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The Greenhouse Affair

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Background

Ocean engineers, in company with their more terrestrially orientated fellows, are not particularly well-known at the moment for throwing down the frontiers of climatology. That is perhaps all the more surprising as it was an engineer, albeit one with markedly mathematical leanings, who gave respectability to the subject in the first place—Milutin Milankovitch. Milankovitch was a Yugoslav and in the early part of this century he built on the earlier work of the Scot James Croll (1875) to lay down the now commonly accepted foundations of the Ice Age mechanism. Milankovitch (1938) determined the close relation between the timing of various astronomical events relating to the Earth's orbit and disposition and that of the occurrence of Ice Ages during the last million years.

But we digress except to note that the author is also an engineer but given much more to a geotechnical bent than the technologically gifted Milankovitch who specialized in concrete structures in his early years. Geotechnics can be practised on land and beneath the sea. Wherever there is need of site investigation to determine the mechanical properties of the ground on which a structure is to be built, there goes the geotechnical engineer. When that takes him to sea to explore the seabed prior to the installation of giant offshore structures or oil pipelines, for instance, he disguises the geotechnical content of his practice beneath the title, ocean engineering.

Both on land and at sea, it is difficult to determine accurately the *in situ* mechanical properties, particularly strength and consolidation characteristics, of engineering soils and sediments that the designer needs to found his structure properly. Sampling itself causes disturbance. An additional problem at sea relates to the recovery of a sample to the sea surface: this allows the total pressure on the sample to reduce so that entrained gases expand, thereby disrupting the soil structure and causing an unknown amount of change in its mechanical properties.

One response to this problem is to do mechanical testing in the seabed and another is to try to correlate the required mechanical properties with index values which can be determined from disturbed or other samples without having themselves been altered during sampling or recovery. There are such parameters. Among them are geotechnical indices relating to plasticity and lithology, microfossil population characteristics and isotope data, all of which have been explored by the author to seek a usable correlation with the elusive mechanical properties. The particular factor of interest to this climatological story proved to be a suite of oxygen isotope data.

An empirical correlation was attempted between a profile of oxygen isotope ratios, from a borehole extending some 560 m into the seabed near the Azores in the North Atlantic and an engineering zoning thought to be typical of the local environment. No such correlation was forthcoming but the oxygen isotope data itself, reported by Shackleton & Cita (1979), proved most intriguing. The isotope ratio was seen to exhibit a cyclic quality with increasing depth into the seabed. As the sedimentation rate has been largely constant there during the last seven million years covered by the 560 m deep borehole, this visual cyclicity represents a truly cyclic variation of global temperature, for that is what an oxygen isotope describes, for several million years. The cyclic content is complex, being the combination of a series of sine components. Their relation to one another is such that each is of half the period and 0.84 times the amplitude of its more fundamental near-neighbour.

This excursion proved sufficient to interest the engineer in climatology and provide the foundation of a climate model described at some length by Denness (1984a,b). In turn the model exposed the Greenhouse Effect to the critical evaluation possible from subtracting the modelled

temperature from the observed Northern Hemisphere temperature during the last century, thereby isolating the Greenhouse component for quantification.

Perhaps the foremost of the earliest workers to promote the idea of the possible impact of CO_2 in the atmosphere was Thorpe (1867) who attempted to measure the carbonic acid content of sea air. However, it was really Callendar (1938) who first studied quantitatively the possibility of a CO_2-induced climatic change. It was again Callendar (1958) who went on to evaluate critically the earlier measurements, leaving little doubt that those made before the 1950s are generally suspect. Much of that evaluation is condensed into the review by Machta (1979) from which an estimate of about 290 ppm for pre-industrial atmospheric CO_2 can be made. Among the more recent overall reviews are those edited by Clark (1982) and the controversial Environmental Protection Agency (EPA) report by Seidel & Keyes (1983). This article seeks to identify accurately the relative quantitative influence of natural and man-made climate components to prepare the way for comprehensive modelling of future global temperature variation to assist strategic planning.

A General Climate Model

The derivation of a new climate model was mentioned above. It is contained essentially within one equation which describes among other things the variation of global temperature through various timescales. It takes the form of a sine series of regular form and thereby constitutes a deterministic method both of hindcasting for comparison with measured and proxy climate information to verify the model and of forecasting.

