DETERMINING NATURAL AND MANMADE CLIMATE CHANGE: HISTORICAL REVIEW AND IMPLICATIONS FOR THE 1990'S AND BEYOND

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Abstract: Global climate is forever changing over every timescale. During the past century the earth has warmed up by more than 0.5 degrees centigrade. This is largely in keeping with predictions for the greenhouse effect. Unfortunately, there have been periods of cooling during that time which must be explained by some other mechanism, i.e. short-term natural temperature changes. These natural changes confuse the interpretation of the steady greenhouse increase and have resulted in the reluctance of politicians and planners to take decisions for remedial action to accommodate expected increases in sea level and changes in the geography of drought.

Here recent models to represent natural climate change are reviewed with particular emphasis on a deterministic model which describes the variation of global temperature. The output of that model is then combined with a steadily increasing greenhouse temperature to give a composite natural and manmade global temperature which very closely matches measured changes over the past century.

The variation of local, regional and global precipitation described by the deterministic model is illustrated over various historical periods with examples from North and South America, Africa and the world as a whole. Implications for regional and global economy are discussed and comment is made on the gross global depression that the model forecasts for the 1990's - whether or not the greenhouse effect has a substantial influence. Sea level changes are similarly reviewed and related to the model both recently and historically. Attention is drawn to accelerations of atmospheric CO_2 concentration in about 1870 and 1950 according to the historical record and these are related directly to simultaneous acceleration in world Population growth.

The combination of the natural and manmade deterministic models forecasts a global temperature rise of almost 1 degree centigrade by the year 2000. Political and socio-economic implications of misinterpreting this rise as solely due to the greenhouse effect are addressed. Finally a range of practical means of containing use of fossil fuels within levels that need not exacerbate the greenhouse effect is discussed with due regard to economic considerations and secondary spin-off problems and their solution.

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1. Introduction

Climate has changed on all timescales in different ways around the world since the earliest geological records. Over the past couple of centuries since the birth of the industrial revolution an anthropogenic component has been added to these natural changes. Observation and measurement of climate change, particularly temperature and precipitation, over the past century has made us increasingly aware of the scale and rate of change over even relatively short periods but has not previously enabled the accurate differentiation of natural and manmade climate change. This problem is addressed here with a view to enabling planners and politicians to respond to a more precisely defined problem than has hitherto been the case. The background to this study encompasses climate change itself and the development of modelling techniques to simulate climate change.

1.1. GENERAL CLIMATE CHANGE

Global climate is forever changing on every timescale. This is reflected in regional and local variations of any of a vast range of climate-related parameters. Over the past century alone the Earth has warmed up by more than 0.5 degrees centigrade: this can be compared with an increase of about 6 degrees centigrade at the end of the last glaciation from about 17,000 to 12,000 years before present (BP) when ice sheets retreated from Eurasia and North America to raise eustatic sea level by about 100 metres. The geological past has seen even greater natural changes but it is the more recent historical past that is better documented and generally thought to be more relevant to interpreting trends and forecasting future climate.

1.2. DIFFERENTIATING NATURAL AND MANMADE CLIMATE CHANGES

Natural climate changes are generally thought to be largely controlled by astronomical phenomena concerned with the Earth's aspect to and orbit around the Sun. The thesis developed here does not challenge that relationship but could accommodate a more fundamental link than simply cause-and-effect. It also seeks to extend the range of frequencies of climate change from those appropriate to the recognition of a link between ice ages and astronomical phenomena to those impacting on recent history and present and future planning.

Manmade climate changes are generally considered to stem from discharges of so-called greenhouse gases into the atmosphere largely as a result of increasing industrialisation and deforestation. To date perhaps the main culprit has been carbon dioxide (CO_2) released from the burning of fossil fuels and no longer able to be as substantially taken up by the decreasing forests. Lesser gaseous elements further aggravate the greenhouse effect, thus termed because the whole family of greenhouse gases enter the upper atmosphere where they behave like the glass in a greenhouse by allowing all the Sun's energy in while reflecting back to Earth much of the infra-red part of the spectrum that would otherwise pass out again through the atmosphere.

The temperature rise thought to result from the greenhouse effect has been calculated from the ledger of CO_2 input to the atmosphere theoretically to lead to a steadily increasing global temperature of about 0.6 degrees centigrade over the past century (Hansen et al., 1981; Denness, 1984 a). The measured response of recorded global temperature over the same period has been more confusing: the first half of the period saw the expected rise but since the 1930's the global temperature has fluctuated about a stable mean. This might at first sight appear to challenge the reality of the greenhouse effect. However, a model of natural global temperature change is extant that, coupled with conventional interpretations of the greenhouse effect, leads to a closer approximation to the observed signal than is otherwise available. The model is totally deterministic and has been extensively reported by Denness (1981, 1982, 1983 a, b & c, 1984 a, b, c & d, 1985 a & b, 1986 a & b, 1987 and 1989 a & b) both with respect to its derivation and the physical and socio-economic implications of its forecasts.

