Unesco reports
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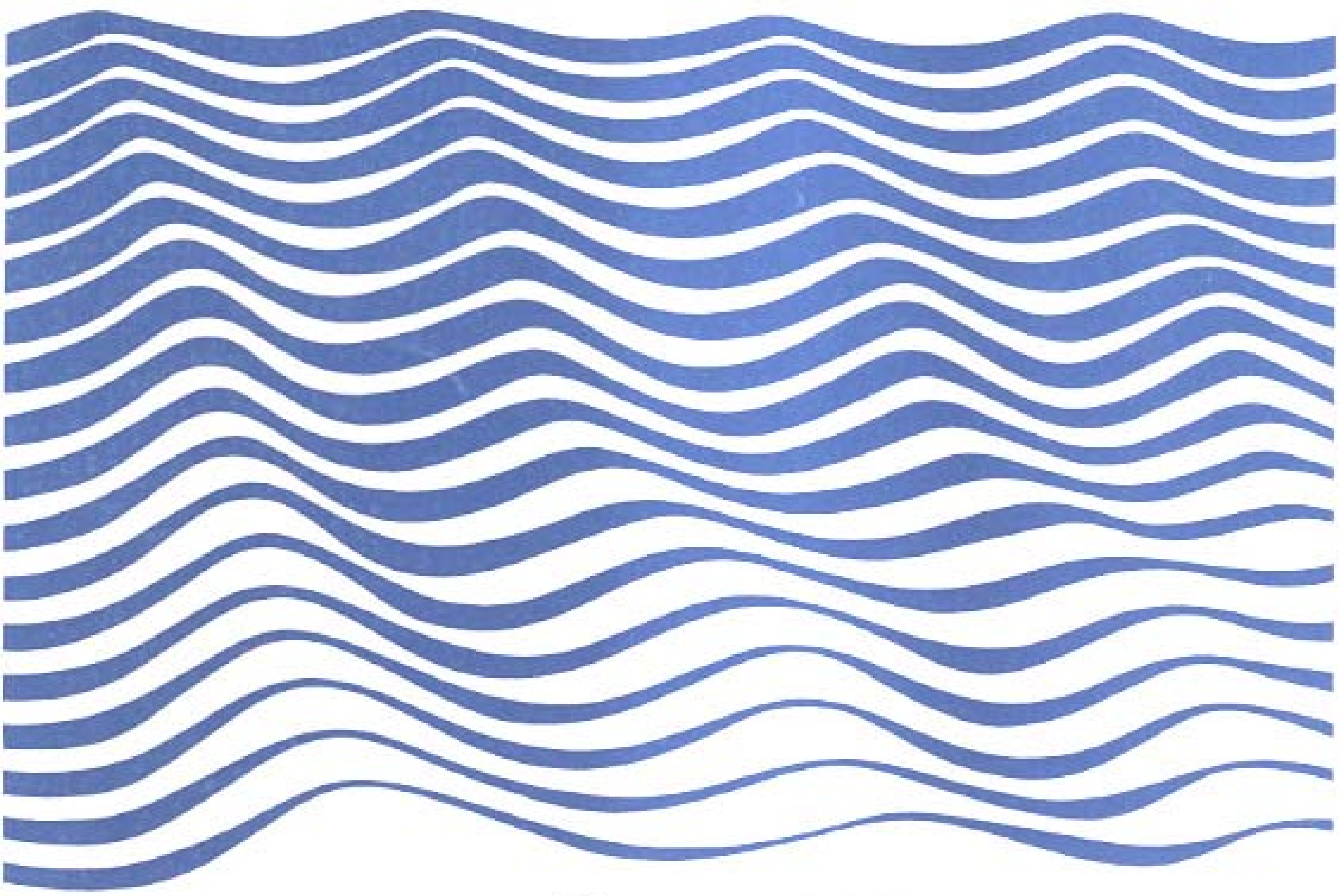
Relative sea-level change: a critical evaluation

Unesco (COMAR) Working Group
on Mean Sea-Level Rise
and its Influence on the Coastal Zone

In collaboration with IOC

Unesco/ICSU co-operation in the framework of the
International Geosphere-Biosphere Programme



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Prepared by:

R.W. Stewart
B. Kjerfve
J. Milliman
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PREFACE

This report was prepared for Unesco by the Working Group on Mean Sea-level Rise and its Influence on the Coastal Zone, established within the framework of the Organization's Major Interregional Project on Research and Training Leading to the Integrated Management of Coastal Marine Systems (COMAR). It was provided for, in 1989, in a memorandum of understanding between Unesco and the International Council of Scientific Unions defining co-operation between the two bodies in the implementation of ICSU's International Geosphere-Biosphere Programme (IGBP). The Intergovernmental Oceanographic Commission (IOC) collaborated in the preparation of the report.

Unesco acknowledges the contributions of the present members of the Working Group: Drs. R.W . Stewart, University of Victoria (BC, Canada), B. Kjerfve, University of South Carolina (USA), J. Milliman, Woods Hole Oceanographic Institution (Mass., USA) and S.N. Dwivedi, Department of Ocean Development, New Delhi (India).

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ABSTRACT

The Unesco COMAR Working Group on Mean Sea-Level Rise and its Influence on the Coastal Zone analyses various aspects of relative sea-level change, both in recent geological and historical times and with a view towards future decades. The report provides a critical summary of the causes, likelihood and consequences of relative mean sea-level change. Most of these are seen to be site-specific rather than global. The Working Group also suggests components and basic considerations for the establishment of international programmes to ascertain sea-level change. Included with the text are six illustrations, one table and a list of references on the subject.

The authors conclude that, while current scientific opinion does not tend toward "doomsday" forecasts of dramatic global sea-level rise, significant changes in the levels of both the land and the sea are likely. Future studies should concentrate on site-specific aspects of such changes in areas under threat.

RESUME

Le groupe de travail du COMAR (Unesco) sur l'élévation du niveau moyen de la mer et son influence sur les zones côtières analyse différents aspects de l'évolution du niveau relatif de la mer, dans les temps géologiques récents, à l'époque historique et dans la perspective des prochaines décennies. Le rapport procède à une analyse critique des causes, de la probabilité et des conséquences d'un changement du niveau moyen relatif de la mer. La plupart de ces éléments paraissent être fonction du site plutôt que planétaires. Le groupe de travail suggère aussi des composantes et des considérations de base concernant la mise en place de programmes internationaux de détermination du changement du niveau de la mer. Outre le texte, le rapport comporte six illustrations, un tableau et une bibliographie sur le sujet.

Les auteurs concluent que si les scientifiques n'ont pas aujourd'hui tendance à formuler des prévisions "apocalyptiques" annonçant une élévation spectaculaire du niveau des mers à l'échelle mondiale, il n'en est pas moins probable que des changements significatifs vont se produire en ce qui concerne aussi bien le niveau de la terre que celui de la mer. Les études futures devraient être axées sur les aspects locaux de ces changements dans les zones menacées.

RESUMEN

El Grupo de Trabajo COMAR de la Unesco sobre la Elevación del Nivel Medio del Mar y su Influencia en las Zonas Costeras analiza diversos aspectos del cambio relativo del nivel del mar, tanto en periodos geológicos e históricos recientes como para los decenios futuros. El informe contiene un resumen crítico de las causas, la probabilidad y las consecuencias del cambio relativo del nivel medio del mar. Se estima que la mayor parte de los cambios son locales y no mundiales. El Grupo de Trabajo indica también los componentes que deben tener los programas internacionales para determinar el cambio del nivel del mar y formula consideraciones básicas para la creación de los mismos. En el texto se incluyen seis ilustraciones, un cuadro y una lista de referencias sobre el tema.

Los autores llegan a la conclusión de que, aunque la opinión científica actual no tienda a previsiones apocalípticas de una elevación espectacular del nivel del mar a escala mundial, es probable que se produzcan cambios significativos tanto del nivel de la tierra como del mar. Los futuros estudios deben centrarse en los aspectos locales de dichos cambios en las zonas amenazadas.