The concept of the model and the background to its derivation were introduced by Denness (1981) in the context of describing an educational device. Its more detailed substantiation over timescales ranging back to only a few years and also back to 3 000 000 000 years with many others between was provided by Denness (1984a,b). Briefly, for the sake of present completeness, the governing equation is:

$$G(t)=\sum_{n=N(T)}^{\infty} A(T)\, a^{n} \sin b^{1-n}\frac{\pi t}{T} \qquad (1)$$

zero registered at time T_0

where $G(t)$ is a time-based climate index, say 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 0.50 respectively,
n is an integer, i.e. the reference number of a particular sine component,
and t is time in years.

In each of the time series figures here this is described by a thin continuous line, the graphic output from Equation (1). Note that in this series time progresses from right to left.

The Climate Model and CO_2

In order to explore the ability of the general climate model to contribute to modern climate trends with proper definition of the likely role of CO_2 it is appropriate to examine the distant past. If the model correlates well with climatic data, and more especially CO_2-based data, over the geological as well as historical timescales, it becomes more logical to anticipate that it should be equally effective over the modern timescale and indeed for contributing to the modelling of the future. The correlations given here of CO_2 and global temperature as represented by the model are independent of Man before he became an atmospheric polluter during the last couple of centuries. The success of the correlations could suggest that natural CO_2 variation may be the effect of global temperature variation as much as the cause.

To accentuate the extent of the timescales over which the model holds sway without being swamped by the minutiae of secular division, three totally different scales are explored here, each separated from its neighbour by about three orders of magnitude. The literature conveniently provides one (110 000 000 years) over a significant part of the Phanerozoic, another (150 000 years) covering just the latter part of the Pleistocene and a third (120 years) bringing us to the instrumental age.

Carbonate compensation depth (CCD); 0–110 000 000 *years*

The CCD was introduced by Arrhenius (1952) to define the level at which the rate of supply of calcium carbonate is equal to the rate of dissolution so that no more sediment is deposited in the ocean. Although the depth of the CCD is mainly controlled by the temperature of the water and the pressure within it, the rate of dissolution tending to increase as the temperature decreases and pressure increases, many other factors are also significant. For instance, Bramlette (1965), Berger &

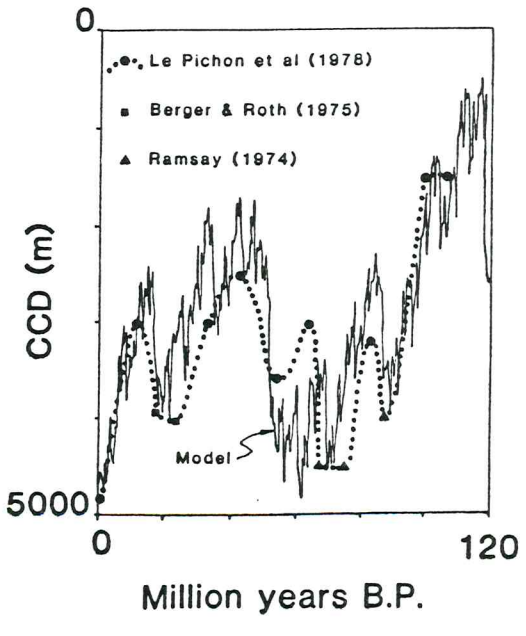

Fig. 1

Roth (1975), etc., describe the impact of primary production, whereas Berger (1970) and Berger & Winterer (1974) examine the influence of carbonate supply rate and the distance to the source continent. The effect of the succession of transgressions and regressions and climate are duly explored by Seibold (1970) and Berger & Winterer (1974). Steeman-Neilsen & Jensen (1957) explain how the fertility of the surface waters can be influential with particular attention drawn to areas of high productivity such as the equatorial zone and upwelling areas in general. All in all there are seen to be several potential links between the CCD and both the biosphere and the global temperature. Little wonder then that the correlation in Fig. 1 is so convincing.

Figure 1 shows the measurements by Le Pichon *et al.* (1978) with additional data from Berger & Roth (1975) and Ramsay (1974) representing CCD fluctuations since Aptian time in the South Atlantic ocean based on average values from the Argentine and Cape basins. These are superimposed to good effect on the output from Equation (1) representing global temperature. It is seen that the CCD variation corresponds very well to the model, as would be expected from the foregoing account of the factors considered to be influential. Therefore, the model is seen not only to describe global temperature variation on this geological time scale but also more specifically the related CCD, which in turn enjoys links with the biosphere and consequently atmospheric CO_2. The correlation appears to be clear but there is no indication whether atmospheric CO_2 variation is the forcing agent or the response to global temperature change.

