated treatment. In the initial stages therefore they are allowed to remain in the data. It is the attention paid to such perturbations and the design of procedures for their elimination from the record which determines the accuracy with which the secular variation of sea level can be establ-

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ished. It is also relevant that one should be assured that none of the perturbing parameters is itself influenced by secular change so that the total secular signal may be ascribed to the basic sea level phenomenon. In fact there has been little anxiety on this score.

The very slow change in the data base predetermines that the discipline proceeds at a pedestrian pace and in fact the major interest lies in the sophistication of the procedures utilized in the elimination of the noise in so far as this is possible. It is interesting that individual workers place stress upon phenomena of which they are aware in their own environment and there has been no attempt as yet to apply a comprehensive model of long period sea level phenomena. For example in North Europe the emphasis has been upon barometric pressure and associated wind stress phenomena with the contributions of storm surges clearly in mind. In contrast, in N.America the absence of large shallow water areas has resulted in lower priority being given to such features and the emphasis has been placed upon steric phenomena resulting from variations in water density and upon the more general features of marine dynamics.

Simple Regression

The European school is perhaps best exemplified by work during the sixties [Lennon, 1966 and Rossiter, 1967]. Here some four thousand station years of annual mean sea level were processed in a regression exercise which for each station took the form

$$Z_y = \sum_{p=0}^{p=3} a_p Y^p + \sum_{r=1} b_r B_r + c_1 \mathrm{Cos}N + c_2 \mathrm{Sin}N + \phi_y \quad (1)$$

where Z_y is annual mean sea level for year Y referred to a working datum, B_r is annual mean value of air pressure at station r for year Y, N is the mean longitude of the Moon's ascending node for year Y, ϕ_y is the contribution to Z_y from all other causes considered inexplicable in this context and therefore regarded as residual noise. The coefficients a,b & c are determined in the regression procedures.

Some comments are appropriate. It can be seen that the term $\Sigma\, a_p Y^p$ is the primary objective of the exercise and does not constrain the secular variation to a linear form. The terms containing N were intended to reproduce the lunar nodal tide with a period of 18.61 solar years. The stations, r, for which observed barometric pressures were obtained, were selected in triplets arranged as far as possible in an equilateral manner around a specific sea area which in turn was considered to be a potential contributor to mean sea level at the station e.g. the North Atlantic, the North Sea, the Baltic etc. It was assumed that such a treatment would reproduce contributions of static barometric pressure and also all directional components of wind stress. Tentative trials were conducted combined with a study of the resultant, ϕ_y, so as to select an optimum set of triplets for each station.

Figure 1 illustrates the treatment of the sea level time series for Newlyn and allows a subjective assessment of the success of the technique. In fact the exercise did show spatial coherency making it possible to produce the regional pattern of figure 2 and its indication of glacial rebound in the Baltic and especially in the Gulf of Bothnia.

What was surprising in this exercise was the apparent success of the barometric triplets in modelling the wind stress phenomena. The latter conceptually are of short duration in the range twelve to thirty hours, whereas the associated variables in the regression model were annual means. To succeed then the barometric terms must represent long term averages of many events, yet even here one is presented with a difficulty. Wind stress is a non-linear phenomenon varying approximately as the square of wind speed. Although in equation (1) one can conceive of barometric gradients being represented, there