РЕЗЮМЕ

Рабочая группа ЮНЕСКО/КОМАР по повышению среднего уровня моря и изучению его воздействия на прибрежную зону анализирует различные аспекты относительного изменения уровня моря как за последние геологические и исторические периоды, так и на будущие десятилетия. В докладе содержится критическое резюме причин, вероятности и последствий относительного изменения среднего уровня моря. Большая часть из них рассматривается не в глобальном плане, а скорее в привязке к какому-либо конкретному месту. Рабочая группа предлагает также компоненты и основные соображения в отношении создания международных программ для установления изменения уровня моря. К этому докладу прилагается шесть иллюстраций, одна таблица и список справочных материалов по данной теме.

Авторы делают вывод о том, что хотя современные научные круги не стремятся прогнозировать "день страшного суда" в связи с ощутимым глобальным повышением уровня моря, весьма вероятными являются значительные изменения в уровнях как земной поверхности, так и моря. Будущие исследования необходимо концентрировать на присущих конкретным местам аспектах таких изменений в районах, находящихся под угрозой.

خلاصة

يقدم فريق العمل الخاص بمشروع كومار التابع لليونسكو ، والمعني بارتفاع متوسط منسوب البحار وتأثيره على المناطق الساحلية ، تحليلا لشتى جوانب التغير النسبي الذي طرأ على منسوب البحار في العصور الجيولوجية والتاريخية الحديثة وكذلك التغير الذي سيطرأ في العقود المقبلة . ويقدم التقرير ملخصا نقديا لأسباب التغير النسبي في متوسط منسوب البحار ولاحتمالات حدوث هذا التغير وآثاره . ويعتقد أن هذه الآثار تهم مواقع معينة وأنها لا تشمل العالم كله . ويقترح فريق العمل أيضا عناصر واعتبارات أساسية لانشاء برامج دولية ترمي الى التحقق من تغيّر منسوب البحار . وقد أدرجت في النص ست صور ايضاحية وجدول واحد وقائمة بالمراجع المتعلقة بهذا الموضوع .

ويخلص المؤلفون الى أنه لئن كان الرأي العلمي السائد حاليا لا يميل الى الخروج بتنبؤات تقول باقتراب "يوم القيامة" نتيجة لارتفاع هائل في منسوب البحار ، فان من المرجح أن تحدث تغيرات هامة في مستوى اليابسة والبحار على حد سواء . وينبغي أن تركز الدراسات المقبلة على الجوانب المحلية لهذه التغيرات ، وذلك في المناطق المعرضة للخطر .

节　录

“教科文组织COMAR 关于平均海面升高及其对沿海地区之影响的工作组”分析了最近地质时期和历史时期以及未来数十年有关海面变化的各个方面。报告提供了对有关平均海面变化的原因、可能性及后果的关键性概述。这些概述大部分被认为是地区性的而不是全球性的。该工作组还提出了查明海面变化的国际计划的内容，并为该计划的制定提出了基本设想。该计划除计划文本还包括六个插图和有关该学科的一份表格与一份参考资料目录。

作者认为虽然目前科学界的意见不倾向于关于明显全球性海面升高的世界末日预报，然而地面及海面的重大变化是很可能发生的。未来研究应当集中在受威协地区的这种变化的各方面问题。

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1. SUMMARY

Because of the increasing concentration of greenhouse gases in the atmosphere, it is probable that the forthcoming decades will witness increased temperatures. One of the likely consequences will be changing relative sea level, probably relative sea-level rise. Both change in temperature and change in relative sea level will be very noisy signals, as they have been in the past. Programmes to study and understand them will require long-term commitment in order to separate trends from noise.

It is no longer considered probable that the great ice sheets of Antarctica and Greenland will melt very rapidly. They will remain too cold to melt *in situ*, and Antarctic ice in particular is too well "buttressed" by terrain to move quickly. Thus other causes of relative sea-level change will be of equal or greater importance. These include steric effects in the ocean, coastal subsidence and failure of the balance between sediment compaction and the addition of new sediments on the surface.

These other causes are largely site-specific, as is the nature of areas under threat. Thus any international programme designed to assist in dealing with the problems of sea-level change should have strongly site-specific characteristics. The programme should include determination of the local causes for relative sea-level change, including changes both of the level of the sea and of the land. Features under threat from various amounts of sea-level rise should be identified.

In structure, the programme should feature "learning-from-each-other", and the sharing of equipment, expertise, data and experiences.

2. CAUSES OF RELATIVE SEA-LEVEL CHANGE

2.1. Introduction

The issue of sea-level rise as a consequence of climatic warming and the greenhouse effect is receiving intense attention by scientists, government officials, the press, and laymen alike. Although at first glance a simple issue, the actual determination of changes in relative sea level is an extremely complex and time-consuming task (e.g. van de Plassche, 1986). It involves the consideration of many factors, and requires decades of high-quality observations, data analysis and modelling. A number of doomsday predictions of accelerated sea-level rise during the next century (e.g. Hoffman *et al.*, 1983) were predicated on the assumption of a rapid melting of ice from the great ice sheets, which is now considered to be improbable. A large number of other effects are now thought to be at least as important as melting of ice sheets. Most of these other factors are site-specific rather than global. In fact, in many parts of the world, relative mean sea level is falling rather than rising, and may continue to do so despite greenhouse warming. Thus, one should speak of sea-level change rather than sea-level rise. It is our objective, in this document, to evaluate critically the issue of relative sea-level change, to discuss the reasons for global and local change, and to consider the consequences for the coastal zone.

The climate system of the earth is now being monitored as never before. Data from satellites, ground-based systems, ships, buoys, tide gauges etc. are being compiled, exchanged, banked in centres, catalogued, collated and interpreted. However the climate system is so "noisy" with weather, and such relatively short-lived events as El Niño recurrences that it is not easy to come to firm conclusions about the present nature and rate of climate change.

The one thing that is certain is that the concentration of greenhouse gases in the atmosphere has been increasing inexorably over the last century. We have already reached one quarter of the "CO_2 doubling"[1], relative to the pre-industrial period, which is usually used by modellers to estimate climate sensitivity. Their models project a temperature increase ranging from 1.5 °C to 4.5 °C for "CO_2 doubling", with the effect stronger at high latitudes and less marked in tropical regions (National Research Council, 1987). Roughly, the response should increase logarithmically with greenhouse gas concentration. Thus, a 25% increase in concentration should yield about 1/3 the increase of doubling. That is, one might expect to have experienced a temperature increase of from 0.5 °C to 1.5 °C.

There is some consensus that global surface temperatures have risen about 0.5 °C during the last century (Fig. 1). It is not an easy determination. Over land it must be made in the face of diurnal plus interannnual fluctuations of about 50 °C, for an annual increase over range-of-

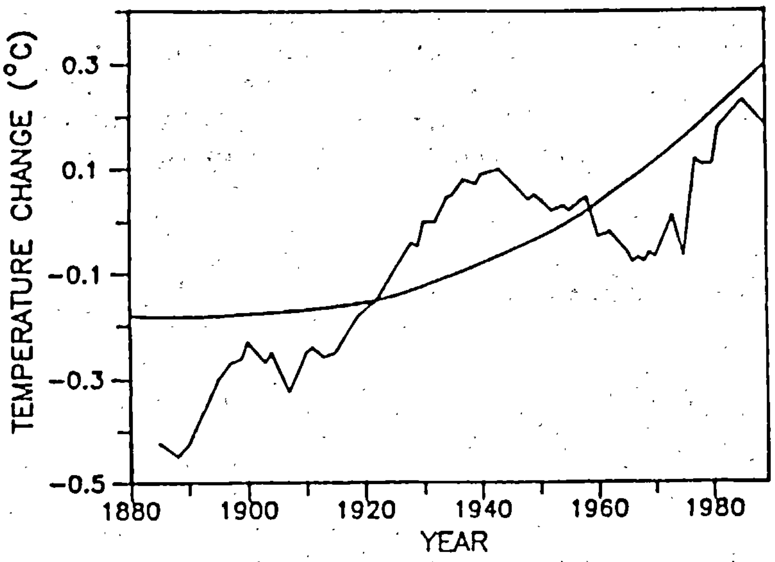

Fig. 1
Comparison between observed global average temperature and calculations based on the greenhouse effect (smooth line). Most data are from the Northern Hemisphere. (After Seitz *et al.*, 1989.)

fluctuation ratio of 10^{-4}/a. Also the areas surrounding many observing stations have experienced important changes in vegetation or urbanization, so that deciding which stations to retain for a time series is difficult. Rather more than half of this 0.5 °C increase occurred in the first half of the century, before most of this additional load of greenhouse gases had been added to the atmosphere. Until a few years ago, this temperature increase was generally ascribed to "getting out of the Little Ice Age", which lasted from 1400-1880 (Grove, 1988). How it should be interpreted today is not entirely clear and is the subject of difference of opinion and debate in the scientific community.