2. Climate Forecasting Models

Forecasters seem to be divided philosophically into two camps: those who believe that natural phenomena change according to a recognisable though possibly complex pattern and are, therefore, deterministic, and those who believe such changes to be stochastic. The former group seeks forecasting models, the ultimate goal of which is to predict events at a given time in the future with certainty - any probability statement being only a measure of ignorance regarding the baseline facts on which the model is calibrated. The latter's models are statistically inclined and necessarily attach a probability to each forecast - even if baseline facts are absolutely known - on the basis of the recurrence frequency of a given event in the past.

The writer is a determinist. a position he arrived at from the need to forecast future climatic events on the strength of only short-term (perhaps 10 or 20 years) baseline input data at sea and in many parts of the developing world. Such data commonly reflect only the climatic "standstill" since the 1940's so that a probabilistic method of forecasting could never predict an unusual event such as the exit from the Little Ice Age in the middle of the previous century - yet such events happen.

2.1. GENERAL CIRCULATION MODELS (GCMS)

GCMs perform as their title suggests:they describe the general circulation pattern of the global atmosphere subject to the input of a wide range of known, inferred or conjectural data concerning the constitution and other physical and chemical properties of the atmosphere and the oceans, and the ocean/air and land/air interface. By so doing they permit interpretations of regional variations of temperature and precipitation in response to various input data suites. It is generally conceded that, matched against current atmospheric conditions, GCMs are better at forecasting temperature than precipitation.

The success of the models can be only as good as the input data and the validity of the relationships used to describe the multitude of interactions and feedbacks (servo-mechanisms) in the total system. Should any of these, say a density-related parameter having an influence on atmospheric pressure, change in a way not reflected by the input data the consequent forecasts will go awry. Overall it would appear that GCMs have much to offer, particularly, with respect to forecasting in areas for which there is little or no observed or measured information, subject to reservations about the validity of input data to simulate future conditions.

2.2. DETERMINISTIC MODELS

Deterministic climate modelling began with the recognition by Croll (1875) that there appears to have been a relationship between the recurrence of widespread glaciation and the variation of certain special planetary characteristics. Milankovitch (1938) consolidated and extended Croll's ideas with the recognition of a more precise connection between planetary deportment and climate over recent geological time. This so-called astronomical theory has firmly entrenched itself in the climatological literature as a cause-and-effect doctrine.

More recently Hansen et al. (1981) have embellished the astronomical principle for the shorter term appertaining to the present century and near-future forecasting by considering the possible influence of the Sun, volcanic activity and so on. Constructive reviews of such modelling were given by Imbrie & Imbrie (1979) for the long term and Liss and Crane (1983) for the short term with particular attention to the greenhouse effect.

The most recent entry to the deterministic forecasting field appears to be the writer's own model which he has, perhaps pretentiously, called a geophysical model to allow for its further application outside the immediate area of climate forecasting. In concert with a forecast temperature rise resulting from the known input of atmospheric pollutants to the greenhouse effect the latter has been tested with interesting results in forecast since 1980.

2.2.1. *Comparison of Selected Models.* Various historical and modern deterministic models are compared here to illustrate the direction of development and the recent urgency to incorporate the greenhouse element properly differentiated from natural changes.

2.2.1.1. Astronomical Models. Croll may have had little idea that his observation of relationships between astronomical periodicities within the solar system and the recurrence of ice ages, only themselves recognised a few years earlier by Carpentier and Agazziz (Imbrie & Imbrie, 1979), would provide the basis for deterministic climate modelling of the future. With Croll's experience behind him and the mind of a mathematician and engineer Milutin Milankovitch was in a better position to realise that his association of glacial recurrences with planetary changes is more or less consistent and therefore forecastable. Milankovitch's observations must rank as one of the cornerstones of modern climatology, albeit that they refer to low frequency climate variation of little direct interest to contemporary engineering or planning.