Interpreted atmospheric CO_2: 0–150 000 *years*

Shackleton *et al.* (1983) provide the raw data of carbon isotope difference between the ocean surface *Neogloboquadrina dutertrei* and the sea flour *Uvigerina senticosa* from a core from the south of the Panama Basin. They reduce this data using the model of Broecker (1982) to the atmospheric CO_2 interpretation shown here in Fig. 2. This is superimposed on the output from Equation (1). In this case the correlation is seen on both the general and the detailed scale with the high global temperature about 130 000 years ago depicted by the model being matched approximately by the CO_2 trend but exceeded by the model output and approached by the CO_2 interpretation only in the last 15 000 years. Between and before these times the modelled temperature and the atmospheric CO_2 level are both lower with weaker correlation between them. Nevertheless the general correlation of model and CO_2 is to be seen showing the more intense glaciation to be a time of lower atmospheric carbon dioxide. Again there is no direct evidence to suggest whether or not the variation of atmospheric CO_2 is the forcing agent or the response to global temperature change. However, with so much of the Northern Hemisphere commonly known (e.g. West, 1968) to have been substantially less vegetated during glacial periods, it would be easy to construct an argument, similar to that by Steeman-Neilsen & Jensen (1957) for the influence of the surface water biosphere, to suggest that the biospheric/atmospheric CO_2 variation during that time was certainly a response as much as a driving force for the global temperature variation. In effect, the views of Woodwell *et al.* (1978), Bolin (1977), Moore *et al.* (1981), etc. condensed by Liss and Crane (1983) to illustrate the possible influence of change in land use on atmospheric CO_2, all point to natural atmospheric CO_2 variation being a response to biospheric changes and thus to climatic change.

Measured atmospheric CO_2: 0–120 *years*

Callendar (1958) summarized a wealth of measured data in categories of reliability. Taking only his declared reliable data which extends up to 1955 and adding the rigorous recent series of measurements from Mauna Loa up to 1980 reported by Keeling *et al.* (1982) leads to Fig. 3 on which they are seen superimposed on the output of global temperature from Equation (1). Nothing more than a very peripheral correlation can be seen at this stage with both CO_2 and modelled temperature exhibit-