1 "CO_2 doubling" is a shorthand notation to indicate the increase in all greenhouse gases (CO_2, CH_4, CFC's) which would have the same radiative effect as a doubling of the CO_2 concentration.

2.2. Sea-surface temperature

With respect to the ocean, the interpretation of sea-surface temperature records is bedevilled by the fact that over the last century there has been a complete change in the techniques of measurement. In the earlier periods, most temperature measurements were made with hand-held thermometers in buckets of water drawn from over the sides of ships. Estimates are now obtained from a composite of satellite measurements, intake of cooling water for ship engines, and measurements from buoys, usually drifting and reporting by satellite. Serious efforts have been made to untangle this puzzle, but it is difficult to be confident about differences in the neighbourhood of 0.5 °C between contemporary and earlier estimates. Nevertheless, modelling studies indicate that mean atmospheric temperature is very sensitive to mean ocean surface temperature, and it is reasonable to assume that the ocean surface also has warmed by about 0.5 °C during the last century. Such a rise is consistent with ocean measurements, although not yet firmly established.

Since July 1984, the World Meteorological Organization (WMO) has issued a series entitled *Climate system monitoring (CSM) monthly bulletin.* Among the data reported is mean sea-surface temperature and sea-surface-temperature anomalies from a 30-year composite climatology centred on 1965 (Reynolds, 1988). A typical map shows some areas of anomalies of more than 1 °C, both positive and negative, and some very small areas with anomalies greater than 2 °C. The 3 °C and greater anomalies, which occur rather often in near-shore waters, cover such small areas that they are not seen on world maps. Only in the equatorial Pacific are 2 °C or greater mid-ocean anomalies frequently reported, associated with the El Niño-La Niña alternation (Leetmaa, 1989).

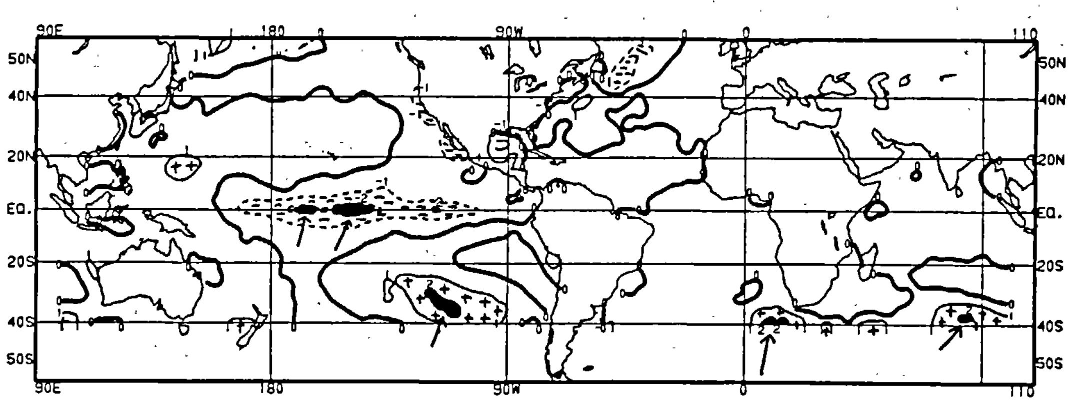

Fig.2
Sea-surface temperature anomaly for December 1988 - February 1989 (from a 30-year climatology centred on 1965). This was a period of fairly strong La Niña -- i.e. cold eastern equatorial Pacific. Areas where the anomaly is between 1°C and 2°C are hatched, plus for positive, minus for negative. Areas where the anomaly is greater than 2°C (either way) are filled in and indicated by heavy arrows. Only a few percent of the ocean displays anomalies greater than 1°C, and they are of both signs. Only a tiny fraction of the ocean area shows anomalies greater than 2°C. (After Arkin, 1989.)

The *Journal of Climate* regularly reports three-month averages of essentially the same data. For these three-month averages it can be seen (e.g. Fig. 2) that typically the total area having anomalies greater than 1 °C amounts to something in the neighbourhood of 10^7 km^2, or a few percent of the ocean surface. Anomalies greater than 2 °C cover only a small fraction of one percent.

Sea-surface temperature thus provides a stable base in comparison with air temperatures over land, yielding information about systematic climate shifts. Any systematic change over the past few decades seems to be a small fraction of 1 °C[2]. It is difficult to find the high-latitude sensitivity predicted by the model simulations, since there is no special concentration of positive anomalies at high latitudes.

Overall interpretation of these data is thus such as to generate controversy (e.g. Seitz *et al.*, 1989; Kerr, 1989). Air temperatures seem certainly to have risen over the last century, and sea-surface temperatures may well have risen. The magnitude of the rise is consistent with the lower ranges of those predicted by model studies. However, the spatial distribution of these temperature increases is not in accord with model predictions, and the rise during the second half of the century is not greater than that during the first half, which should not have been influenced very much by increased concentrations of greenhouse gases (cf. Fig. 1).

Nevertheless the decade of the 1980s has been particularly warm (cf. Fig.1). It is quite common, even in scientific circles, to assume or assert that recent climate changes are associated with the greenhouse effect. Although most of the scientists in the field continue to stress the uncertainty and advise caution in interpretation, it is evident that it would be most unwise to assume that the increase in greenhouse gas is having no effect. The scientific consensus remains that a temperature increase is to be expected during the next century. Prudence calls for preparation to deal with the consequences of such a change.

2.3. The expected magnitude of sea-level change

Among these consequences, none have caused more concern than a possible significant rise in sea level. This concern arises from a number of considerations: A large and growing proportion of the world's population inhabits coastal areas, in particular coastal plains and deltas, which are the most vulnerable to the effects of sea-level rise. There is a widespread recognition that the disappearance of the great northern hemisphere ice sheets, which marked the end of the last glaciation about 10,000 years ago, was accompanied by a rise of some 100 m in sea level. The possibility of the rapid disintegration of the West Antarctic Ice Sheet, yielding about 5 m of rise in sea level, was seriously discussed (e.g. Mercer, 1978).

Public opinion became attuned to the notion of several metres of sea-level rise within a lifetime, and sketches of new coastlines, adjusted for such new sea levels, were widely published (e.g. Fig. 3, after Houghton and Woodwell, 1989). Houghton and Woodwell's figures (on pages 42 and 43 in their paper) provide an outstanding example of the sort of doomsday material which was promulgated a few years ago. However there is no mention of extreme sea-level rise in the text. Apparently the authors adjusted their text to account for the moderation of scientific opinion, but were unable to have the diagrams modified.

The resulting concern led to considerable study of the question of the disintegration of the West Antarctic Ice Sheet. The conclusion was although it was indeed the case that the sheet was grounded below sea level, it was in fact well buttressed so that very rapid disintegration could largely be dismissed as a possibility (e.g. Frolich, 1989). Further, it has been recognized that increased temperature will be accompanied by increased evaporation and precipitation. Some of this increased precipitation may fall on the great ice sheets, tending to cause them to grow. Thus it is uncertain whether there will be a net rise or a net fall of sea level associated with changes in the mass of the ice sheets (e.g. Stewart, 1989a). In any

[2] The 0.1 °C/a rise in sea-surface temperature suggested by Strong (1989) for the mid 1980s on the basis of satellite data has been refuted by Reynolds *et al.* (1989), using a wider, composite data set.

case, the annual source and sink terms in the mass balance of the ice sheets are now about equal, each equivalent to about 1 cm/a in sea level. Any imbalance created by changing climate is unlikely to amount to more than a fraction of this. It could go either way. The end result could just as well be sea-level fall as sea-level rise.