Hansen appears to have spanned the astronomical gap between the long timescale of ice age recurrence and the short timescale of modern planning. In addition to astronomical phenomena such as sunspots (the variation of which appears to have an association with earthly climate change but for which no concrete explanation has yet been convincingly demonstrated). Hansen's model also embraces a consideration of nearer geophysical phenomena such as changes in the intensity of volcanicity. Nevertheless, published forecasts using Hansen's empirically deterministic model do not appear to allow for dramatic changes in the near future. Several other deterministic models proliferating in the literature seem to be equally enthusiastic in their representation of past events but also to point on average to a uniform future.

2.2.1.2. Geophysical Model. Among the more recent newcomers to the deterministic scene is the writer's own forecasting model. The origin of this model was described by Denness (1981) who pointed to the separation of the multi-frequency components of variation in a 7 million year oxygen isotope time series from Shackleton and Cita (1979) as the starting point for its derivation from published climate time series. The initial components of the subsequently much more extensive compound sine series from that work are shown in Figure 1 with periods of about 4.8, 2.4 and 1.2 million years - ever doubling frequency and amplitude simultaneously reducing by 0.81. Through a series of other publications Denness (op. cit.) extended that sine series by matching geological timescales and beyond and to the short-term interpretation of less than a year.

The governing equation of the geophysical model, which describes global temperature variation on all timescales as well as other geophysical parameters, is

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

which is zero-registered at time T_0 and in which:
G(t) is a time-based climate 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 0.81 and 0.5 respectively, n is an integer, i.e., the reference number of a particular sine component and t is time in years.

The geophysical model can be used in forecasting mode with t negative from the end of 1980 when the model was completed. Of course, it represents only the variation of natural global temperature with no anthropogenic influence.

2.2.1.3. Greenhouse Effect Models. As noted earlier the greenhouse effect describes that (rising) component of overall global temperature change that is due to the pollution of the atmosphere by manmade gases that allow all elements of the Sun's energy in to the Earth but do not allow all of the infra-red part of the spectrum to be reflected out again. The main pollutant is CO_2 and it has been calculated by Moore et al. (1981) as a mean among other estimates that about three gigatonnes of carbon in the form of CO_2 enters the atmosphere each year. In turn this has been shown by, for example, Hansen et al.(1981) and Denness

