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Sea-Level Modelling: The Past and the Future

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ABSTRACT

The development of an analytical expression to describe the natural variation of global temperature and related climatic variables over periods from a few years or less to over a billion years is shown and seen to match the variation of eustatic sea-level over similar periods. An additional anthropogenic factor to take the greenhouse effect into account is added to this natural climatic variation giving close correlation between the combined natural-plus-anthropogenic model of global temperature variation and its observed history over the past century. This provides grounds for confidence in the subsequent deterministic forecast for the combined model and its sea-level counterpart of, for instance, about 0.7m rise by 2050AD.

A tentative physical explanation of the natural climate model is given invoking the possibility that the Universal Gravitational Constant (G) may, in fact, be a variable. In parallel, the anthropogenic climate model is underlined by alluding to a theoretical explanation of the population growth mechanism which largely drives it. The interactive nature of the impact of man on sea-level rise and *vice versa* is stressed.

CONTENTS

1. INTRODUCTION

Ever since climatology became a respectable science with the quantitative analyses of MILANKOVITCH (1938) and his astronomical theories building on the previous foundations of CROLL (1875) and his forerunners who included KUHN, HUTTON, ESMARK, BERNHARDI, PERRAUDIN, CARPENTIERS and AGASSIZ, mathematical models have been sought to mirror the observational record frozen in the geological, historical and recently instrumental past (see IMBRIE and IMBRIE, 1979). The driving force has been the expectation that such models would open the way to forecasting future climatic trends.

Few would dispute that sea-level fluctuates to the beat of climate. As global temperature increases in the atmosphere and the sea, so ice landlocked on Greenland and Antarctica melts increasing the volume of the oceans so that sea-level rises and *vice versa*. Therefore, the ambitions of climatologists blend comfortably with those of sea-level researchers; both camps seek the hitherto elusive model.

Here it is shown that a mathematical climate model, introduced by DENNESS (1981), matches the variation of global sea-level change not only over the whole Phanerozoic timescale, but also throughout the most intense part of the last ice age. Essentially it matches global warmth to high sea-level. The model is substantiated by reference to various climatic records ranging over periods from several billion down to a few years or less. The last full ice age is selected as a specific example introducing others of shorter term.

The success of the natural climatic model is then added to by the consideration of anthropogenic global temperature modelling (i.e. the greenhouse effect) to emphasise a forecasting potential for future sea-level change. The combined model, with its sole variable time, can be used equally well for forecasting as hindcasting. Socio-economic considerations interact with purely environmental factors to provide the basis for forecasts over periods from a matter of decades to many millions of years ahead.

2. BACKGROUND

The various elements of this deterministic approach to climatology and hence sea-level investigation, arose from ocean studies. The author, a civil engineer, in attempting to correlate engineering design parameters such as sediment strength and consolidation characteristics with simpler, more cheaply determined sedimentary indices, came upon sediment profiles of oxygen isotope records. Although they were plentiful and were relatively cheaper to acquire than engineering design parameters, they did not correlate with the engineering properties. Nevertheless, it was immediately clear from the isotope profile under review (SHACKLETON and CITA, 1979) that the trends in the isotope record reflected climatic and, by inference, sea-level fluctuations over the past seven million years. Of course, this is common knowledge to the climatologist but a bit of a shock to the average civil engineer.

In view of the dating uncertainties in the oxygen isotope record the general trend and superimposed variations were separated by eye. There were cyclic variations of approximate periods 4.8, 2.4 and 1.2 million years with amplitudes correspondingly decreasing at a lesser rate. These cycles were superimposed on longer term trends indeterminable from the seven million year record; in turn higher frequency components were evident as residual values but the data spacing was too wide to allow the definite recognition of a periodicity less than 1.2 million years.

A series of cyclic components is apparent which are not distributed secularly at random. They form part of a series of frequencies of ever-halving period and slightly reducing amplitude, each zero-registered at the same fixed point in time as shown schematically in reconstruction by DENNESS (1983a). There was a clear challenge to pursue this series of sinusoidal cycles towards both the longer and shorter periodicities of geological and historical timescales respectively.

First the series of linked sinusoidal cycles, which together represent among other things global temperature, was extended to longer periods. DENNESS (1984a) showed how superimposed periodicities of approximately 38.4, 76.8, 153.6, 307.2, 714.4, 1428.8 million years could be detected in geological time series ; however, the 9.6 and 19.2 million year periods needed to complete the series have not yet been detected. Among the data considered were global temperature, precipitation estimates and oxygen isotope ratios measured on chert over a timescale extending back to 3000 million years - two thirds the estimated age of the Earth - by FRAKES (1979) and KNAUTH and EPSTEIN (1976) respectively. To these were added (a) the secular variation of global evaporite volume (GORDON, 1975), (b) variations of solar radiation absorption (BURNETT, 1982), (c) the occasion of major glacial epochs (WHYTE, 1977), (d) variations in high latitude marine water temperatures (SAVIN, DOUGLAS and STEHLI, 1975), (e) variation of carbonate compensation depth (LE PICHON, MELGEUN and SIBUET, 1978), (f) changes in oxygen isotope ratio in planktonic Foraminifera (SCLATER, 1978), (g) proportions of fish debris in a marine sediment (MELGUEN and THIEDE, 1974), (h) fluctuations in Foraminifera abundance (KENNETT and VELLA, 1975), (i) cycles in Weddell Sea sediment temperatures (ANDERSON, 1972), (j) New Zealand fauna variation (HORNIBROOK, 1971), and (k) further oxygen isotope ratio profiles (SHACKLETON and KENNETT, 1975; VAN DONK, 1976).