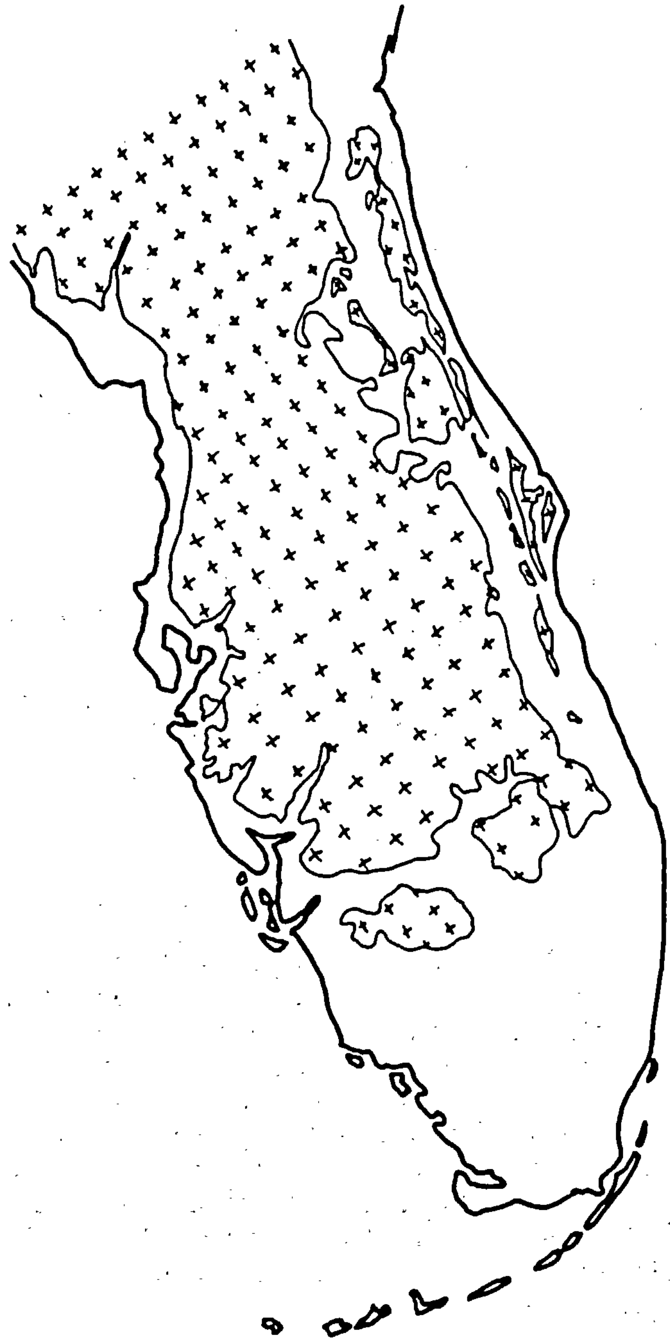

Fig. 3
Florida after a 7.6m sea-level rise. The hatched area is all that would remain above sea level. (After Houghton and Woodwell, 1989.) This sketch is typical of doomsday material which was widely published a few years ago. It is now generally accepted that sea-level rise of this magnitude is unlikely, at least for many centuries.

Recent estimates for future sea-level rise tend towards lower values than did previous ones. While there remains a wide range in the estimates, most estimates now lie around 60 cm for around the year 2100, with an uncertainty of about a factor of three (Figs. 4 and 6) (e.g. Church *et al*, submitted for publication).

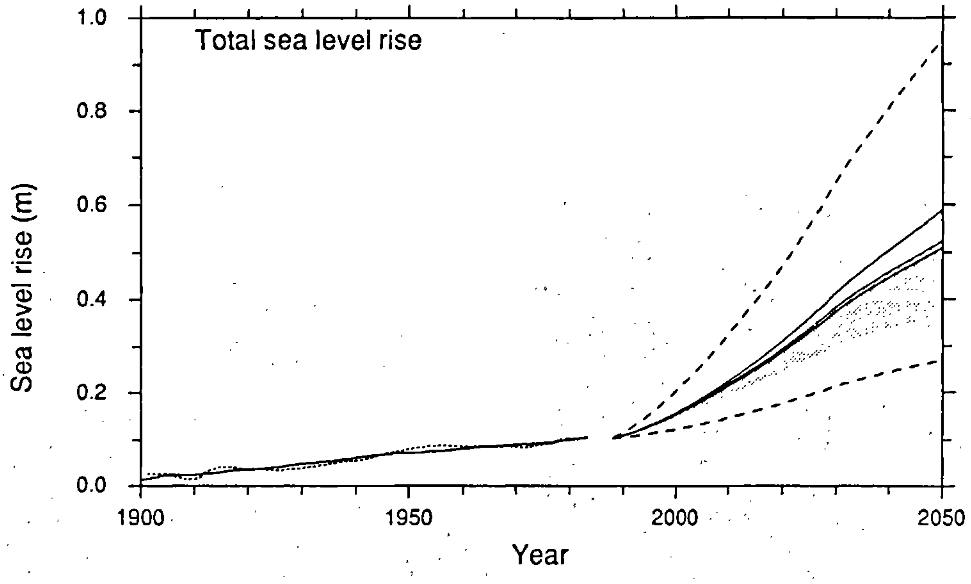

Fig. 4
Total sea-level rise, observed and predicted (after Church *et al*, submitted for publication). This figure is fairly typical of projections appearing in recent literature. Before 1985 it shows the output of their model (solid) and an interpretation of the observations (dotted lines) similar to that of Gornitz *et al*, 1982. After 1990 the central projections are the output of their model under various assumptions. The stippled band indicates uncertainty concerning the effect of increased stability in the ocean resulting from surface heating. The dashed lines represent extreme cases.

2.4. Sources of sea-level change

Interpretation of past data on sea-level change causes at least as much uncertainty as does interpretation of past air and ocean temperatures. The order of magnitude of recent past changes in relative mean sea level (RMSL) is 1 mm/a. This must be arrived at in the face of fluctuations (tidal, storm surges etc.) of the order of 5 m, for a ratio of 2 x 10^{-4}/a, which is not very different from the 1 x 10^{-4}/a noted in 2.1 for temperatures on land. However with respect to relative sea level there is a problem which has no analogue in temperature measurements: There are no permanent absolute terms of reference. Because the sea-level change that concerns us reflects both movement of the sea level and the level of adjacent land, we do not measure absolute sea level, but rather relative sea level. (In the long run, for oceanographic purposes, we would like to measure both with respect to the geoid -- but that is a topic beyond the scope of the present discussion.)

In general terms we can divide the factors affecting RMSL into four categories:

A. Those which determine water volume,
B. Those which determine sea surface shape,
C. Coastal subsidence, and
D. Large scale crustal and subcrustal movements.

These may be subdivided as follows:

A. (1) Change in the mass of the ocean as a result of melting or accumulation of land-supported ice in the great ice sheets of Antarctica and Greenland, and in the smaller ice sheets and mountain glaciers.

(2) Change in the volume of water in the ocean by heating or cooling, leading to expansion or contraction, and thus to a steric rise or fall of sea level.

B. (1) Change in the way in which water is piled up against, or pushed away from coasts by the local wind field.

(2) Changes in the atmospheric surface pressure field.

(3) Changes in river run-off regimes.

(4) Changes in ocean currents caused by changes in the wind field over the ocean basin.

C. (1) Changes in the thickness of coastal unconsolidated sediments, caused by sediment deposit, erosion, compaction or consolidation of sediments, or the withdrawal of fluids from the sediments.

(2) Crustal movements of coastal areas, relative to the geoid.

D. (1) Changes in the depth of the ocean basins.

(2) Changes in the geoid, mainly due to change in the volume of ice and to flows in the earth's mantle.

With the conclusion that very rapid melting of the great ice sheets is unlikely, none of these influences can be neglected relative to the others. It is common experience that smaller ice sheets and glaciers have lost mass during the past century. Meier (1984) concludes that this effect has contributed about 0.4 mm/a to sea-level rise. There remains the equivalent of about 50 cm of sea-level rise in such bodies of ice, should they all be melted. It is noteworthy that with the exception of numbers A(1) and D(1) above, and some possible aspects of A(2), these influences are local or regional, rather than global. Thus, changes in relative mean sea level differ substantially from place to place and from region to region (Fig. 5). These differences can be expected to continue into the next century although there may well be a bias towards accelerated sea-level rise everywhere.

It may seem surprising that so many geological and geophysical influences are listed, since most causes of change "on a geological time scale" are too slow to have much effect within a human lifetime[3]. However, it is even possible to argue (e.g. Pirazzoli, 1986; Stewart, 1989b) that almost all relative mean sea-level change over the past century, apart from that caused by small ice field melting (Meier, 1984), has been the result of earth movements. We are living in a geologically unusual time (Rice and Fairbridge, 1975), since it is only about 10,000 years since the end of the most recent northern hemisphere glaciation and the earth is still recovering (rapidly on a geological time scale) from this event.