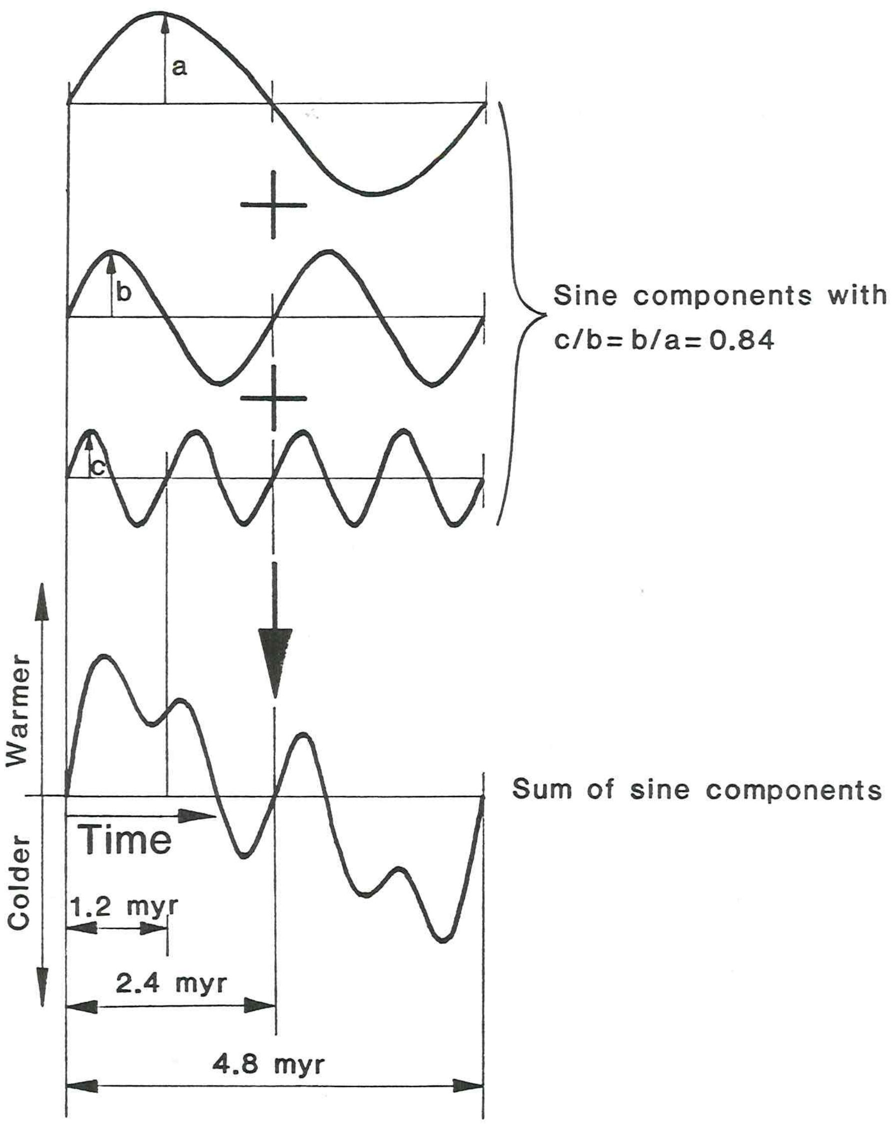

Figure 1. Combination of sinusoidal components.

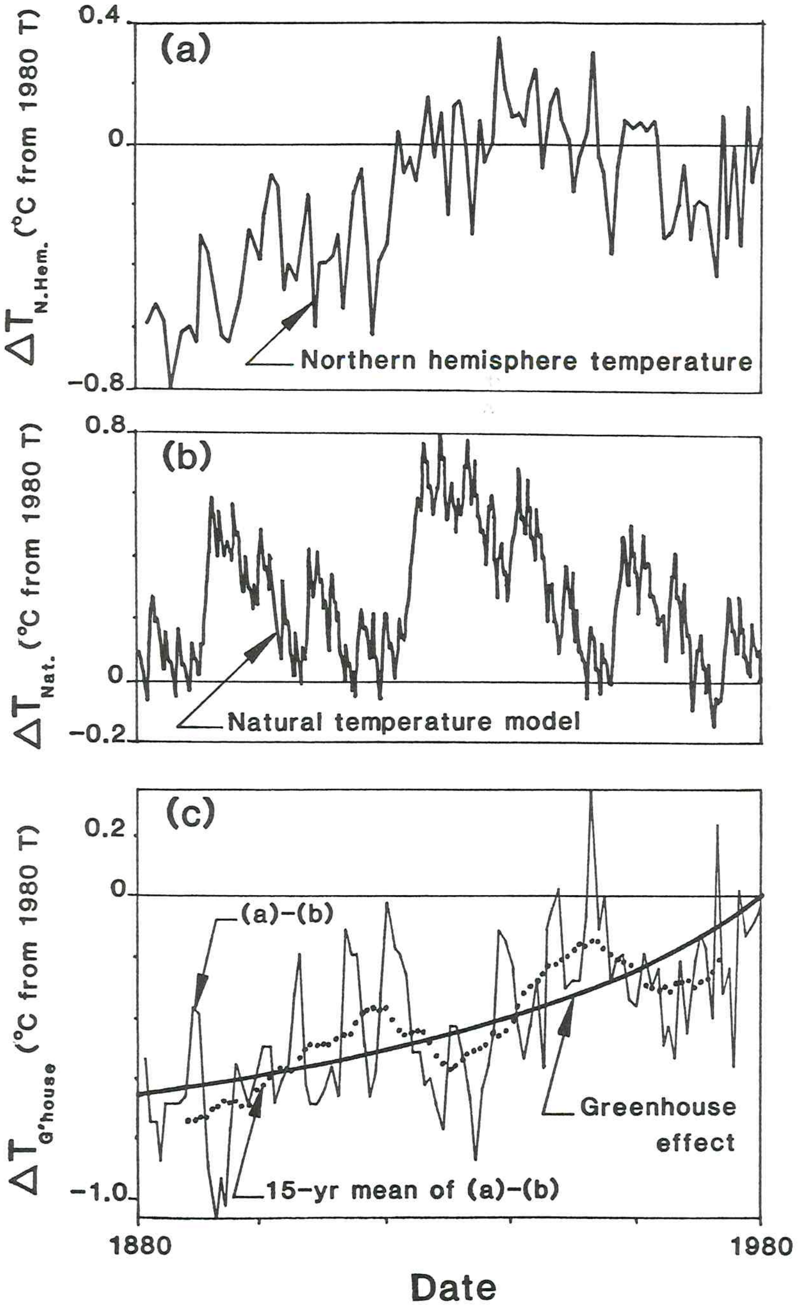

Figure 2. Separation of natural and manmade temperature change.

(1984 a) theoretically to have resulted in a rise of about 0.6 degrees centigrade over the last 100 years; doubling atmospheric CO_2 is commonly estimated to raise the global temperature by about 3 degrees centigrade, e.g. Wetherald and Manabe (1981).