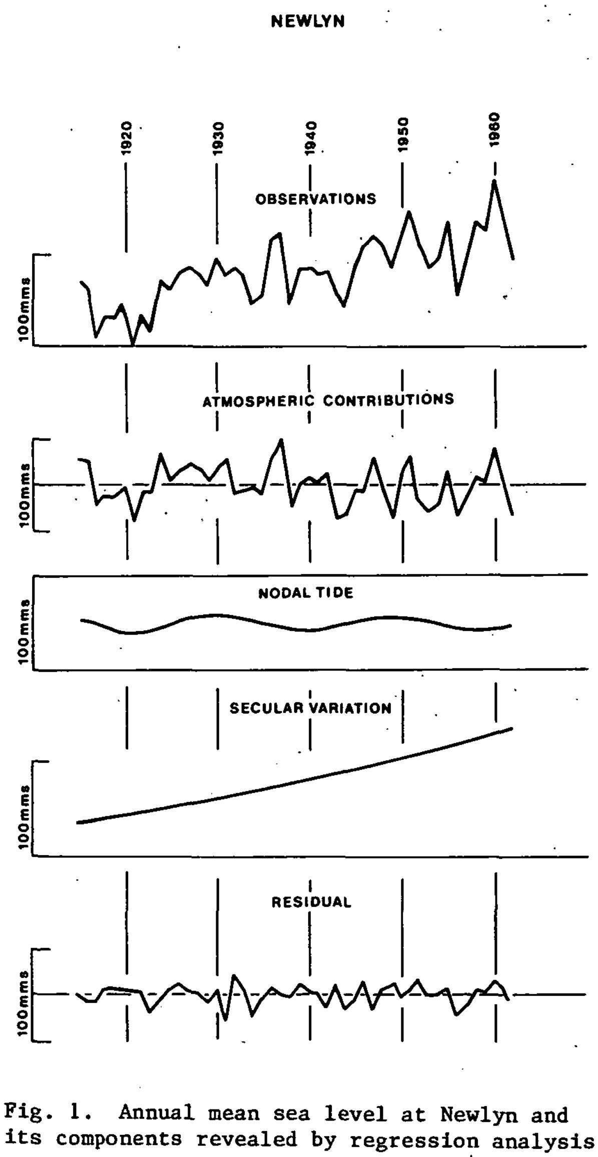

Fig. 1. Annual mean sea level at Newlyn and its components revealed by regression analysis.

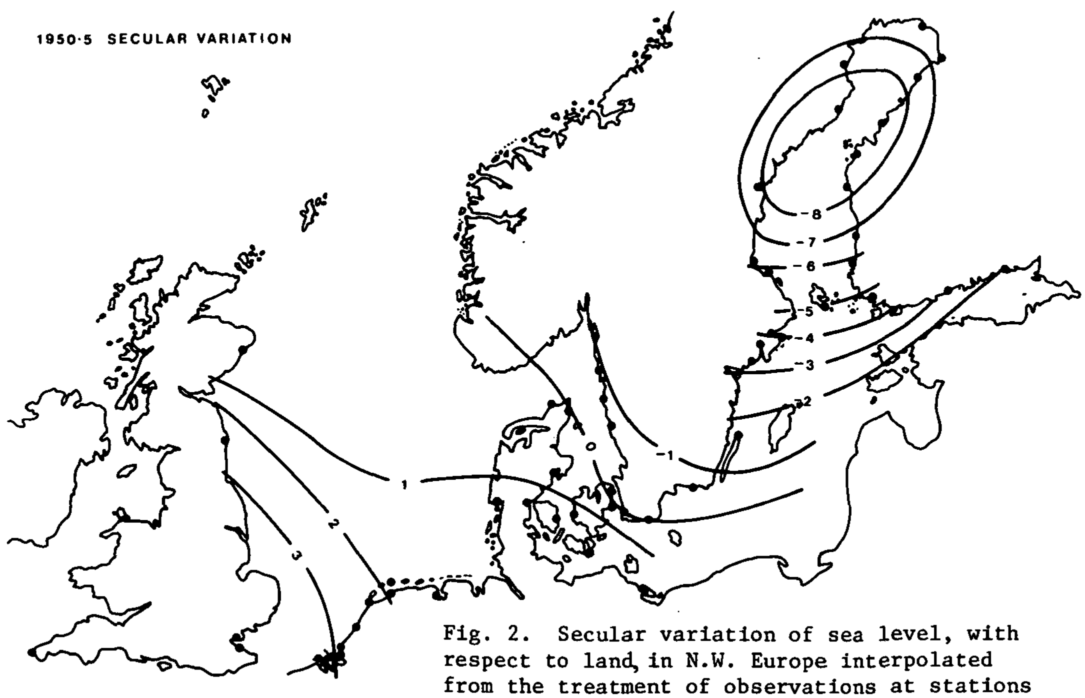

Fig. 2. Secular variation of sea level, with respect to land, in N.W. Europe interpolated from the treatment of observations at stations marked by solid circles.

is no attempt to reproduce a non-linear wind stress. Again one may comment that there is no simple solution in the time scales used since the square of the mean wind, possibly derived from annual mean pressures, cannot be equated with the mean of the squared wind from a succession of discrete events such as occur in nature. The success of the procedure outlined above is puzzling and has initiated much thought as to the manner in which techniques may be improved.