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[3] e.g. Cloetingh *et al.* (1985), who discuss a flexure of the earth's crust leading to sea-level changes of about 0.1 mm/a. Such a change of 1 cm per century is negligible in a lifetime but amounts to a very significant 100 m in a million years, which is not particularly long from a geological point of view. It is considered by geologists to be an extremely rapid rate for a widespread phenomenon.

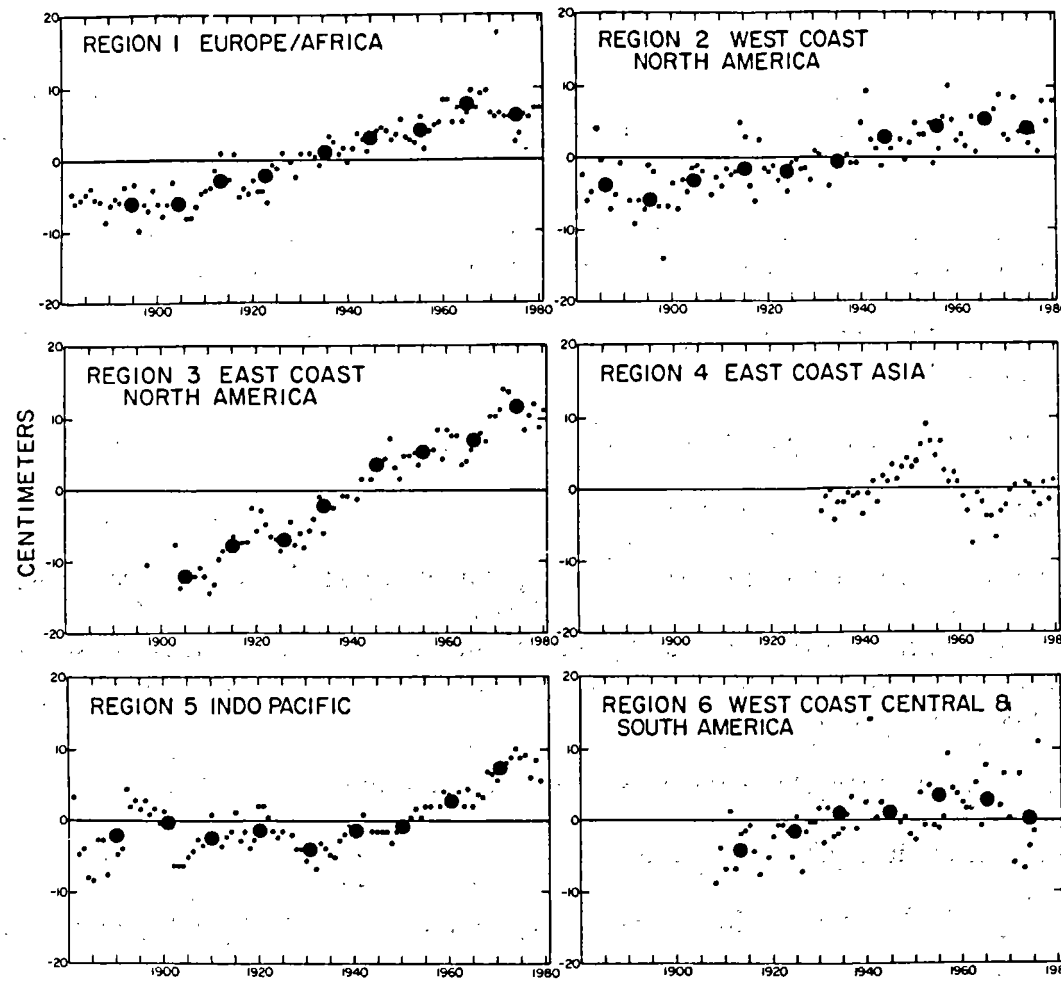

Fig. 5
Relative sea-level change as measured by tide gauges. The data have been grouped according to regions with coherent behaviour. The heavy black dots are five-year medians. (Figure adapted from Barnett, 1984.)

The nature of this recovery is such that it is still producing very significant effects upon sea levels (e.g. Peltier and Tushingham, 1989, 1990). Over a few thousand years, as the glaciers receded, something like 5 x 10^{19} kg of water was added to the ocean, mostly from the northern hemisphere although with some Antarctic contribution (Nakada and Lambeck, 1989; Peltier and Tushingham, 1990). The ocean is mostly in the southern hemisphere, so the centre of mass of this water moved several thousand kilometres south. In response, the centre of mass of the solid parts of the earth moved north some tens of metres. This rearrangement of mass led to increased pressure on the bottom of the oceans, with no corresponding change on land except on the land which had been bearing the load of ice, which now experienced a great reduction in pressure. The resulting stress field in the earth led to flows in the earth's mantle. These continue to the present day, although since this is a relaxation process, the rate of change has decreased. Mantle material is flowing in under the areas formerly glaciated, causing them to rise relative to the geoid and to sea level (e.g. Stewart, 1989c). These flows are causing the geoid itself to change. To a lesser extent the same is occurring under other land masses, which can be pictured as floating up because of the deeper ocean. Mantle material is flowing out from under the ocean basins, causing them to sink, taking the ocean down with them.

Peltier and Tushingham (1989) have modelled this process and shown that a consistent picture can be drawn. Their model accounts for the rapid fall of relative mean sea level observed in formerly glaciated areas of the northern hemisphere and the comparatively rapid rise of RMSL on the east coast of North America. On the basis of this model, they have re-examined sea-level data and come to the conclusion that there has been a rather general rise of about 2.4 mm/a in sea level during the past half century. They speculate on the source of this rise, and conclude that most of it must represent melting of the large Antarctic and/or Greenland ice caps, perhaps associated with greenhouse warming. If one extrapolates from these conclusions in a scenario for the future where temperature rises (say) 0.04 °C/a, rather than the 0.005 °C/a of the last century, it might be concluded that we could expect sea level to rise by 2 cm/a, or 2 metres per century. This is near the upper limit of present estimates of future sea-level rise.

Peltier and Tushingham's (1989, 1990) 2.4 mm/a is considerably more than estimates for recent general rate of rise which most authors (e.g. Gornitz *et al.*, 1982; Gornitz and Lebediff, 1987; Barnett, 1984) have derived from the same data set, held at the Permanent Service for Mean Sea Level at the Institute of Oceanographic Sciences Bidston Laboratory (UK) for the International Association for the Physical Sciences of the Ocean (IUGG-ICSU). These other authors did not make use of any model for the post-glacial readjustment of the earth, and Peltier and Tushingham (1989, 1990) have performed a valuable service in drawing sharp attention to these phenomena. However their results should not yet be taken as definitive, as they themselves acknowledge (Peltier and Tushingham, 1990). Other, independent estimates of increase in water volume yield results more consistent with the usual 1.0 - 1.5 mm/a (e.g. Church *et al.*, 1990). The (approximately) 200 km grid used in their model is much finer scale than that of previous work on global scale, but remains rather coarse when trying to deal with phenomena taking place on the border between the land (going up) and the ocean (going down). Further work is necessary, perhaps using more detailed models and, if possible, using new kinds of measurements, to refine the treatment of these phenomena.

There are other causes for substantial vertical movement of the land. For example, along many active margins, where subduction of one plate under another is taking place, the crust may crumple under compression, leading to uplift in some areas and sinking in others, perhaps within only about 100 km of each other. Such motions can be of as fast as 2 mm/a. They are probably shortlived on a geological time scale, but persistent on a human scale (e.g. Riddihough, 1982).

2.5. Anthropogenic causes of sea-level change

Other processes, some of which are influenced or induced by human activity, can substantially affect the level of the land surface, without much changing the level of the underlying rock. In the normal course of events, loose unconsolidated near-surface sediments become more compact with time. Water is squeezed out, pores become smaller and grains become cemented together. The density increases and the surface level sinks. This is a natural process, gradually giving rise to semi-consolidated sediments and ultimately to sedimentary rock. However, the withdrawal of fluids, usually water but also oil and natural gas, from near-surface sediments can hasten the compaction of these sediments and lead to a drop in the land level and therefore to a relative sea-level rise. This influence is observed in such places as Venice and Bangkok (Milliman *et al.*, 1989). In recent years, Bangkok has been sinking at a rate greater than any other major city, indeed at a rate greater than almost all estimates for sea-level rise induced by greenhouse gases (Fig. 6).