2.2.1.4. Natural and Manmade Global Temperature Models. Measurement of global temperature since 1881 has been accomplished by several workers (e.g., Jones and Wigley, 1980) with the result that a fairly steadily increasing trend until about the end of the 1930's is seen to be followed by fluctuations about a steady mean up to recent years. This is superficially at odds with the steady rise throughout required by the greenhouse effect. The differences between the postulated greenhouse component and the observed temperature is thought to be due to natural temperature change, as indicated for example by Hansen, which often tends to be treated as "noise" on the main signal.

Better recognition of the form of variation of the natural component would allow more confidence to be placed in the greenhouse calculations. The geophysical model described above permits this. Figure 2, based upon data presented by Denness (1984 a), illustrates how the subtraction of the temperature represented by that model from the observed global temperature leads to a residual temperature that has generally increased over the past century much in keeping with the trend commonly postulated for the greenhouse effect as shown. It is suggested that this is an encouraging demonstration for proponents of the greenhouse hypothesis.

2.2.2. *Testing the Geophysical Model.* The ability of the geophysical model to match climate-related time series has been tested against several hundred published data suites over geological, historical and instrumental timescales in hindcast. The present theme is concerned with water variation: therefore, additional examples of hindcast matching to precipitation time series that have recently come to the writer's attention are presented here by way of further demonstration of the model's potential.

2.2.2.1. Colombia, South America. Figure 3 portrays the variation of annual rainfall at the cities of Bogotá and Popayán situated in very different geographical regions of Colombia. Both show virtually the same cyclic fluctuations with a period of little under 17 years, one of the components of the geophysical model, precisely in step with the model in such a way as to indicate a reduction of rainfall in response to natural global warming (hindcast by the model) as previously calibrated by Klein (1982).

2.2.2.2. Northern Africa. In view of the current theme figure 4, rearranged from Denness (1985 a), is presented to illustrate the matching in hindcast of the geophysical model with a series of historical time series from Lamb (1977) relating to drought and flood in a region still notorious for such events today. The model is presented here in its basic form, i.e. not subject to moving average smoothing; this illustrates the greater complexity of interpreting its unadulterated output but still permits attention to be drawn to general peaks and troughs. It should be noted that periods of relatively high global temperature correspond essentially to drought in the west and flood in the east of the region, whereas the precipitation response

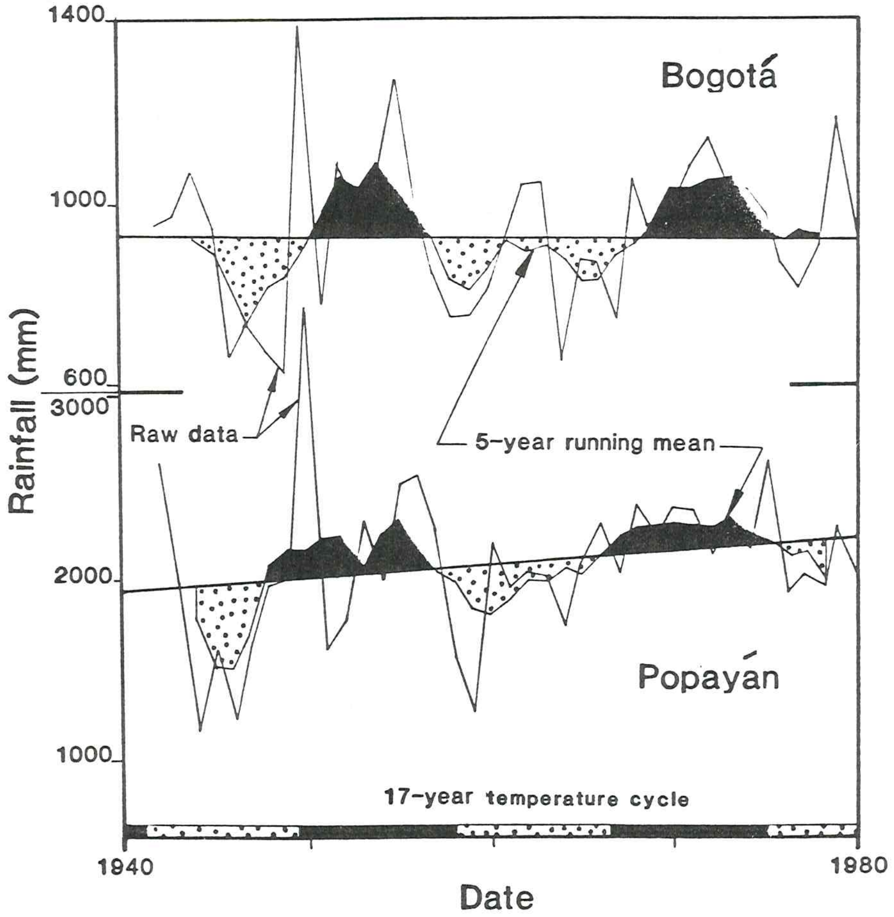

Figure 3. Colombian rainfall cycles.