Cycles of shorter periodicity were sought. DENNESS (1984b) illustrated that the series can be identified over the cycle periods of 600 and 150 thousand years before continuing with 75, 37.5, 18.7, 9.3, 4.6, 2.3, 1.1, 0.275 and 0.137 thousand years in Quaternary geological, archaeological and historical records; only the cycles of 300 and 0.55 thousand years are yet to be identified to complete the series. Among the data considered were (a) an isotopic temperature curve from the Caribbean (WEST, 1968), (b) a generalised sea-level curve (BLOOM, 1971), (c) carbonate variations (HAYES, SAITO, OPDYKE and BURCKLE, 1969), (d) oxygen isotope ratios from the Greenland ice sheet (DANSGAARD, JOHNSEN, CLAUSEN and LANWAY, 1971), (e) insect population variations in the Netherlands (VAN DER HAMMEN, MAARLEVELD, VOGEL and ZAGWIJN, 1967), (f) abundances of Mediterranean tree pollen (VAN DER HAMMEN WIJMSTRA and ZAGWIJN, 1971), (g) variations in foraminiferan populations (IMBRIE and KIPP, 1971), (h) South American vegetation changes (HEUSSEN, 1966), (i) treeline shifts (LA MARCHE, 1973, 1974; MARKGRAF, 1974), (j) variations in Australian *Eucalyptus* pollen abundance (CHURCHILL, 1968), (k) changes in deuterium proportion in Californian bristlecone pines (LAMB, 1977), (l) the timing of global glacier advances (BRAY, 1968), (m) the drift of the winter severity index across Europe (LAMB, 1977), (n) the secular variation of cloud cover in China (LINK, 1958), (o) variations in Chinese raininess index (YAO, 1943, 1944; see SHOVE, 1949), (p) changes in temperature in China (CHU, 1973), (q) the freezing date of a Japanese lake (LAMB, 1977), (r) population growth trends (DENNESS, 1986a), (s) landslip and flood occurrences (GROVE, 1972), (t) variations in the retreat rate of a coastal cliff (DENNESS, CONWAY, McCANN and GRAINGER, 1975) and (u) the variations in Hong Kong landslip activity (MALONE and SHELTON, 1982).

BURNS and DENNESS (1985) extended the examples of these shorter period cycles further identifying 68 years cycles by the examination of time series data from (a) Australian lake levels and salinity (CURREY, 1970; BOWLER, 1970), (b) the progress of the Indus civilisation in India (BRYSON and MURRAY, 1977), (c) changing duration of polar ice occurrence off Iceland (KOCH, 1945), (d) variations in the monsoons in India (SING, 1971; BRYSON, 1975), (e) the rise and fall of the Viking colonies in Greenland (VEBAEK in LAMB, 1977), (f) the trend in cultural habits of the Mill Creek Indians of North America (BRYSON and MURRAY, 1977), (g) changes in wheat prices in NW Europe (LIBBY in LAMB, 1977), (h) Japanese temperature variations (LAMB, 1977) and rainfall variations (YAMOMOTO, 1972), (i) famine, drought, plague and river level variations from northern Africa (NICHOLSON in LAMB, 1977), (j) fluctuations of global-scale energy production (CIPOLLA, 1978) and industrial production (KUCZINSKI, 1980), (k) global economic progress by VAN DUIJN (1977) and analysed by DENNESS (1983b, 1983c and 1984c).

Even shorter period cycles of 17, 8.5, 4.2 and 2.1 years can also be recognised (though the expected 34 year period has not yet been detected), e.g. from (a) the variation of winter conditions in eastern Europe (LAMB, 1969), (b) changing positions of Alpine glacier termini (AHLMANN, 1953), (c) instrumental records of temperature variation in the Northern Hemisphere (JONES and WIGLEY, 1980), (d) capture dates of spawning Arcto-Norwegian cod (CUSHING and DIXON, 1976), (e) accumulation of snow (FLETCHER, 1969), (f) local Canadian annual temperatures (JONES, 1976) and (g) snowfall and duration in the Shetlands (MORTH, 1978).

There are more than 400 time series which can be combined to enable the derivation of an equation which describes a sinusoidal series to match global temperature variation (and other climate-related phenomena by calibration) for timescales as long as billions of years and as short as a few years or less.

$$G(t) = \sum_{n=N(T)}^{\alpha} A(T) a^{n-1} \sin b^{-n} \pi \left(\frac{t}{T}\right) \tag{1}$$

which is zero-registered at time T_0 and in which:

G(t) is a time-based climatic index, e.g. global temperature,
A(T) is the amplitude of a reference periodicity T,
N(T) is the reference integer for periodicity T,
a,b are absolute constants, here taken as 0.84 and 0.5 respectively,
n is an integer, i.e. the reference number of a particular sine component, and
t is time in years.