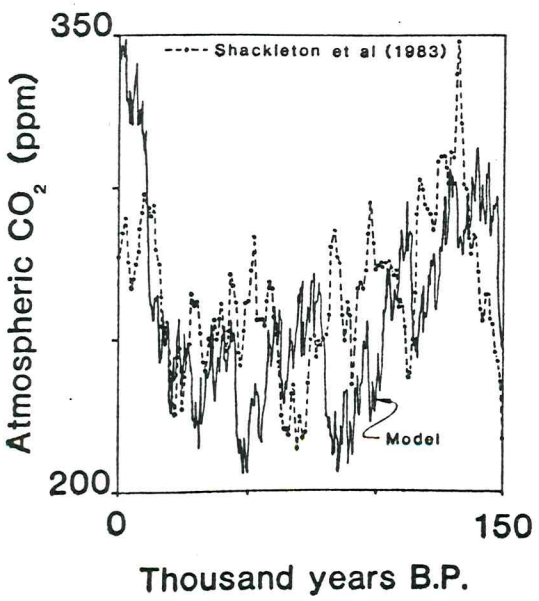

Fig. 2

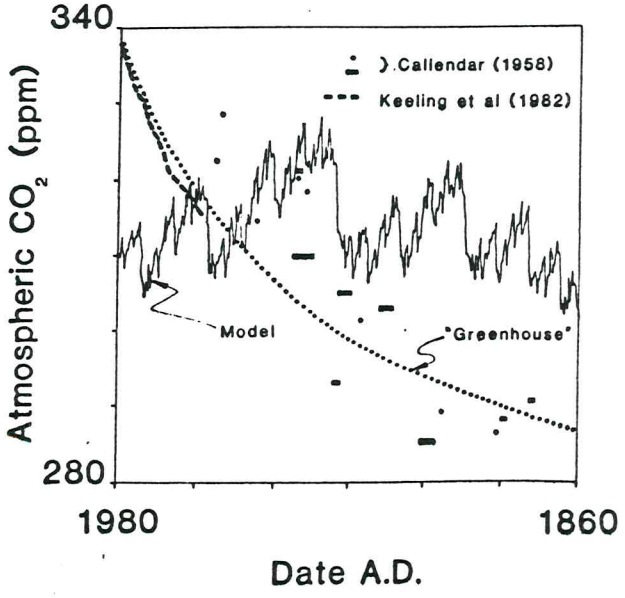

Fig. 3

ing low values in the early years, rising until the early 1930s; after that the model suggests a substantial fall in temperature before beginning to recover in the mid 1970s whereas the measured CO_2 decreases only slightly before rising again more or less steadily to 1980. By comparison with the record of measured Northern Hemisphere temperature variation reported by Jones & Wigley (1980) and repeated later in Fig. 6c, it is seen that there is little more agreement between the real temperature and CO_2 variation on this timescale than there is between the model of Equation (1) and CO_2 variation. This, of course, requires explanation as attempted later and involves the separation of manmade 'Greenhouse' CO_2, calculated later and shown as a dotted line in Fig. 3, from the total atmospheric CO_2 record.

Other Models

There are many other models of climate than that due to Denness (1981, 1984a,b). Those for the longer term focus on the astronomical cycles described by Milankovitch (1938). They exhibit cyclic components of a similar order of both periodic and amplitudinal variation to the Denness model as shown, for instance, by the spectral breakdown for gross climatic change over the past half million years prepared by Hays *et al.* (1976). When applied to the future such astronomical models forecast a return to glacial conditions within another 20 000 years or so as shown by Mitchell (1977). Those with concern for the Greenhouse Effect make allowance as did Mitchell for a global CO_2-induced heating to be superimposed on this during the next 2000 years, thereby holding back the impending ice age by an artificial short warm period.

Shorter term models tend to exhibit a far greater preoccupation with the Greenhouse Effect. For instance, Hansen *et al.* (1981) expound the Greenhouse theory and illustrate the possibility of disentangling the relative theoretical impacts of CO_2, volcanic activity and solar output on various atmosphere–ocean models. While admitting the uncertainties relating to the roles of volcanic emissions and the effect of solar luminosity, they nevertheless contrive to produce a model which matches well the measured Northern Hemisphere temperature since 1880. Their admission throws the analysis into question inasmuch as the adjustment of the relative impacts to achieve the favourable fit of theoretical and observed data could be varied to achieve that goodness-of-fit for many different models. In turn, though not attempting to compile a quantitative model, Raper *et al.* (1983) report measurements of temperature changes in the Arctic (since 1880) and Antarctic (since 1957) with inconclusive implications for the likely strength of the Greenhouse Effect.

Towards a Climate Model Embracing Natural Temperature Variation and the Greenhouse Effect

In Figs 1 and 2 it was shown that over periods of millions and of thousands of years there has been a noticeable correspondence between atmospheric CO_2, as determined by proxy measures, and the global temperature modelled by Equation (1). During those timescales whatever was responsible for that coincidence was certainly not Man. However, it is possible to conceive a mechanism to account for the variation of global temperature by going some way towards explaining Milankovitch's astronomical connection. There the comments of Lyttleton (1982) can be developed, themselves based on the concept of Dirac (1938), that the Universal Gravitational Constant, G, is in fact a variable. This would account for global temperature variation by altering the separation of the Sun and Earth. It would also simultaneously influence other parameters, some of them local climatic characteristics as shown by Wigley *et al.* (1980) to vary regionally. In turn these regional variations and their global sum should have an impact on the biosphere both regionally and globally. This would lead to changes in the atmospheric CO_2 regime.

Such a mechanism would thus naturally promote global climatic change which would as a result influence atmospheric CO_2 through the biosphere link, thereby apparently providing a natural counter to the Greenhouse argument. In the light of the output from many independent General Circulation Models (GCMs) which clearly indicate a strong influence of a manmade Greenhouse Effect along with a biospheric CO_2 component, e.g. from Manabe & Wetherald (1975, 1980) and Wetherald & Manabe (1981), this evidently requires further analysis to attempt to resolve the apparent inconsistency. This is all the more important in view of the difference between the trends of accurately measured atmospheric CO_2 and temperature over recent decades.

A model of natural climate variation, as summarized by global temperature change, has already been described here; this is independent of the manmade Greenhouse Effect but joins with it to describe the total climate. The derivation and substantiation of the natural model has been described in detail in the literature to which the reader has already been referred here. Let us now turn our attention to the Greenhouse component.