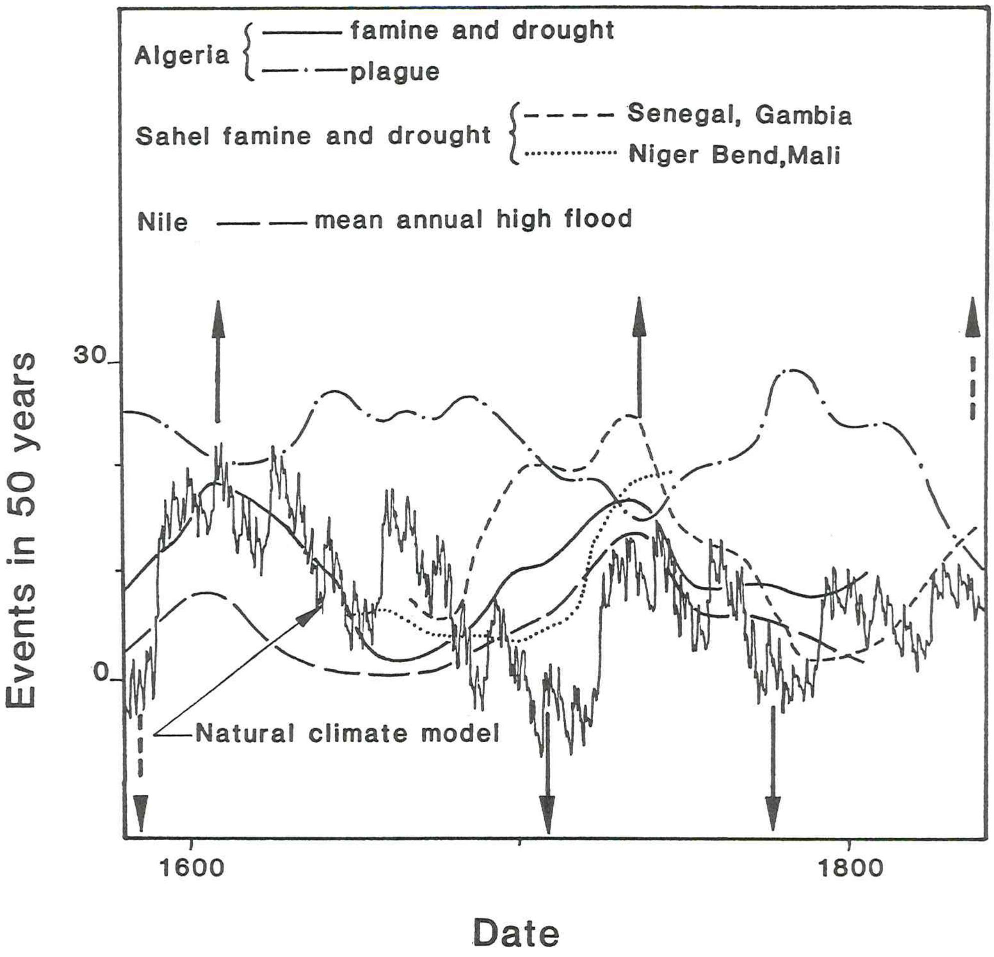

Figure 4. Historical drought in northern Africa.

is reversed for relatively low global temperature.

3. Climate and Man

Man is by nature deeply concerned by economic trends. Here the impact of drought and sea level rise on those trends and other distant historical events is demonstrated with regard to both natural and manmade climate changes.

3.1. RELATION OF DROUGHT AND ECONOMY TO GEOPHYSICAL MODEL

Here we are concerned with the natural component of climate change - that part that happens with or without a greenhouse effect. In order to explore the regional variation of precipitation (especially drought) in response to northern hemisphere temperature change it is appropriate to consider Figure 5, taken from Wigley et al. (1980). Here it is seen that as global temperature increases so some parts of the world become wetter and others drier. This influences agricultural productivity; generally the drier land becomes the less productive it is. This results either directly in an economic slump or using agricultural irrigation and/or artificial fertilisers as described in greater depth by Denness (1983 c and 1984 d).