So far 26 of the 30 sine components in the orderly series of ever-halving periodicities have been identified with amplitudes reducing successively by a factor of 0.84, starting at about 1429 million years and ending at 2.1 years. However, there seems to be no theoretical reason why the missing components may be omitted and there is every reason to expect them eventually to be identified in more complete data sets. Also there is no reason to expect the series to be restricted to the presently identified range of 1429 million-2.1 years.

3. NATURAL SEA-LEVEL CHANGE

Sea-level has changed continuously over geological time. Long term variations approximately correlating with the above climate model have been detected as far back as 600 million years worldwide (Fig.1) (HOLSER, 1984) and 100 million years or more for the Otway Basin of Victoria, Australia (GLENIE, SCHOFIELD and WARD, 1968). GLENIE *et al.*(1968) also noted similar variations at Auckland, New Zealand extending back about 50 million years bp. TANNER (1968) described a steady fall in general sea-level of 70-100m from about 20 million years bp to the end of the Tertiary, similar to the general trend described by the theoretical climate model for global cooling over the same period.

However, more detailed fluctuations of sea-level have been measured for the last major glaciation, since about 130,000 years bp. BLOOM (1971) gave a generalised sea-level curve for the Caribbean for the last 130,000 years, and Figure 2 illustrates how the general trend in shoreline levels coincides with the smoothed output of the climate model since 130,000 bp.

The global data of VEEH and CHAPPELL (1970) is shown in Figure 3 in comparison with the less smoothed output of the model since 100,000 bp. Also superimposed on Figure 3 is the variation of temperature of tropical Atlantic surface waters (EMILIANI, 1961). The two data curves correspond fairly closely both with each other and the model (see the bold line). Smoothing the model output in Figure 2 provides a close match to the generalised sea-level data at the expense of sensitivity, which disguises the model's true interpretation of more detailed temperature and sea-level rise. However, this sensitivity is restored in Figure 3 which also shows a good match for most of the period.

Sea-level fluctuations during the global warming since the coldest part of the last ice age (20,000 bp) have been dominated by the input from melting ice. JELGERSMA (1966) extended the work of FAIRBRIDGE (1961) to prepare a eustatic sea-level curve for that period for

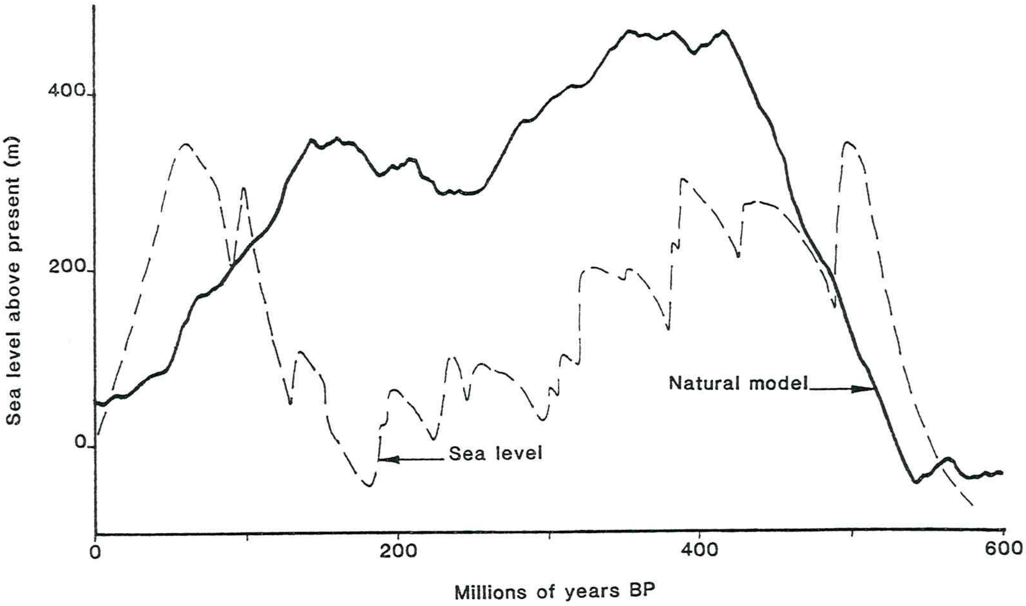

FIG.1. Comparison of climate model and sea level change since 600 million years bp.