Let us consider first the direct manmade atmospheric CO_2 component as distinct from the biospheric CO_2 component influenced by landuse alteration. From a basic mean of C_1 GtC per year at the beginning of substantial global industrialization the annual increase in this atmospheric CO_2 has risen with the industrial growth rate primarily as a result of increasing energy production. If that rate of increase is taken as e% per year the production of atmospheric CO_2, not yet allowing for only proportional uptake of emissions, in any year is $(1+e/100)$ times that of the previous year. After the tth year this rate of production is consequently $C_1(1+e/100)^t$.

Integrating this over a period of t years since the beginning of substantial industrialization, here taken as 1880, without allowing for any subsequent removal from the atmosphere (though this can simply be done if required), leads to the expression below for the total industrial atmospheric CO_2 in year t:

$$C_i(t) = C_1 \int_0^t (1+e/100)^t \, dt$$

$$= \frac{C_1}{\text{Log}_e\,(1+e/100)} \{(1+e/100)^t - 1\}. \qquad (2)$$

To the industrial component of atmospheric CO_2 in the overall Greenhouse element must be added a biospheric component. Between the extremes estimated as 0.4–1.6 GtC per year by Bolin (1977) and 4–8 GtC per year by Woodwell *et al.* (1978), Moore *et al.* (1981) suggest that the present biospheric component is between 2.2 and 4.7 GtC per year (with a mean of about 3.0) having risen approximately linearly from about 0.6 GtC per year in 1880. Again, assuming complete uptake and no subsequent removal, this can be summarized by the equation below:

$$C_b(t) = \int_0^t (0.6+0.024t)\,dt$$
$$= (0.6+0.012t)\,t. \qquad (3)$$

Combining the industrial and biospheric components by adding Equations (2) and (3), we can derive the following expression for the total Greenhouse atmospheric CO_2 in the tth year after 1880, $C(t)$ in GtC per year, as:

$$C(t) = \frac{C_1}{\mathrm{Log}_e(1+e/100)}\{(1+e/100)^t-1\}$$
$$+(0.6+0.012t)t. \qquad (4)$$

Extending the data range of Keeling (1973), Rotty (1977) has established that the growth rate of atmospheric CO_2 from the combustion of fossil fuels since 1880, barring a few short-lived exceptions, has been about 4.3% per year. This accords well with the growth rates of capitalist world industrial production from Kucztnski (1980) and of world energy production from Cipolla (1978), both of which are condensed here into Fig. 4. Therefore, in Equations 2 and 4, $e=4.3\%$.

Liss & Crane (1983) advise that present fossil fuel combustion injects about 5 GtC equivalent of CO_2 into the atmosphere per year. Allowing for a steady annual increase in production of 4.3% since 1880 this leads to a value for C_1 of:

$$C_1 = 5/1.043^{103} = 0.0654 \text{ GtC/year in 1880.}$$

This allows the completion of Equation (4) as:

$$C(t) = 1.554\,(1.043^t-1)+(0.6+0.012t)t. \qquad (4a)$$

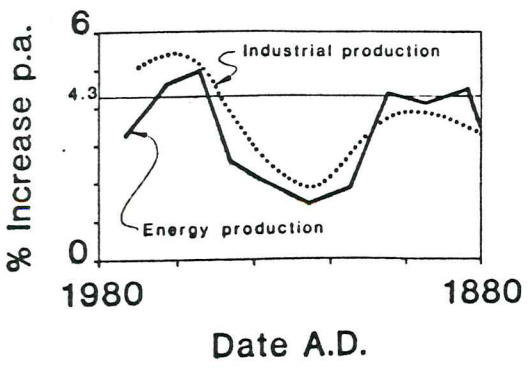

Fig. 4

Liss & Crane (1983) also describe the total amount of CO_2 in the atmosphere at present as 711 GtC in terms of gigatonnes of carbon. If we assume their data to refer to the present as at the time of their publication, i.e. 1983, and simultaneously extrapolate to 1983 the Mauna Loa CO_2 record of Keeling *et al.* (1982), which is reported to have been about 338 ppm in 1980, it would appear that this 711 GtC is equivalent to about 342 ppm.