Complex Regression

As one attempts to provide more rigorous treatment of the meteorological perturbations yet another problem emerges with increasing significance, namely that of the high degree of intercorrelation of the meteorological variables. More sophisticated techniques also call for longer data bases, only forty-seven annual mean levels for Newlyn in the earlier exercise, for example, being a serious restriction. A notable attempt to face these and other problems has been made by Thompson of the Institute of Oceanographic Sciences in the U.K. [Thompson, 1978].

Here an interesting exercise is based upon monthly values of mean sea level and this approach inevitably carries the premium of careful attention to other long period tides in particular the solar annual and solar semi-annual tides. At the expense of this complication a useful extension of the available sea level time series is effected. However the basic innovation is the treatment of the North Atlantic barometric pressure field expressed in terms of monthly mean pressures from a five by five grid at 5° spacing in latitude and 10° spacing in longitude. These pressure series clearly demonstrate a high degree of intercorrelation but treatment by the Principal Component Analysis effectively replaces the set of correlated monthly air pressures by a set of uncorrelated eigenvector coefficients. Two further attractive advantages emerge as a bonus. In the first place a highly convergent system is produced in that the first eigenvector accounts for 54% of the total variance of the standardised pressure fields in this particular application, while the first eight account for 99% of the total variance. In the second place the eigenvectors assume a physical significance as modes of variation over the grid showing progressively detailed structure as the order of the eigenvectors increases. In figure 3 the respective patterns of the eigenvectors are shown as positive and negative areas so as to illustrate this point.

This preparatory analysis set the scene for the treatment of some eighteen years of monthly mean sea levels at Newlyn. Incorporating also trend, and tides, a stepwise regression procedure automatically selected an optimal subset of eigenvector coefficients with a satisfying result. Over 90% of the variance of the original mean sea level series was explained and insight obtained into some large scale marine dynamics of the region.

The relevance to the present survey lies largely in the fact that the secular variation of sea level at Newlyn computed from a sea level record, eighteen years in duration from 1957 to 1974, emerged as 1.42 $\pm$ 0.19 mm per year. The earlier exercise had used forty seven years of data up to 1962 and produced a trend of 2.15 $\pm$ 0.14 mm per year. The first indicat-

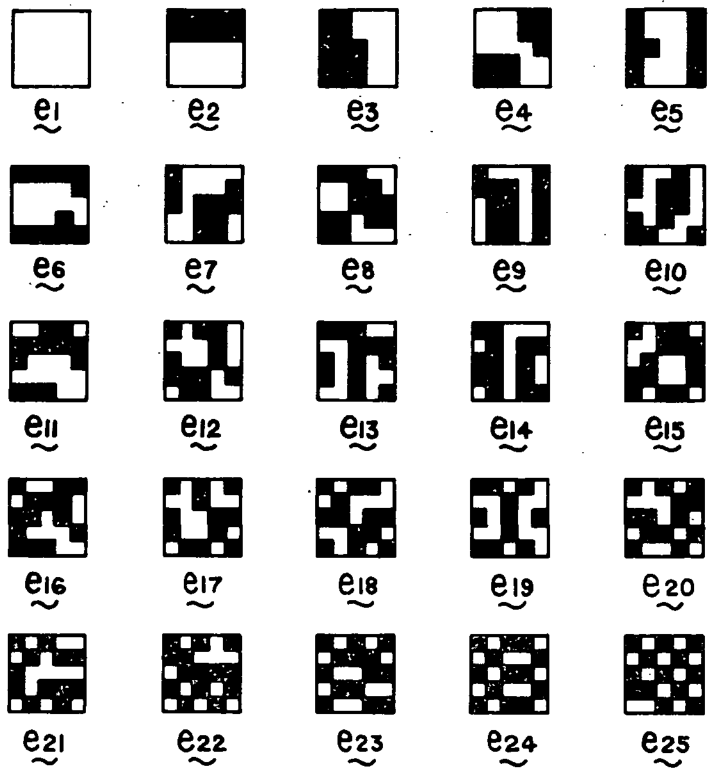

Fig. 3. The physical features of the eigenvectors representing air pressure variation over a North Atlantic grid.