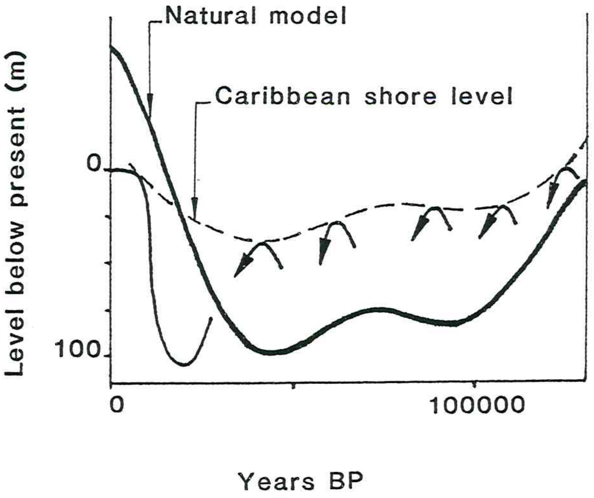

FIG.2. Comparison of climate model and sea level change since 170,000 years bp

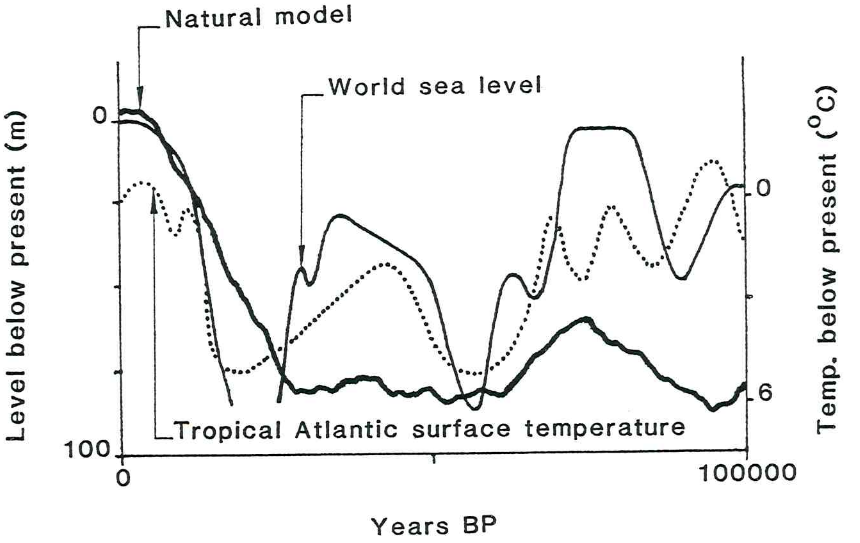

FIG.3. Comparison of climate model, sea level and temperature change since 100,000 years bp.

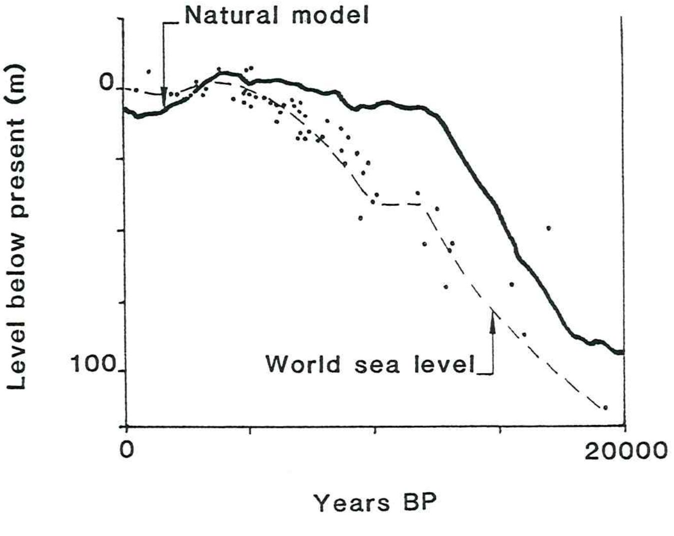

FIG.4. Comparison of climate model and sea level change since 20,000 years bp.

geologically stable areas. Figure 4 shows that it closely matches the smoothed output of the model even to the extent of the still-stand around 10,000-12,000bp. Many regional and local measurements of sea-level trends, (e.g. DEVOY, 1977 for several English regions; MÖRNER 1980, for Fennoscandia) when due allowance is made for isotacy and crustal movements, also tend to describe similar trends. When considering short term instrumental records over the last couple of centuries, we may need to take account of the possible influence of man.

4. ANTHROPOGENIC SEA-LEVEL CHANGE

Since the industrial revolution there is a need to consider the potential influence of the greenhouse effect on climate. The greenhouse effect is the warming of the atmosphere caused by increasing man-made trace gases, particularly carbon dioxide (CO_2) but also methane, ozone, and nitrous oxide etc.Recently another group of anthropogenic gases potentially as significant as CO_2 has begun to be released, the chlorofluorocarbons, and their impact was recently quantitatively estimated by DICKINSON and CICERONE (1986). They warned of the seriousness of the global experiment now underway and part of that experiment involves the impact of Man's activity on sea-level rise.

Convincing the scientific community and the public at large of the reality of the greenhouse effect is hampered by the present difficulties in separating manmade from natural climate changes over the last 100 years or so. Plenty of data exist relating to the increasing amount of CO_2 in the atmosphere (e.g. CALLENDAR, 1958; KEELING, BACASTOW and WHORF, 1982) and many models predict with remarkable consistency the likely temperature increase it must have induced already (see LISS and CRANE, 1983). The variations of global temperature (at least northern hemisphere) over the last century have been as great as these predicted greenhouse temperature changes, but not always in the same upward direction, so the natural climatic variation in temperature has been sufficient to prevent positive identification of the greenhouse effect.

Nevertheless DENNESS (1984d) added the greenhouse model (Fig.5a) of WETHERALD and MANABE (1981), a model which forecasts a rise of 3°C in global temperature as a result of doubling atmospheric CO_2, to the model of natural temperature change (Fig.5b) described by Equation 1 and derived a further model representing the combined effect of natural and manmade temperature fluctuations. Figure 5c shows that the model compares favourably with the observed fluctuations in Northern Hemisphere temperature since 1880. As the natural model (Equation 1) has been shown (DENNESS 1984a,b) to correspond to natural climatic changes on geological, archaeological, historical and instrumental timescales, it is logical to suppose that the combined model provides clear evidence of the greenhouse effect.