Referring to the evidence of Machta (1979), Liss & Crane (1983) report the often accepted assumption of a value of 290 ppm to be representative of atmospheric CO_2 concentration prior to large scale industrialization. While accepting that substantially lower figures of perhaps 260–270 ppm have been proposed recently (e.g. Wigley, 1983), it would appear from the recorded data in Fig. 3 that a value of 290 ppm would indeed seem reasonable for the year 1880. From the above this is equivalent to an amount of CO_2 in the atmosphere of $\frac{290}{342}\times711=603$ GtC in 1880. For subsequent reference the total amount of CO_2 in the atmosphere in 1980 was $\frac{338}{342}\times711=703$ GtC.

Adding the largely pre-industrial component of CO_2 to the post-1880 Greenhouse component from Equation (4a) we have for 1980:

$$603+n\{1.554\,(1.043^{100}-1)+(0.6+0.012\times100)\,100\}$$
$$=603+283n=703,$$

where n is the fraction of released CO_2 taken up by the atmosphere. From this it is seen that $n=0.35$, which contrasts a little with the apparent airborne fraction of 0.56 sometimes reported as resulting from the Mauna Loa data (e.g. Liss & Crane, 1983) and is indeed just outside the range of 0.38–0.67 suggested by Oeschger & Heimann (1981), though a minor adjustment of the latter's calculations to allow for a slightly greater influence of modern biospheric interference could account for the apparent discrepancy. A check can, however, easily be carried out here by repeating the above calculation for 1959 whereupon we have, using $n=0.35$, a total CO_2 of:

$$603+0.35\{1.554\,(1.043^{79}-1)+(0.6+0.012\times79)79\}$$
$$=660 \text{ GtC.}$$

But 660 GtC is equivalent to $\frac{660}{711}\times342=317$ ppm, which compares favourably with the value of about 316 ppm for 1959 reported by Keeling *et al.* (1982). Consequently the determination of Greenhouse CO_2 used to complete the dotted line in Fig. 3 uses the values calculated from the above reasoning and is seen to represent a fair average through the observed data.

The dotted line of Fig. 3 can be translated into an equivalent temperature impact by reference to the consensus opinion of Liss & Crane (1983) based on a review of several GCMs to examine the effect of doubling and quadrupling the atmospheric CO_2 concentration. Mean values for both conditions appear to result from the study reported from Wetherald & Manabe (1981) indicating a rise of 3°C in global temperature for a doubling of the CO_2 concentration and 6°C for its quadrupling. This semi-logarithmic relation is shown in Fig. 5 in which it is

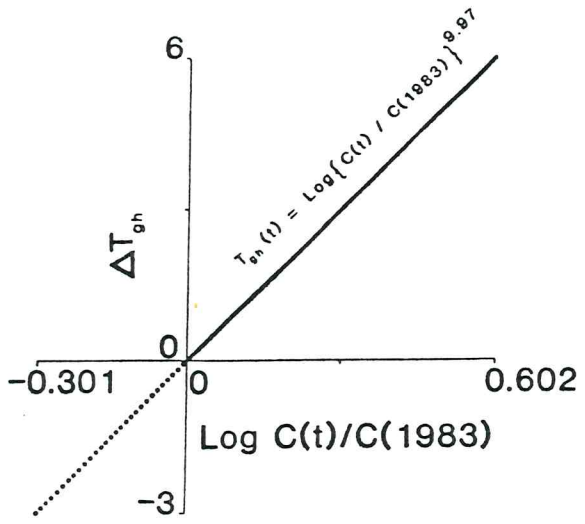

Fig. 5

extrapolated into the wholly negative quadrant relative to the interpretation of the Greenhouse impact on the global temperature of the past century. Using the derived expression:

$$\Delta T_{gh}(t) = \mathrm{Log}\{C(t)/C(1983)\}^{9.97} \qquad (5)$$

in which t is the number of years after 1880, $\Delta T_{gh}(t)$ is the incremental global temperature increase due to the Greenhouse Effect in the tth year, $C(t)$ is the atmospheric CO_2 concentration in the tth year and $C(1983)$ is that in 1983, provides the Greenhouse component to Fig. 6.

Figure 6 presents again the model of natural climate variation (a) after Denness, already cited, above the Greenhouse component (b) derived herein from Equation (5). These are then combined (c) for comparison with the recorded temperature of the Northern Hemisphere reported by Jones & Wigley (1980).

Discussion of Model Derivation

This article has attempted to quantify the relative influences of natural and manmade climate components. To do so it has presented briefly a model of natural climate variation described more fully elsewhere in the literature; it has then gone on to prepare a new model of the separate Greenhouse Effect which is superimposed onto natural climate variation. Some of the assumptions made during this presentation deserve additional comment, especially in the light of the marked differences between them and those from other sources.