ion is therefore given that the rate of rise of sea level with respect to the land may be decelerating with time at this station and certainly a powerful tool has been created which, depending upon relatively short time spans, can investigate the fine structure of secular variation in time. The same exercise gave an assessment of secular trend at Corunna over the identical period 1957 to 1974, as 0.57 $\pm$ 0.42 mm per year showing a clear disparity in space of crustal motion.

Sea Level Perturbations

It has already been suggested that the European school has been influenced by the environment of a broad continental shelf on which the mechanics of wind stress have free rein. With a deep ocean aspect, as in North America, it is not unreasonable that the concentration should be on the large scale phenomena of ocean circulation, on the western boundary currents intensified by planetary vorticity and on dynamic height phenomena associated with the thermohaline vertical structure of the oceans [e.g. Sturges, 1974 and Chew, 1977]. These phenomena are also associated with time-variations and as yet have not featured in detail in studies of secular variations.

If the accuracy with which long term trends can be extracted from the records depends upon an understanding and elimination of other perturbations, then it should be noted that our knowledge of such mechanisms is far from complete. For example in recent time certain evidence is accumulating which suggests that in the Southern Hemisphere the greater exposure of the oceans, combined with the circumpolar nature of the Southern Ocean itself, allows a range of phenomena to be generated which may be unique to southern waters. Taking examples from Australia there is evidence on both east and west coasts of thermohaline structures associated with tongues of warm water, showing anomalies of 5°C or more, moving southwards in late summer. Much work has been done in the Tasman Sea [e.g. Hamon and Cresswell, 1972, also Andrews and Scully-Power, 1976] on the phenomenon of associated anticyclonic eddies, somewhat similar to those recorded in connexion with the Gulf Stream in the Atlantic, but having a recorded life of the order of one year. Dynamic heights up to 80 cms, accompanying geostrophic flow in excess of 100 cms per sec. are recorded. In this and in other contexts the tendency seems to be to provide sea level perturbations with periods greater than their counterparts in the European exercise previously outlined. More particularly a study of non-tidal residuals reveals evidence of energy at characteristic periods as follows:

circa two days, and here it should be noted that this corresponds to the inertial period at latitude 14.4°