Let us now consider sea-level changes for a similar period. Figure 6 combines the Amsterdam tide gauge record for the period 1700-1860 (FAIRBRIDGE, 1961, from VAN VEEN, 1954) with global eustatic sea-level changes for the period 1880-1980 (BARNETT, 1984). There was little change in sea-level during the latter part of the Little Ice Age, but since about 1920 there

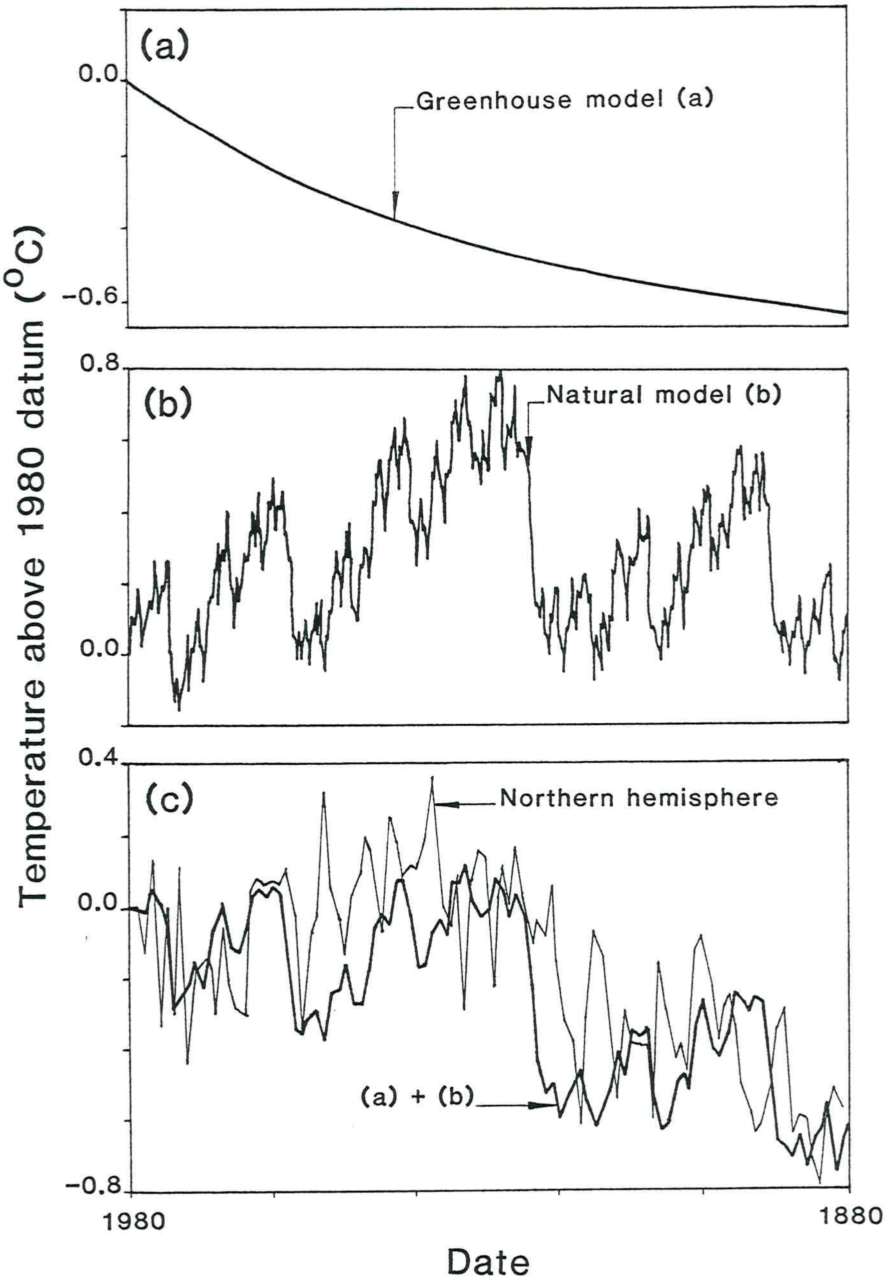

FIG.5. Combination of greenhouse (a) and natural climate (b) models to match observed northern hemisphere temperature (c) since 1880.

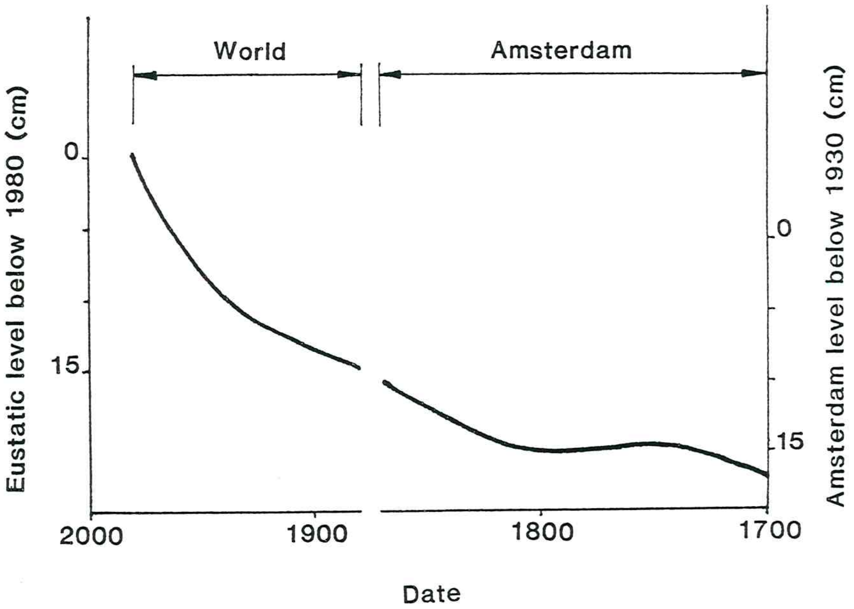

FIG.6. Recorded sea level change since 1700ad.