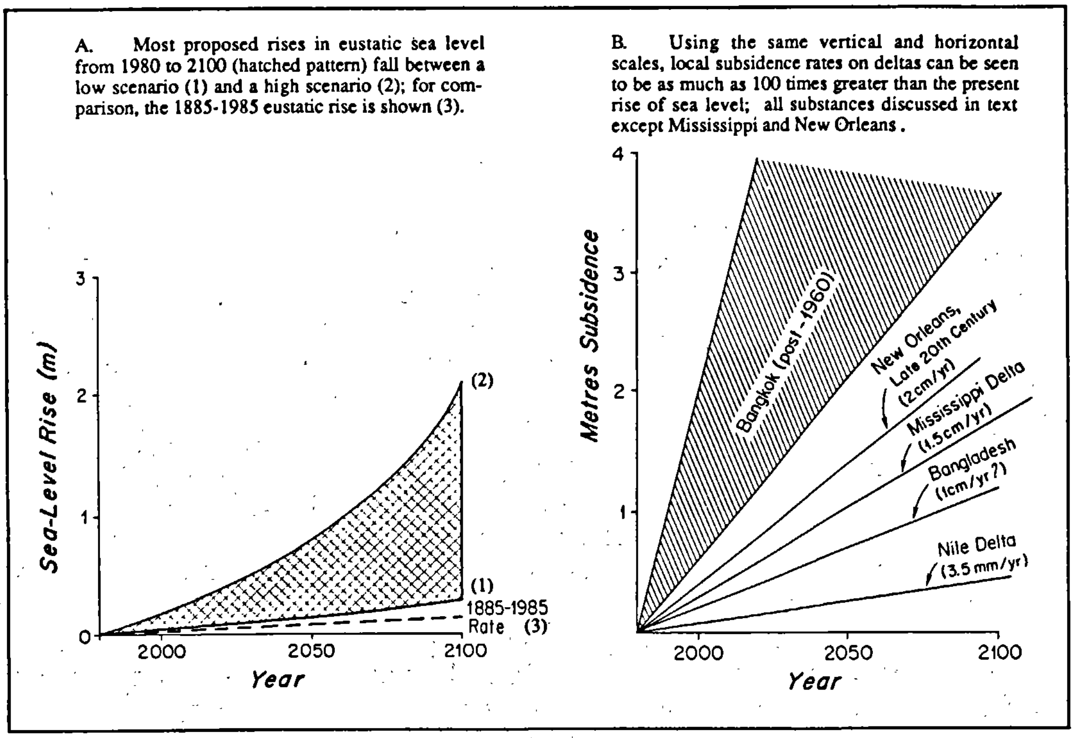

Fig. 6
(After Milliman *et al*, 1989.)
A. Most contemporary estimates for sea-level rise associated with the change in the volume of the ocean lie within the hatched area.
B. Local subsidence rates on deltas, using the same scales on ordinate and abscissa as in A. Note that these rates are fully comparable with anything expected from changes in the volume of the ocean.

Other human activities have influenced relative sea level. The natural sediment flow has been altered in many ways. For example, rivers have been dammed and/or diverted to irrigation projects, so that the sediment load never reaches the coastline. The situation at the mouth of the Nile is an outstanding example, where the construction of the high Aswan dam has largely eliminated the flow of sediment to the coast, which is now experiencing very rapid change (Milliman *et al.*, 1989). Levees and dykes have been constructed, and river channels are dredged, so that floods are inhibited; water and sediment flow out through defined channels rather than spreading over the deltas. Sinking and compacting sediments are then not renewed by additional layers, elevation of the surface relative to sea-level drops, and the area becomes increasingly vulnerable to inundation from the sea. This effect can be seen clearly in the area of the Mississippi delta (Wells and Coleman, 1987; Coleman, 1976).

2.6. Steric effects

Expansion of the ocean by heating, and sea-level changes associated with changes in ocean currents show up in measurements as a change in the steric effect[4]. Modern techniques permit determination of steric effects on sea level with an accuracy of about 1 cm, although fluctuations associated with internal waves mean that such accuracies are attainable in the mean only if a great deal of averaging is possible. A number of authors, including Barnett (1983),

[4] The steric effect describes the effect of the difference in the volume of a mass of water relative to the volume at a standard salinity and temperature (e.g. Pattullo *et al.*, 1955). If water has higher temperature and/or lower salinity than the standard, then for a given pressure at the bottom the surface will stand higher than would be the case for water at standard salinity and temperature. Thus heating or diluting sea water, at any depth, leads to a steric rise of the surface. Steric effects due to temperature differences are referred to as thermosteric, while those due to salinity differences are halosteric.

Roemmich (1985), and Thomson and Tabata (1988, 1989), have examined past oceanic data in search of evidence for a steric contribution to sea-level rise during the last few decades. While Roemmich (1985) and Thomson and Tabata (1989) believe they have detected such a rise in their data, with magnitude about 1mm/a, Barnett (1983) did not detect any significant rise in the data he has examined, and in any case the signal-to-noise ratio is very low because of the presence of interannual fluctuations of as yet unknown origin. Nevertheless, the techniques for determining steric sea-level change are now well tested. Unfortunately, there are only very few oceanic stations in the world where systematic time series to the necessary depth (at least 2000 m), accuracy and frequency (at least seasonally) have been taken. Steric data are very noisy, if one is looking for long-term trends of the order of a few millimetres per year. If new time series are commenced in the immediate future it will be a decade or more before definitive trends can be identified. Nevertheless it is important to make such measurements (or some surrogate for them like those from upward-looking bottom-mounted echo sounders) if the various causes of changes in relative mean sea level are to be sorted out.

Salinity also influences the steric effect on sea level. Thus the difference between evaporation and precipitation in any area changes sea level. Perhaps more importantly, the addition of large volumes of river water in a relatively localized region causes very significant dilution with an accompanying halosteric rise of sea level. Since river flow is usually quite variable on all time scales, in many estuarine regions halosteric effects contribute importantly to the fluctuations of sea level. For example, due to monsoon runoff, the upper Bay of Bengal experiences a seasonal halosteric effect approximating 1 metre (Pattullo *et al.*, 1955).

Even at depths of hundreds of metres in deep water, time-dependent halosteric effects of unknown origin have been observed to amount to several centimetres (e.g. Thomson and Tabata, 1989; Levitus, in press.)

All scenarios for future sea-level rise associated with greenhouse warming incorporate an element of thermosteric effect. Models variously take into account vertical diffusion (Revelle, 1983), upwelling plus diffusion (Wigley and Roper, 1987), or wind-forced subduction (Church *et al.*, submitted for publication). All suffer from uncertainty over the way in which increased stability associated with surface heating will influence the situation (Stewart, 1989a,b; Church *et al.*, submitted for publication). Typically, sea-level rise of a few tens of centimetres is suggested from this cause in "CO_2 doubling" scenarios.

A quick, rough calculation can show the magnitude of steric rise which might be expected in a warming world. Although the thermal coefficient of expansion of sea water varies significantly with both temperature and pressure, almost all values vary within a factor of two, centered on 2×10^{-4}/°C. 1 J of heat will warm 1 m^3 of water about 2.4×10^{-7} °C. Hence 1 W/m^2 will cause a steric rate of rise of about 1.5 mm/a. The effect of "CO_2 doubling" is estimated to be equivalent to an additional heat flux at the surface of about 3-5 W/m^2 (e.g. Schlesinger and Mitchell, 1985), so the rate of steric rise might be expected to range from a fraction to a few mm/a, depending on the proportion of the additional heat flux absorbed by the ocean.

It is difficult to see any mechanism that would lead to a thermosteric rise of more than a few centimetres within a century, before there is a greater rise of sea-surface temperature than the half degree which seems to have occurred. Thus thermosteric effects are unlikely to be playing a very important role at the present time. However the nature of ocean circulation is sufficiently poorly understood that it may yet hold surprises, and monitoring for any possible steric rise should be an integral part of sea-level rise study.