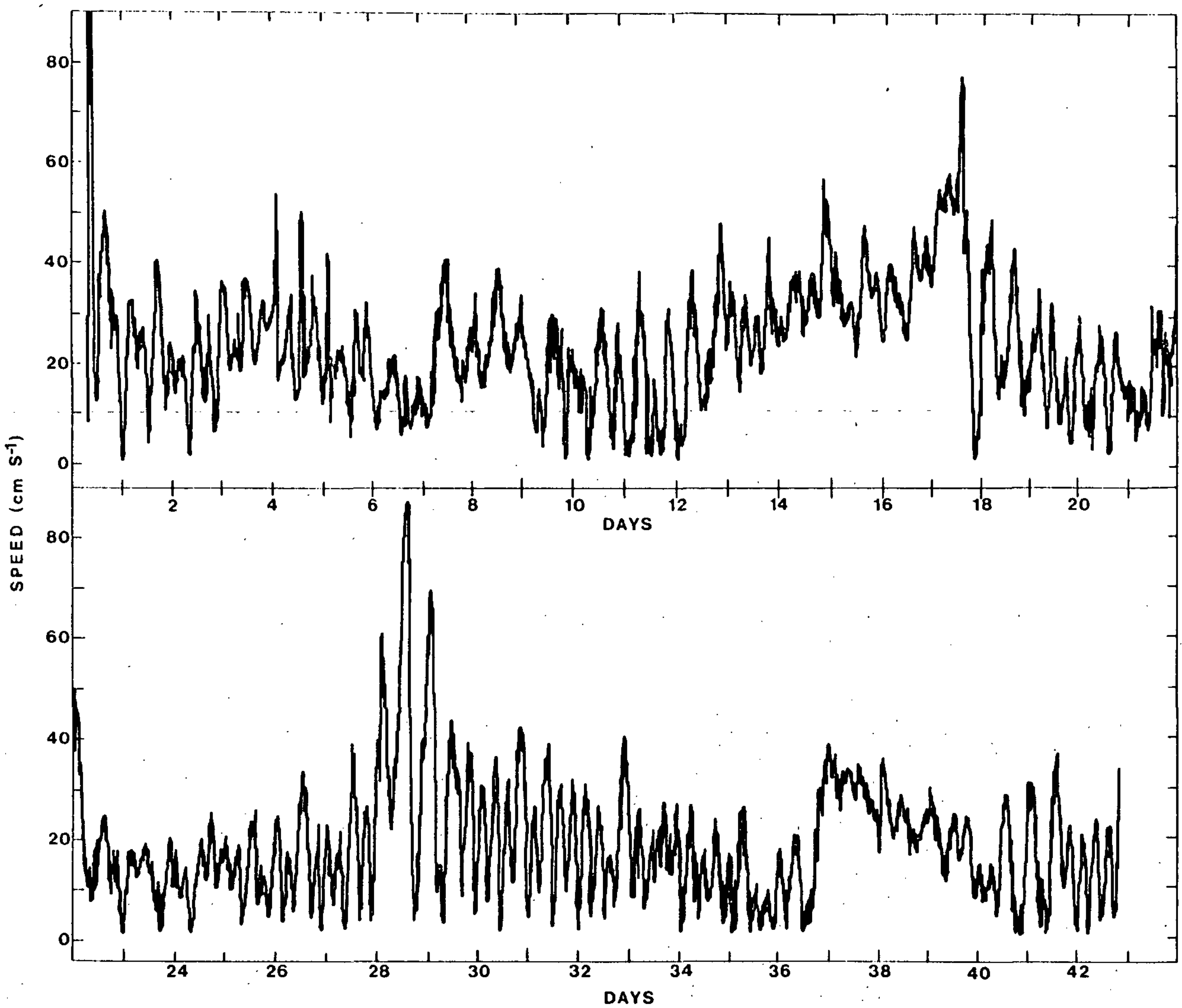

Fig. 4. An extract from a record of current speed at a typical station on the N.W. Australian Shelf.

circa four days, to which reference is increasingly appearing in the marine dynamics of equatorial and southern latitudes.

in excess of twenty days, which is most uncommon elsewhere yet waves of amplitude greater than 0.5m and apparently trapped on the Australian coastline have been traced and tracked as coherent phenomena over distances in excess of 5000 kms, from Dampier in the north-west, southwards along the west coast, across the Great Australian Bight and finally dissipating northwards along the east coast.

It is only in the last few months that commercial operations off-shore, notably on the North West Shelf, have stimulated experimental work and this is revealing exciting perturbing phenomena. The material in figure 4 has its origin in a personal communication from R.K. Steedman and Associates, Perth, contracted to Woodside Petroleum Development Limited. Here in a region of large vertical and horizontal tides, the stream record shows such tides to be superimposed upon significant disturbances. Note the two day event near day 28, the four day event commencing day 36 and the longer period feature commencing day 12. Supporting evidence confirms that these phenomena are real, common in occurrence and of considerable spatial scale. The inference may be drawn that they will interact with sea level topography in a complex manner yet their mechanisms remain obscure at this time.

In the context of this symposium the message seems to be that there is much to learn of marine phenomena which influence the temporal topography of the oceans. Any attempt to explain and eliminate these features in secular studies would be premature, but at least techniques developed for such studies must be aware of their existence. It is also clear that the developing science of satellite altimetry should not be too confident that the problems of ocean topography are close to a final solution. It would appear that collaboration between oceanographers and space scientists offers prospects of fruitful mutual progress.