has been a steady rise of some 15cm. At the same time there was a global temperature rise of about 0.4°C between 1920-1980 (JONES and WIGLEY, 1980). Thus a sea-level rise of *ca.*15cm coincided with a steady temperature rise of 0.4°C over a period of 60 years, i.e. a rate of rise in sea-level of 2.5mm y^{-1}.

At the end of the last ice age over a period of some 2000 years equatorial temperature rose by 6°C (EMILIANI, 1961; WEST, 1968; etc.) and the average global temperature, by analogy with modern temperature anomalies, by perhaps 50% more, say 9°C. The sea-level also rose at a rate of nearly 25mm y^{-1} (e.g. JELGERSMA, 1966) finally rising by about 100m despite the rate of rise slowing down after a few thousand years. In other words the sea-level rose at 25mm y^{-1} as the global temperature increased by 9°C, with a slower continuing rise due to the continued melting of landlocked ice persisting over the following several thousand years after the temperature had risen. Empirically this natural event could be interpreted as causing a rise in sea level of 25/9=2.7mm y^{-1} for every degree increase in global temperature and by analogy a rise of 0.4°C would result in a rise of 1.1mm y^{-1}, about a half that apparent from 1920-1980.

This crude analogy may disguise the true influence of several integral physical processes, any one or combination of which could alter the relationship. Nevertheless empirically it represents a fairly consistent global calibration.

Between the end of the Little Ice Age and 1960 the global temperature rose by 0.8°C or so which included the greenhouse component of about 0.4°C (Fig.5a). Thus the rate of sea-level rise in response to the greenhouse element of the nearly synchronous rises in natural and anthropogenic temperature should have been 25 x (0.4/9) = 1.1mm y^{-1}. Figure 5 shows that since about 1960 or perhaps as early as 1940, the natural global temperature expected from the model has decreased balancing the rise in anthropogenic temperature so that temperature has remained more or less constant over recent decades. However, sea level has continued rising as ice still melts in the warmer atmosphere of this century, much as it did at the end of the last full ice age.

5. POSSIBLE FUTURE SEA-LEVEL CHANGES

While the short-term thermal expansion of the oceans can be neglected, there has been since the industrial revolution and for the foreseeable future there will continue to be the need to consider the impact of both natural and manmade global temperature changes on sea level. Models of both these phenomena have been tested in some detail so that it is now possible to use them quantitatively either separately or in concert in a similar fashion to the qualitative approach of MITCHELL (1977) but leading to a less benign scenario.

The natural climate model represented by the above equation forecasts a global temperature rise of about 0.5°C largely during the early 1990s. It then forecasts a natural levelling off during the first half of the next century and a subsequent fall to the present temperature by about 2100AD. Over the following few centuries its forecast of natural temperature change remains approximately within these same bounds, leading to another Little Ice Age within about 700 years.

The greenhouse model, reinforced by the recent work of DICKINSON and CICERONE (1986) paints a far more dramatic picture. It foresees a global temperature increase of about 3°C by 2050AD - and that is only the foothills of a mountainous rise to come if population increases, industrialisation spreads and mankind continues to engage in burning fossil fuels, deforestation and the discharge of manmade trace gases; all of which are virtually certain in the absence of any international political intervention. Since in hindcast the combined natural and anthropogenic model is entirely consistent with events of the past century, its forecast for the future deserves very serious consideration.

Together combined natural and man-induced temperature increase is predicted to be at least 3.5°C by the middle of the twenty-first century. Thereafter, unless Man dramatically changes his habits, the greenhouse component will overwhelm natural climate change. This timescale of about 65 years is within the expected service life of many if not most major engineering, agricultural and other social undertakings at or near present sea-level. Therefore, let us explore the significance of the likely sea-level change resulting from this increased temperature.

The earlier "calibration", which described the events at the end of the last full ice age and over the past century indicated that for each 1°C rise in atmospheric temperature there is a global sea level rise of about 2.7mm y^{-1}, i.e. so a rise of about 9.5mm y^{-1} is to be expected for a 3.5°C rise in atmospheric temperature. The previous records suggest that the sea-level rise will begin almost simultaneously with the temperature rise and will quickly attain the estimated rate of increase; this implies that there will be a eustatic sea-level rise of about 0.62m by 2050.

The likely extent of sea-level rise by 2050 can be estimated by a different approach using a more analytical approach applied to, for example, the estimate of increased trapping of thermal radiation given by the WORLD METEOROLOGICAL ORGANISATION (1982). Its 2050 scenario envisages increased thermal trapping due to anthropogenic trace gases to be in the range 2.2-7.2Wm^{-2}. Taking an average increase of 4.7Wm^{-2} what are the implications of this effective increase of thermal energy on the melting of ice?