It is here suggested that Fig. 6c illustrates an encouraging correlation between the measured Northern Hemisphere temperature since 1880 and that hindcast from the current analysis. It is encouraging inasmuch as, even though both temperatures are depicted on an annual basis, their comparison is judged to be at least as close as those of other leading authorities, e.g. Hansen *et al.* (1981), who use smoothed data only. With that in mind it could be suggested that the models illustrated here and the assumptions inherent in their preparation are at least as valid as those of their competitors.

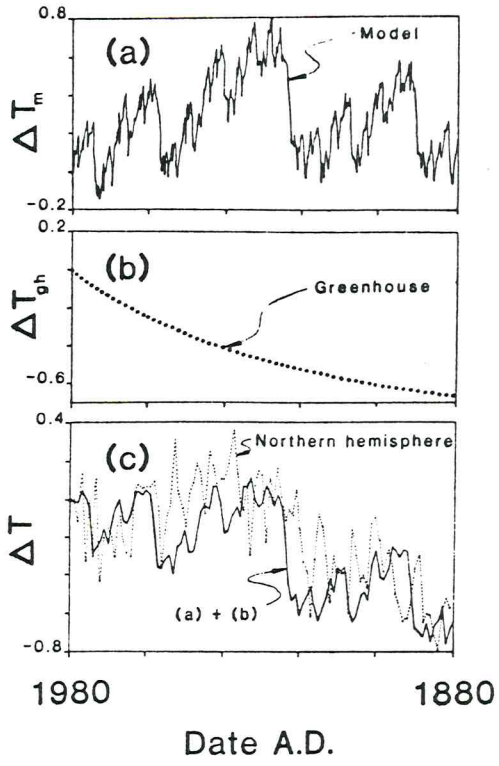

Fig. 6

As the natural climate model has received close attention in other publications referred to herein, the emphasis here is to clarify the Greenhouse assumptions. First let us consider the atmospheric CO_2 concentration prior to large scale industrialization. This is here pegged at 290 ppm in 1880, both from a qualitative visual interpretation of Fig. 3 and by reference to consensus opinion in the literature. As such it is presumably unlikely to cause concern. However, the backward extrapolation of the Greenhouse model before 1880 permits the additional comment, that if we allow for an earlier date for the beginning of major industrialization, we could accommodate a lower concentration of, for example, 287 ppm in 1850 and 285 ppm in 1830, before which there can be little suggestion of significant industrialization or substantial interference with the biosphere according to a backward extrapolation from the data of Moore *et al.* (1981). This compares well with the mean of the currently accepted 290 ppm (e.g. Liss & Crane, 1983) and the 260–270 ppm of Bjorkstrom (1979), Stuiver (1978) and Wigley (1983)

Considering the airborne fraction the analysis here uses only the 'apparent' airborne fraction of Oeschger & Heimann (1981) with no attempt to separate the respective influences of industrial and biospheric releases. Although Oeschger & Heimann comment that the apparent airborne fraction would lead to over-estimation of the fossil fuel CO_2 remaining in the atmosphere if there were net release from the biosphere (as envisaged here), the value of the apparent airborne fraction (n), determined here from the raw data reported for measured atmospheric CO_2 by Callendar (1958) and Keeling *et al.* (1982), is 0.35 which is slightly less than the minimum estimated by Oeschger & Heimann. This area of estima-

tion is naturally somewhat conjectural as estimates of both fossil fuel CO_2 production and biospheric release cannot be very accurate; for instance, Rotty (1977) estimates his fossil fuel release data to exhibit a 13% possible error margin while those relating to biospheric release vary far more widely, thereby readily allowing an extension of Oeschger & Heimann's range to incorporate the present $n = 0.35$. However, the value determined here is based solely on the consensus figures for both sources reported by Moore *et al.* (1981) and as such is seen merely as the mean value to give the best fit of the composite analysis to both the observed atmospheric CO_2 and temperature based on working backwards from reported present-day release from both manmade sources, which are here considered to be probably more reliable than historical data.