3. CONSEQUENCES OF RELATIVE SEA-LEVEL CHANGE

3.1. How sea-level rise will reveal itself

It is clear that relative mean sea level can either rise or fall locally as a result of a combination of factors. As most lesser developed countries are located in low latitudes more likely to experience a relative rise rather than fall of sea level, we will address some probable consequences of relative mean sea-level rise.

There is no reason to suspect that there will be any particular exacerbation of problems associated with dropping relative sea level, although they will continue to occur in some areas, particularly at high latitudes.

It is important to recognize that relative mean sea-level changes which may take place in a few decades are in fact rather small compared with changes in sea level which take place on much shorter time frames. There are few places in the world where the tidal range is much less than a metre, and a tidal range of five metres is far from unusual. It is quite normal for the difference between high neap tides and high spring tides to be more than a metre. Storm surges of elevation 50 cm are very common everywhere, and in regions subject to tropical storms such surges may be an order of magnitude larger. Ordinary weather changes, with corresponding changes in wind fields, can result in changes in sea level of around 20 cm, and the annual heating-cooling and runoff cycles, together with associated wind field changes, lead to seasonal sea-level cycles of the same magnitude but up to 1m in exceptional cases like the Bay of Bengal. Sea-level records typically show interannual fluctuations of the order of 10 cm, which sometimes persist for a few years before being reversed (Pugh, 1987; Thompson and Tabata, 1989). Some such changes are the result of causes which are not clearly identifiable.

A higher relative mean sea level will cause flooding associated with some combination of these events to occur more frequently. However, one is dealing with the statistics of small numbers and it will be difficult for the public to interpret such an increase in the frequency of occasional events, even if it is noticed at all.

Thus a higher relative mean sea level most usually will not be noticed by the general public as an insidious, gradual rise but by some extraordinary event. If sea level has risen significantly, and if chance produces a coincidence among, for example, a high spring tide, the seasonal sea-level high and a strong storm surge, the combination may raise the sea to unprecedented levels, inundating areas which had not before been flooded. Since the storm surge will most usually be accompanied by strong wave action, damage will be done to areas which had heretofore been considered too high or too far inland to be affected.

3.2. Coastal inundation

These formerly untouched areas are likely to have some properties making them very vulnerable, including vegetation with low tolerance to salt water and unconsolidated sediments and soils which could be dramatically rearranged by the water. Some of these effects can in fact be assessed now, since river diversion and dam-building often alters river environments into brackish and saline estuarine waters. As the soil salinity increases, the original vegetation can die off on time scales from months to years if the marine inundation persists for any length of time (Kjerfve, 1976; Bradley *et al.*, 1990). These affected areas are then frequently recolonized by salt marsh or mangrove vegetation, as long as they continue to experience marine tidal flooding, although the time-scale of recolonization is measured in years.

Closer to the ocean, areas which had in the past occasionally been inundated only very rarely might find themselves covered with enough water to sustain appreciable waves, leading to significant changes on the bottom. Also structures not designed to resist wave action could be damaged or destroyed.

The particular condition of the river at the time of the unusually high sea level can also influence the degree of flooding. The details of the coastline can interact with the details of the trajectory of a storm in ways that can either exacerbate or ameliorate the situation. Thus, areas which relative mean sea-level rise had made much more vulnerable might escape unscathed for long periods of time, while other areas, in principle less subject to damage might be devastated by some freak combination of events. Chance plays a significant role in these events. Wave set-up, for example, can add tens of centimetres to the sea level at some locations along the shore (Longuet-Higgins and Stewart, 1964; Tait, 1972), perhaps without affecting an adjacent tide gauge, which might even experience wave set-down.

3.3. Disappearance of beaches

One likely local effect of increasing relative mean sea level is accelerated coastal erosion. An increase in sea level would result in more severe wave erosion of dunes and beaches and a resultant offshore sediment transport to create a flatter offshore beach profile (Bruun, 1962; National Research Council, 1987). Although this would occur episodically in response to storm wave events, the result would be a diminishment of local beach environments as sand sediments are transported offshore beyond the depth at which they participate in seasonal onshore-offshore sediment cycles.

3.4. Salt-water intrusion

Of course the more insidious effects will also take place if a location experiences relative mean sea-level rise. The boundary between fresh and brackish water in aquifers will retreat upward and landward. The resulting contamination of freshwater aquifers will, no doubt, have major adverse impact on coastal population centres, which often rely on groundwater for drinking water. Also, a salt water wedge of bottom marine water will intrude a greater distance upstream in stratified estuaries, and tidal mixing will extend the estuarine zone further upstream in partially and well mixed estuaries. The end result, in both cases, will be an inland intrusion of the marine or brackish water zone. This influence may be particularly damaging in the case of the freshwater lenses beneath low-lying islands, where an already limited fresh water supply may be further reduced.

3.5. Changes in coastal production

As the estuarine salinity zone moves further inland, in areas experiencing relative mean sea-level rise, there are likely to be dramatic effects not only on the adjacent bank and wetland vegetation, but also on coastal primary and secondary productivity. Undoubtedly the coastal terrestrial vegetation will be stunted or destroyed. Whether the long-term effect will cause increased or decreased marine primary production is highly speculative.

On time-scales of a century, however, it seems reasonable to expect increased production by salt marshes, mangroves, benthic algae, and coastal phytoplankton production as a result of inland erosion induced by a relative sea-level rise. For example, a significant increase in production of *Spartina alterniflora* cord grass in South Carolina salt marshes is positively correlated with years of detrended, anomalously high mean sea levels during the growing season (Morris *et al.*, 1990). One explanation for this is that the anomalously high mean sea level implies a geater likelyhood that nutrient exchange can take place between estuarine waters and the adjacent marsh.

Morris *et al.* (1990) also found a significant positive correlation between the years of anomalously high mean sea level and commercial landings of penaeid shrimp and menhaden (*Brevoortia* spp.) from the Southeastern and Gulf coasts of the USA. Since these species utilize the *Spartina* marshes as juveniles, both increased habitat area and available food sources can be used to suggest the role of high sea-level anomalies in explaining increased secondary coastal production. These results are also consistent with positive correlations between shrimp landings and size of adjacent intertidal wetlands for salt marsh (Turner, 1977; Turner and Boesch, 1988) and mangrove (Martusubroto and Maamin, 1977) environments.

4. PROGRAMME TO ASCERTAIN SEA-LEVEL CHANGE

4.1. Suggested programme components

Since both relative sea-level change and the nature of the areas under threat are site-specific, any international programme designed to deal with the situation should also have strong site-specific features (e.g. van de Plassche, 1986). An important characteristic of such a programme is that it should stress "learning-from-each-other", and the sharing of any equipment which is both expensive and only occasionally used.

The first, and *sine qua non*, requirement is a suitable tide gauge network, carefully maintained, and subject to careful data analysis and regular careful vertical control. Because of the site-specific character of the task at hand, the need cannot be met by the sparse Global Sea-level Observing System (GLOSS, coordinated by IOC) network (Pugh, 1987), valuable as that network is for determining ocean-scale variations in sea level. Each stretch of coast threatened by inundation in the event of abnormally high sea level (say 1 metre above the highest astronomical tides) should have a well-sited tide gauge. To the extent possible, tide gauges should be sited in locations particularly suitable for determining long-term changes in RMSL. Such locations will frequently not be in ports or at military installations, where most existing gauges are sited. Maintenance, periodic vertical control, and data analysis should be a clearly recognized responsibility of some competent authority. A serious effort should be made to ensure that the tide gauges would survive, and if possible continue to function, in severe conditions such as tsunamis and storm surges.

Tide gauge records will show fluctuations on all time scales not deliberately filtered out. Over any finite period of time, a trend will be detectable, but its magnitude and even its existence may be uncertain unless the record is at least decades long. Interpretation of the record will be considerably improved if a full suite of supporting measurements are carried out: atmospheric pressure, offshore steric height, wind force and direction, wave characteristics, changes in local gravity, levelling and Global Positioning System (GPS) control of vertical position. The TOPEX/Poseidon satellite, with its accurate altimeter and its special non-synchronous orbit, will give a very good description of global tides which will help in interpreting local observations. Indeed observations from all satellite altimeters, a considerable number of which are planned or expected, should be examined for clues in sorting out the various sources of relative sea-level change.

Even with all these supporting measurements, the interpretation will require skill and training, and will benefit from comparison with what is done elsewhere.