The landlocked ice covers about 1/30th of the Earth's surface, i.e. about $15\mathrm{x}10^{12}\mathrm{m}^2$. Therefore, in 2050 the global ice sheets will be absorbing about $7\mathrm{x}10^{13}$ Watts more than at present (i.e. $2.2 \,.\, 10^{21}$ joules y^{-1}). Assuming the surface temperature of the ice is -20°C (DAHL-JENSEN and JOHNSEN, 1986), this additional heat would melt $5.3\mathrm{x}10^{18}$ grams of ice = V.

The oceans cover about 70% of the Earth, i.e. about $3.2\mathrm{x}10^{18}\mathrm{cm}^2$ = A. The expected sea-level rise in the year 2050 from the melting of landlocked ice (sea ice-melt causes negligible change), will be V/A=1.66cm. Therefore, from the 2.5mm y^{-1} rise seen during the decades in the middle of the twentieth century, the average rate of rise between now and 2050 will be about ½ (1.66+0.25) = 0.95cm y^{-1}, amounting to about 0.62m, due to anthropogenic effects.

There are several areas in which the assumptions of this analysis can be challenged, for instance, the suggested surface ice-melting mechanism is an unreal concept (R THOMAS, pers. comm.) but nevertheless reflects an equivalent energy transfer mechanism. More likely the absorbed thermal energy will merely decrease ice viscosity and result in more rapid ice transfer to the sea where it will melt later. Also changes in the global distribution of trace gases and temperature increases in the atmosphere will be far from uniform but will favour the polar regions.

Furthermore, there is a natural temperature rise of 0.5°C to be expected from the natural climate model by 2050 and this would imply an additional 9cm (0.5x0.27x65) rise in sea level to supplement the 62cm from the greenhouse effect to give a total rise of about 0.71m. Both the analytically derived estimate of 0.71m and the empirically derived 0.62m fall within the middle of the range emanating as a consensus opinion from BOLIN (in press).

DENNESS (1985, 1986b) recently exaggerated these estimates by a factor of four or five in earlier estimates which have evoked no comment. A similarly disturbing forecast was made by HOFFMAN, KEYES and TITUS (1983). The rise up to 2050 is only the forerunner of even greater rises to follow, but is enough to threaten with inundation vast expanses of agricultural land, coastal cities (including further risk to London even with its new multi-billion pound flood barrier) and engineering structures - within the lifetime of a large number of people already alive today. ROSSITER (1962) and ALCOCK (1984) estimated that a rise of only 15cm is enough to double or treble the probability of storm surge damage around Britain. More serious consequences were envisaged for the USA by BARTH and TITUS (1984) and WOODWORTH (in prep.) foresees that a 0.5m rise will have a major impact on people living in coastal areas.

6. DISCUSSION

Since the industrial revolution the WORLD METEOROLOGICAL ORGANISATION (1982) estimated that thermal trapping due to increasing anthropogenic trace gases has increased by about $2.2Wm^{-2}$. By simple analogy, this implies that there should be an annual sea-level rise of 7.8mm which is three times the presently observable rate. This could be seen as a calibration of the analytical approach taking into account currently unknown factors relating to the precise mechanism of atmospheric energy absorption, transfer to the ice and ice melt. It may also reflect a measure of differentiation between apparent relative sea level rise and the eustatic rise: the foregoing "eustatic" data are all, in fact, "relative" (K EMERY, P PIRAZZOLI pers.comm.). If it is taken as a global calibration the forecast for the rise to the year 2050AD should be adjusted to about 0.34m, very much to the lower end of current estimates and only slightly higher than a summation from the simple extrapolation of the present rate. Clearly further work is required to clarify this important anomaly.

Apart from the serious implications of sea-level rise for the near future, even at the lowest realistically calculated rate, it is appropriate also to consider the impact of the past major prehistoric rise on the timing of the apparent birth of civilisation. *Homo sapiens* evolved about 100,000 years ago with an estimated population of about 1.7 million (McEVEDY and JONES, 1978). By 12,000bp the population had increased only to about 4 million at the time of the ice age when the sea level was almost 100m lower than at present (Figs.2-4). By 7,000bp Man's population still appears to have numbered only about 5 million - an increase of 25% in 5,000 years (McEVEDY and JONES, 1978). Thereafter the population explosively increased to about 160 million by 2,000bp; this time an increase of 3150% in 5,000 years. There was a particularly rapid rate of growth occurring around 6,000bp when sea-level had risen and stabilised to within a metre or so of the present level (Fig.4). Therefore, it might be surmised that the apparently poor population growth of Palaeolithic and early/middle Mesolithic man relative to his late Mesolithic and Neolithic successors was due more to the drowning of many of his earlier habitations by marine incursion, thereby depriving the present-day archaeologist of a large proportion of relic sites prior to about 6,000-7,000bp, and hence leading to a substantial underestimation of population.