This assessment of the proportion of released CO_2 which is taken up by the atmosphere invites further comment on the amount that stays there and the duration of its residence. It has been assumed for all calculations here that all the CO_2 to reach the atmosphere stays there. However, it is recognized that in reality this is unlikely to be so. Various physical and biological sinks are continuously active in absorbing CO_2 while other natural sources are supplying it. By assuming that all manmade CO_2 emissions to be taken up by the atmosphere remain there we are, in fact, assuming that the natural atmospheric CO_2 budget is in balance and cannot be changed. The foregoing sections have shown that in the long term at least this is not so but in the absence of a reliable model for the transience time of CO_2 through the atmosphere the current model takes the view that its residence tenure is effectively permanent. An alternative could be to accept the view (e.g. Liss & Crane, 1983) that the residence time of CO_2 in the atmosphere is about seven years. In view of the excess influence of fresh CO_2 over returning CO_2 at the rates known for the past century a consideration of this transience would not affect the hindcasting very much in the long term in any case. In the short term, however, surges of input (and hence later return) would be important and could have the influence discussed below in relation to alternating global prosperity and depression.

Another point of interest is the assumed 4.3% growth rate in atmospheric CO_2 production from industrial sources, primarily fossil fuel. This value is consistent with that suggested by Rotty (1977) for the mean of the past century. It has also been shown to accord well with world industrial and energy production for the majority of that period estimated by Kueztnski (1980) and Cipolla (1979) respectively. However, in the light of the comparison of the composite natural and Greenhouse climate model with the measured Northern Hemisphere temperature, which is generally good but shows two particular periods of divergence when the measured temperature is higher than the model's hindcast, a more detailed examination is appropriate.

From Fig. 6c it is seen that the measured temperature exceeds the hindcast for most of the two periods 1900–1920 and 1935–1960 in broad terms. The rest of the time there is substantial general agreement. A gross global economic assessment by Cleary & Hobbs (1983) would suggest that it is possible that the general global downturn of the first half of this century suggested in Fig. 4 was, in fact, much shorter. They propose that the global prosperity with its associated high energy and industrial output of the turn of the century lasted until about 1920, followed by a rapid recession and depression lasting till 1930, followed by recovery and then prosperity until recently. The decline of the past decade is common knowledge.

Allowing a measure of flexibility in this general interpretation leads to a tentative correlation of the periods of twentieth century prosperity with those during which the measured temperature was higher than that hindcast by the composite model. It is proposed here that the reason for this is that the higher output of atmospheric CO_2 associated with periods of prosperity, in which industrial and energy production are higher if assessed in detail, leads to a greater warming than forecast from a single average growth rate for the whole period. It would be easy to re-enter the analysis with variable CO_2 production figures based on consensus opinions from other energy, industrial and land use assessments but the confusion generated by the multiplicity of interpretations available in the literature mitigates against this at this stage.

The Future

The foregoing analysis can be used not only to hindcast for the comparison with the observed temperature shown in Fig. 6c for the past century but also to forecast. However, it is the main purpose of the present article merely to introduce and substantiate the model without the distraction of forecasting. Nevertheless, in view of the marked differences between its forecast—even during the next decade—and the consensus of those already appearing in the literature, a brief comment seems in order.

Many forecasts are available in the literature. Depending on the assumed continuing growth rate of fossil fuel consumption (essentially economic growth rate), scenarios range from an almost inconsequential Greenhouse temperature increase for zero growth during the next few centuries to a doubling of present CO_2 concentration and consequent increase of 3°C by about 2040 for a high uptake and 4% continuing growth (e.g. Liss & Crane, 1983). The latter, which is the worst case normally considered, suggests a maximum atmospheric CO_2 of about 390 ppm by the year 2000 with implied temperature increase of 0.57°C; this worst case exceeds the 0.25°C mean prediction by Hansen *et al.* (1981) which itself goes beyond the so-called 'noise level' represented by two standard deviations away from the mean temperature of the previous 20 years by about 1994.

Wigley (1982) also considers that the Greenhouse influence will become distinguishable from the noise sometime between 1990 and early next century. Madden & Ramanathan (1980), Ramanathan (1980), and Lacis *et al.* (1981) conclude that the Greenhouse impact should be detectable from the noise even earlier—if not already. This article suggests that about 0.67°C rise is already attributable to the Greenhouse Effect during the century

ending 1980 and that a further 0.36°C will be attributable to it by the year 2000.

Of greater significance is the component of variation forecast by the natural climate model. This represents the noise of other models but is here an integral part of the overall analysis. Suffice it to say at present that the combination of the natural and Greenhouse components, to provide an extension of the model in Fig. 6c into the future, grossly exceeds other forecasts by the turn of the century and that its impact should become irrefutable early in the next decade.

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