The Mean Sea Level Data Bank

In spite of these apparent limits to the present capability of sea level studies to provide an extensive and definitive survey of crustal motion, the potential of the discipline to provide unique evidence in this context is recognised. It has also been apparent that although the discipline is limited to existing historic data with all its limitations, two positive actions may be taken. In the first place there is an obligation to ensure that long sea level time series should be continued, that instrumental developments should be monitored so as to ensure that the desirable 'absolute' character of measurement should not be degraded and that strenuous effort be expended to maintain datum stability. Indeed recommendations from the I.U.G.G. urge participating nations to set up high quality sea level monitoring stations for this purpose. In the second place it has been recognised that the quality of the existing data bank can be improved in retrospect and this is the current task of the FAGS Permanent Service for Mean Sea Level (PSMSL) operating from the Institute of Oceanographic Sciences, U.K. Although the PSMSL has worked for many years in accessing, collating, treating and publishing monthly and annual mean sea level values on a global basis, it has recently embarked upon a re-processing and re-publication programme. The point at issue is that many countries in the past adopted the practice of referring sea levels at a station to the primary national reference level, often at great distance from the marine station itself. This procedure had the unfortunate disadvantage of incorporating within the sea level time series all the uncertainties of geodetic levelling. Of late we have had the experience firstly of attempting to understand the anomalous sea level slopes which emerged when attempts were made to make spatial geodetic connexions between observed sea level at individual stations, and secondly of beginning to appreciate that geodetic procedures perhaps contain systematic error, or at least are demonstrably imperfect as evidenced by marked discrepancies between repetitive exercises. In consequence the PSMSL has revised the entire data bank with a view to the production at each station of a sea level record which is referred to a local fixed mark (Revised Local Reference). The revised series then are, hopefully, homogeneous with respect to datum. This arrangement attempts to delineate the respective responsibilities of oceanography and geodesy and, given a stable local mark, ensures a more representative sea level record. The work is now well advanced with the publication in 1976 of data from 250 stations in Europe, Africa and India. This was followed one year later with a publication of similar content incorporating stations from North and South America. The global coverage will be completed in 1978/9 with the publication of data from Japan, the Phillipines, Australasia and the Pacific Islands [Lennon and Spencer, 1976, 1977]. Albeit bearing in mind cautionary remarks expressed earlier, this updated data bank offers a new prospect for the global study of the mean ocean level trend in an attempt to identify eustatic changes. Although of great scientific interest in its own right, it is relevant in the present context to note that the programme has the potential to remove the final perturbation in sea level trends. Hitherto the subject has dealt with the relative movements of land and sea levels. If it is possible to identify the secular trend of ocean levels then the identification of crustal motion becomes a more exact science.

Conclusion

The treatment of sea level time series to identify vertical crustal motion requires the elimination from the record of the effects of marine dynamic phenomena which in this context must be treated as noise.

Unfortunately these perturbing phenomena are not in many cases fully understood and perhaps this is particularly true of the southern hemisphere.

Despite the hazards and acknowledging the imperfections of historic observations, experience has shown, in certain specific cases, that it is possible to establish with some certainty the secular trends in the relative levels of land and sea surface at discrete stations.

Where vertical crustal motion is large with respect to the eustatic rise of sea level, say, of order 5mm per year and above, positive achievement is entirely possible.

Recent work of PSMSL offers to improve this situation by providing higher quality sea level data for treatment and also by making possible the identification of the common eustatic element.

Meanwhile techniques have been developed whereby the general interaction of atmosphere and ocean may be reproduced so that it is now feasible to construct a global model to attain this end in such a manner that not only eustasy, but also seasonal variations, with their inherent evidence of large scale ocean dynamics, and long period tides will emerge together with the evidence of crustal motion. PSMSL is currently planning such a treatment.

Nevertheless it is salutary to note that the stability of the apparent topography of the geoid itself is still uncertain and may present the ultimate obstacle to a definitive solution.

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