This hypothesis appears to be substantiated by the observation that about 80% of modern Man lives <100m above present sea-level. If his ice-age predecessor had exhibited similar habits about 80% of his original dwellings would now lie beneath the sea so population estimates could be as little as a fifth of the actual figure. DENNESS (1986e) provided a mathematical expression for the global population growth curve which almost exactly matches modern and historical data and, by backward extrapolation, the prehistoric estimated (McEVEDY and JONES, 1978) growth pattern, except during the ice age when its hindcast is about five times greater than archaeological evidence. Therefore, by making allowance for the proposed influence of sea-level rise on the archaeological estimates, the expression has proven validity for describing Man's population growth over the last 2.5 million years (ie throughout his existence as a species):

$$P = 2 \times 10^{11} (44 + t)^{-1} \qquad (2)$$

where P is the global population and t is the number of years bp. The rapid growth described by this equation, which is similar to those by MEYER (1958) and MEYER and VALLEE (1975), and to a lesser degree by TAAGEPERA (1976), is still occurring today. The theoretical justification for the equation was given by DENNESS (1986c).

The implications of this population growth model are twofold with respect to future sea-level rise. Firstly the model forecasts a substantially greater population next century than the conventional models currently used to estimate future anthropogenic atmospheric trace gases and the impact of the consequent greenhouse effect on sea level rise. Therefore, it suggests that sea-level will be higher than currently envisaged unless the population is contained below that forecast by the growth model. Secondly since the population growth model suggests that 80% of sites occupied by Man during the ice age period were drowned by the major marine incursion which occurred between 17,000-7,000bp, it contains a warning to modern man of the potential consequences of uncontrolled ice melt from the greenhouse effect - there is sufficient landlocked ice left to cause a further sea-level rise of 60m.

Figure 1 suggests that occasionally sea levels of 400m or more above the present levels have occurred during the geological past (HOLSER, 1984). At first sight this appears to be nonsense since there is only sufficient ice at present to cause a sea-level rise of 60m if it completely melts. Hence these apparent overestimates are of relative rather than purely eustatic sea-level and are possibly very seriously influenced by isostatic subsidence of the land. However, in view of the fairly close matching of Holser's palaeo-sea-level interpretation with the output from the natural climate model described above, which in all other respects provides a sensible interpretation of climate and sea-level, it is appropriate to comment on this further.

If the Universal Gravitational Constant (G) is variable with respect to time as suggested, for example, by DIRAC (1938), LYTTLETON (1982) and DENNESS (1984d) then we have:

$$\frac{\dot{G}}{G} = \frac{-\dot{a}}{a} \qquad (3)$$

where a is the distance between the Sun and the Earth and the numerators are the first derivatives with respect to time. From the inverse square law of radiation we have:

$$T = \frac{k}{a^2} \qquad (4)$$

where T is the temperature at the surface of a cold body (the Earth) at a distance, a, from a hot body (the Sun) and k is a constant. Therefore:

$$\dot{T} = \frac{-2k\dot{a}}{a^3} \tag{5}$$

and so

$$\frac{\dot{T}}{T} = \frac{-2\dot{a}}{a} = \frac{2\dot{G}}{G} \tag{6}$$

Consequently the well-documented observation, from records of all timescales, that T varies with time could equally well be a consequence of simultaneous variation of G. If that were so we should expect other consequences of variable G, among them a change in the size of the Earth which would reduce as G increases, thereby inducing the "excessive" sea level rises during high temperature/high gravity periods as shown in Figure 1. Accepting that this must remain conjectural at present, DENNESS (1986d) suggested that the absence of real-time measurement of a temporal variation of G could not in itself be seen as evidence that G does not vary.

Finally, in view of the linear relationship between halocarbon content of the atmosphere and increased trapping of thermal radiation, according to the WORLD METEOROLOGICAL ORGANISATION (1982) and RAMANATHAN, CIRERONE, SINGH and KIEHL (1985), only a slight enhancement of the projected emission of these gases, well within the capacity of existing technology and resources, may be sufficient to inhibit the onset of a future ice age of a similar intensity to the last which reduced the sea-level by 100m only about 20,000bp. Therefore, man already has the ability to prevent sea-level falling by atmospheric engineering, even if fossil fuels become exhausted or are diverted for other use; hence we need be concerned only with sea-level rise.

7. CONCLUSIONS

Theoretical models have been demonstrated to match in hindcast the progress of both natural and anthropogenic climatic and sea-level change over relevant timescales extending over all durations from a few years to many millions. Their combination describes an overall theoretical model which matches observed temperature change (at least in the northern hemisphere) very closely over the past century.

The rate of sea-level rise per 1°C temperature has been shown to have been about 2.7mm y^{-1} at the end of the last full ice age and during much of this century, i.e. both for overwhelmingly the most significant recent geological event and since accurate instrumental records became available. Forecasts for the combined natural and man-made climate models, both of which are fully deterministic, propose that global atmospheric temperature will have risen by about 3.5°C by 2050AD. By empirical analogy with both recent and geological events this suggests a simultaneous sea-level rise of about 0.65m with associated flooding by that time, even without further increases of population and industrialisation, unless the greenhouse effect is drastically reduced voluntarily or by legislation. A similar conclusion can be drawn from an analytical consideration of the implications of expected changes in trapping of thermal radiation by trace gases.

Various implications of population growth for past and future sea level and *vice versa* are relevant. A possible global calibration is considered based on thermal trapping observations to date. Also a possible effect of varying G on sea level can be shown and it can be argued that man already has sufficient technological ability to avert a future ice age.

For the foreseeable future anthropogenic sea-level rise will overwhelm natural sea-level changes.

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