Among the earliest examples reported by the writer of a significant economic response to drought introduced by global temperature change is the expansion and withdrawal of agriculture in Roman Tripolitania (approximately modern Tunisia) during the period 300 BC - AD 300 (Burns and Denness, 1985). The progress of economic trends in England and France for a similar period after AD 1300 was followed by a review of the economic progress of the whole world since the early 1800's by Denness (1984 d). Many other examples are available.

Figure 6 portrays the smoothed output of the geophysical model in hindcast representing global temperature change since 1920. It also shows the simultaneous smoothed trend of the U.S. economy (inverted for easier correlation) from Batri (1987). As would be expected from figure 5 and the agricultural link, the U.S. economy has marched inversely in step with the global temperature hindcast by the model: the hotter the global temperature, the drier the mid-west agricultural (corn) belt and the worse the economic situation - as forecast by the model for the 1990's.

3.2. RELATION OF SEA LEVEL RISE TO GEOPHYSICAL MODEL

Sea level has changed over all timescales both globally (eustatic) and locally (isostatic/tectonic). The essential thesis is that higher global temperature, for whatever reason, induces a rising eustatic sea level as a result of density decrease (thermal expansion) and ice melting: the impact of isostasy is not part of this argument.

In the more recent past, the calculation of eustatic sea level change by Barnett (1984) as a steady rise, in keeping with expected greenhouse growth, over the last century has been challenged by Pirazzoli (pers. comm.) and Klige (pers. comm.) both of whom recognise