Analysis of the data records should go considerably beyond those often undertaken. Once the usual tidal components, including annual tides[5], have been determined and the usual tidal prediction tables prepared, the record needs regular careful examination for anomalies, i.e. differences between observed and predicted elevations. Such an examination should be designed not only to detect the kind of phenomena of interest to GLOSS, and interannual variations and long-term trends, but should involve a search for the effects of shorter-term phenomena such as tsunamis and storm surges.

The statistics of these latter phenomena should then be examined to determine such things as:

(1) What extreme values are to be expected in the next decade? in the next half-century? (using log-normal or other appropriate extrapolation techniques). Projections for changes, associated with climate change, of such characteristics as the intensity and the areal and temporal extent of tropical storms should be taken into account.

(2) What sea level would have been reached if a particular observed storm surge or tsunami had occurred at a time of highest astronomical tide?

(3) What is the expected recurrence period of high sea levels of various magnitudes, determined by combining the astronomical tide statistics with the anomaly statistics, if possible taking account of nonlinear tide-surge interactions (Pugh, 1987)?

(4) Regional coherence of sea-level anomalies.

The data should be examined with and without correction for changes in atmospheric pressure. Without correction, they provide more accurate estimation of sea-level anomaly statistics. With correction, they provide data more suitable for determining astronomical tides and long-term mean trends. The techniques for this type of analysis have already been well established (Pugh, 1987), and only need adapting to local requirements.

From information of this kind, the actual threat of relative sea-level rise can be ascertained, recognizing that coastal areas will be subject to periodic inundation long before they become part of the intertidal zone, let alone are permanently flooded.

If there is an existing tide-gauge record, analysis can be commenced on the data record, even if quality is not up to the standard of new data. A good deal of information can be gleaned. Data analysis can start with new data records after only a few months have elapsed. It is by no means necessary to wait until, for example, the annual tides have been well defined in order to search for anomalies from predictions made from the data already accumulated. Such early estimates can be refined as the data record grows. It is necessary, once more, to emphasize that decades of tidal data are required for determination of relative mean sea-level change with any reliability.

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[5] The "usual tidal components" are obtained by harmonic analysis of the tide gauge record. The analysis captures all phenomena which are phase-locked to any astronomical frequency. These include not only the gravitational influences of the sun and moon but, for example, the influence on sea level of annual cycles of heating and cooling, evaporation and precipitation, river runoff, atmospheric pressure, wind field and ocean currents (Pugh, 1987).

An international team should be encouraged to compare experience concerning suitable land-use strategies for areas subject to various occurrences and severity of inundation.

For each critical area, a serious effort should be made to determine the local causes of sea-level change. Relative changes in mean sea level are the difference between changes in the water level relative to the geoid and changes in the land level relative to the geoid. As we have seen, these may be of comparable magnitude. For some purposes, it makes little difference whether the ocean is rising or the land is sinking. However, for some others, the difference is important. For example, one cause of sinking land is extraction of fluids from below. This is a human activity, subject to modification. If the negative results of such activity are greater than the positive values, a decision can be made to desist. However, it is necessary to know whether or not fluid extraction is indeed the source of ground subsidence before such a decision is enforced. Otherwise the positive values might be lost without any reduction in the negative results. On the other hand, where subsidence is the result of withdrawal of fluids the process is generally irreversible so that caution is called for.

In some areas the "natural state" has been a balance between compaction and sinking of coastal sediments with build-up by the addition of new sediment and organic matter. Where this state has been altered, the compaction and sinking can continue without the compensating build-up. Such situations need to be identified where they exist, partly so that informed decisions can be made about continuing or changing the alterations, and partly so that experience can be documented and used by other jurisdictions which might be contemplating comparable alterations.

An important part of the international programme should be the compilation of such information in readily accessible form. It should also involve collating, and in some cases commissioning, case studies showing characteristic behaviour in representative situations.

The development of the Global Positioning System (GPS) makes possible very accurate relative vertical control over substantial areas. Eventually it or its successors will be used to make accurate geocentric elevation measurements, which will be used together with geocentric geoid determinations to detect changes in the geoid and changes in elevation relative to the geoid. Any system put in place should recognize the probability of this development and be readily adaptable to it when it becomes operational.

If vertical movement is simply the result of compaction, or change in phase or temperature of the material below, there is no significant change in the geoid and there is a direct relation between the vertical motion and the change in gravitational acceleration at the surface. Where there is movement in or out of material below, a change in the geoid results and changes in gravitational acceleration can no longer be so simply interpreted. Nevertheless, very accurate gravity measurements can make an important contribution to sorting out among changes in the earth surface relative to the geoid, changes in the water level relative to the geoid and changes in the geoid itself (Carter et al., 1989).

The actual profile of the surface should be determined by standard surveying methods supported where appropriate by a grid of relative GPS measurements. Contours at e.g. 0.25m separation should be plotted. These contours should be compared with the observations of inundation (probably best defined by aerial photography) for various occurrences of extremely high sea level, so that the local peculiarities of behaviour may be ascertained. In due course, it will probably become possible to undertake laser (LIDAR) profiling from aircraft, themselves positioned by relative GPS, to an appropriate accuracy.

Vertical land movements are sufficiently slow (at most a couple of centimetres per year) that any one area need be controlled only every few years by GPS, accurate gravity determination, and profiling. However there may be enough appropriate areas in the world to allow the required equipment and key personnel to be active continuously in a co-operative programme.

After any significant inundation, the surface should be resurveyed to identify changes. This resurvey should be conducted even if the inundation was caused by river flooding rather than high sea level, in order to identify erosion and deposition patterns.

An effort should be made to ascertain the steric sea-level change associated with the coastline under threat. This requires a time series of deep (at least 1000 m) hydrographic stations taken with good, well maintained equipment. Observations should be taken at least quarterly. The Panuliris (Roemmich, 1985) and Station PAPA (Thomson and Tabata, 1988) time series can be used as models. Again, equipment and perhaps some key personnel can be shared, although the ships, which require suitable winches, can probably not be shared beyond a regional basis. Where resources permit, deeper stations, to 2000 m, 3000 m, or the bottom, should be taken in order to add to global data necessary to detect any global steric change.

4.2. Responsibility matrix

Dealing with relative mean sea-level change involves the responsibilities of many agencies and jurisdictions, and many levels of government. Some aspects are global; others are very local. Some aspects require a research emphasis, best met by involving university and research institute personnel. Monitoring over long periods of time is best undertaken by government agencies with personnel and terms of reference attuned to this task, which is closely analogous to that undertaken by weather services. However, there should be close association, which may or may not be reinforced by institutional arrangements, between those responsible for the research and those responsible for the monitoring. Such association strengthens the motivation of those undertaking the monitoring, and thereby improves the quality of the data. At the same time, it gives those undertaking the research a realistic understanding of the nature and limitations of the data set. It also permits improvements and modifications to be made in the way in which data is collected and archived, without destroying the continuity and comparability needed for valid interpretation.

The matrix (Table 1) summarizes a number of the responsibilities to be undertaken and suggests the level of jurisdiction or nature of the agencies which might be most suited to undertake them.

Table 1. Matrix of causes of sea-level change vs. groups or agencies that ought to be responsible for research and monitoring tasks.

CAUSES OF SEA-LEVEL CHANGE	STUDIES TO BE CARRIED OUT BY: RESEARCH GROUPS		AGENCIES		
	International	Regional	National	Sub-National	Local
1. Melting of ice and snow with transfer to oceans					
1.1. Ice caps and large glaciers	X	X			
1.2. Small glaciers		X	X	X	
2. Steric changes					
2.1. Temperature changes	X	X	X		
2.2. Salinity changes	X	X	X		
3. Change in land elevation relative to the geoid					
3.1. Large scale geophysics (Plate tectonics, mantle flows)	X	X	X		
3.2. Local tectonics and warping			X	X	
3.3. Changes in unconsolidated sediments					
3.3.1. Natural (sediment erosion, sedimentation, compaction, expansion)			X	X	X
3.3.2. Anthropogenic (dams, development, land-use, engineering structures)			X	X	X
3.3.3. Changes in ground fluids	X	X	X		
4. Changes in Geoid	X	X	X		
5. Changes in ocean-atmosphere dynamics (currents, wind, atmospheric pressure, waves, runoff, tidal rectification)	X	X	X		

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