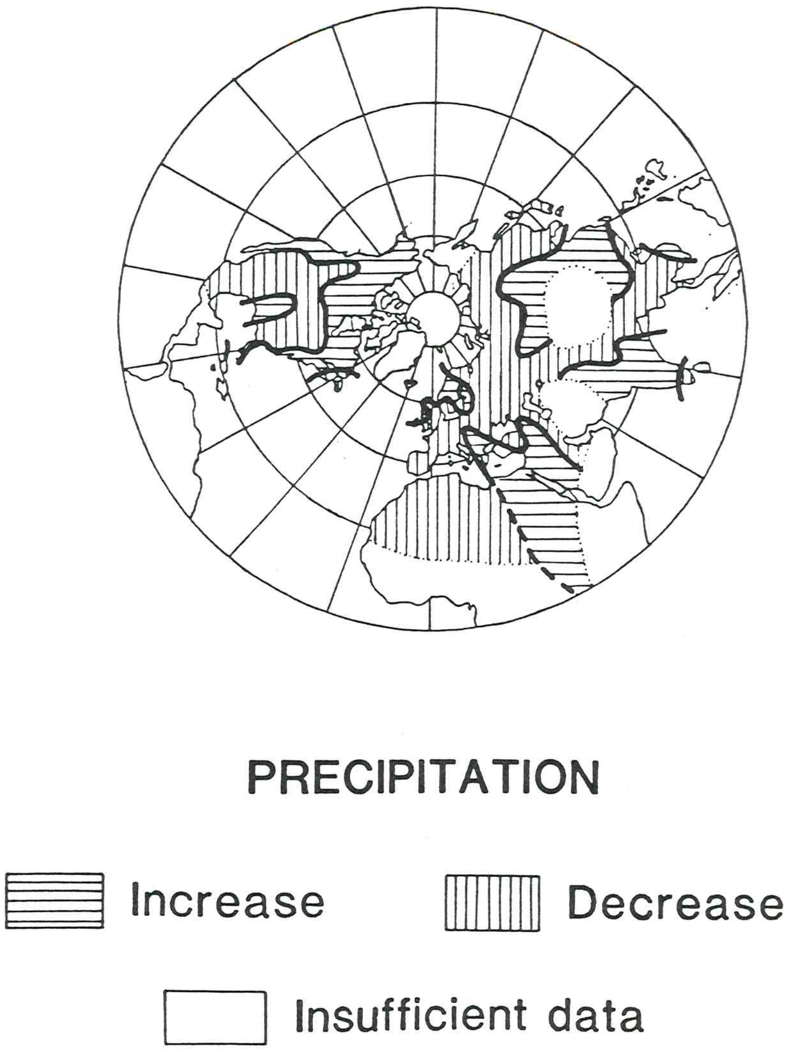

Figure 5. Precipitation change with global warming

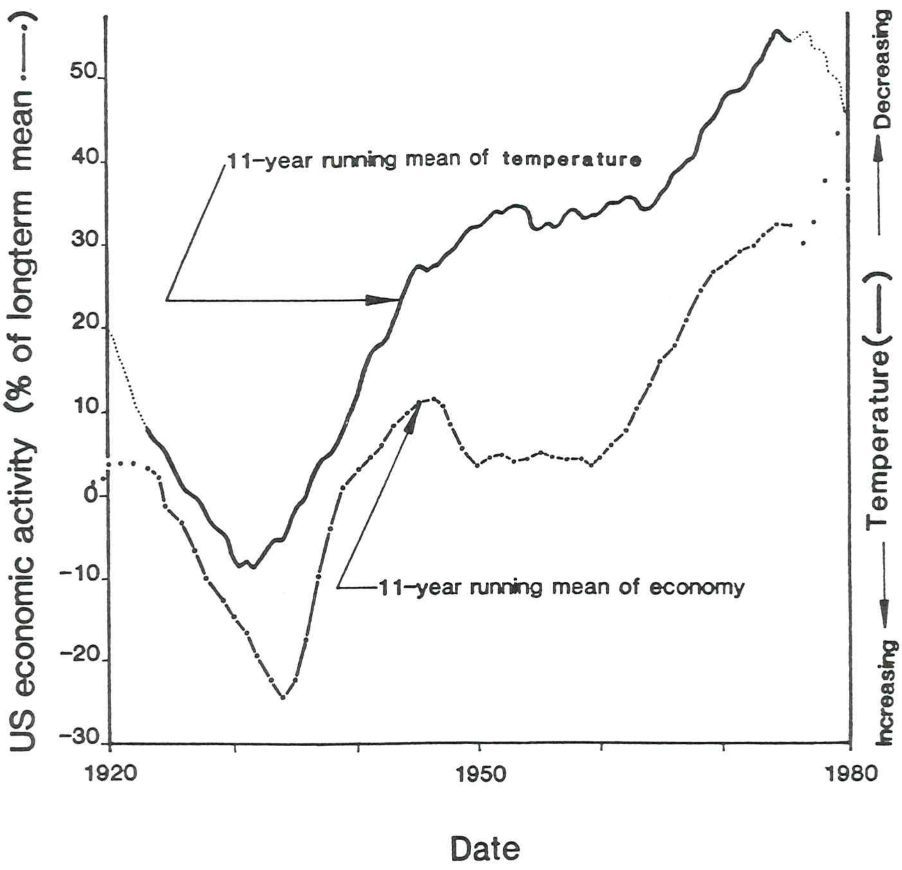

Figure 6. Economic response to global temperature change

a fairly steady rise to about 1930 followed by fluctuations about a stable mean thereafter. Pirazzoli's and Klige's reviews match parallel observations of temperature change (e.g., Jones and Wigley, 1980) to show that sea level change is, as expected, in step with temperature change. The separation of the greenhouse effect from natural climate change by Denness (1984 a) explains these observations and illustrates the reality of both the greenhouse effect and natural climate change with respect to sea level rise.

3.3. GREENHOUSE REVISITED

The previous cases involved sea level rise in response to a natural climatic signal. What is the scale of the recent manmade overlay? To gain a sense of anthropogenic proportion one might first refer to the natural changes in the atmospheric greenhouse gas CO_2 recorded in various marine and glacial successions over much of geological time. Denness (1984 a) provided a brief compendium showing that there has been a close association of global atmospheric CO_2 with the geophysical model over all timescales from a few thousand years or less to hundreds of millions of years.

Figure 7 describes the rapid increase of atmospheric CO_2 (much faster than any rise in the geological past) that followed the inception of the Industrial Revolution, which started in the early eighteenth century in Europe and encapsulated the whole world by the 1870's. The longer term trend from the mid 1800's, after Machta (1979) is seen to exhibit two accelerations in growth rate about 1870 and 1950; the shorter term covered by the more precise data of Callander (1958) and Keeling et al. (1982) can show only the 1950 breakpoint. Both of these trends establish the increase in atmospheric CO_2 to be real (even if only about half of that calculated to result from fossil fuel burning, etc.) and increasing as global population increases according to the models derived empirically by Meyer and Vallee (1975) and analytically in the Appendix here.

4. Reacting to Deterministic Forecasts

In order to react sensibly it is necessary to know with confidence what one is reacting to. Both physical and social change factors are considered here before addressing possible preventative and mitigating actions.

4.1. CLIMATE FORECASTS AND IMPLICATIONS FROM THE GEOPHYSICAL MODEL

It is stressed that the following represents the minimum changes that can be expected with no account taken of the aggravating impact of possible additional population growth and that of the greenhouse effect beyond that of natural climate change has not been considered with regard to the geography of drought or social implications.

4.1.1. *Physical Changes.* The main physical changes expected to result from global climate change, whatever the cause, concern sea level rise and drought. Other factors such as floods,

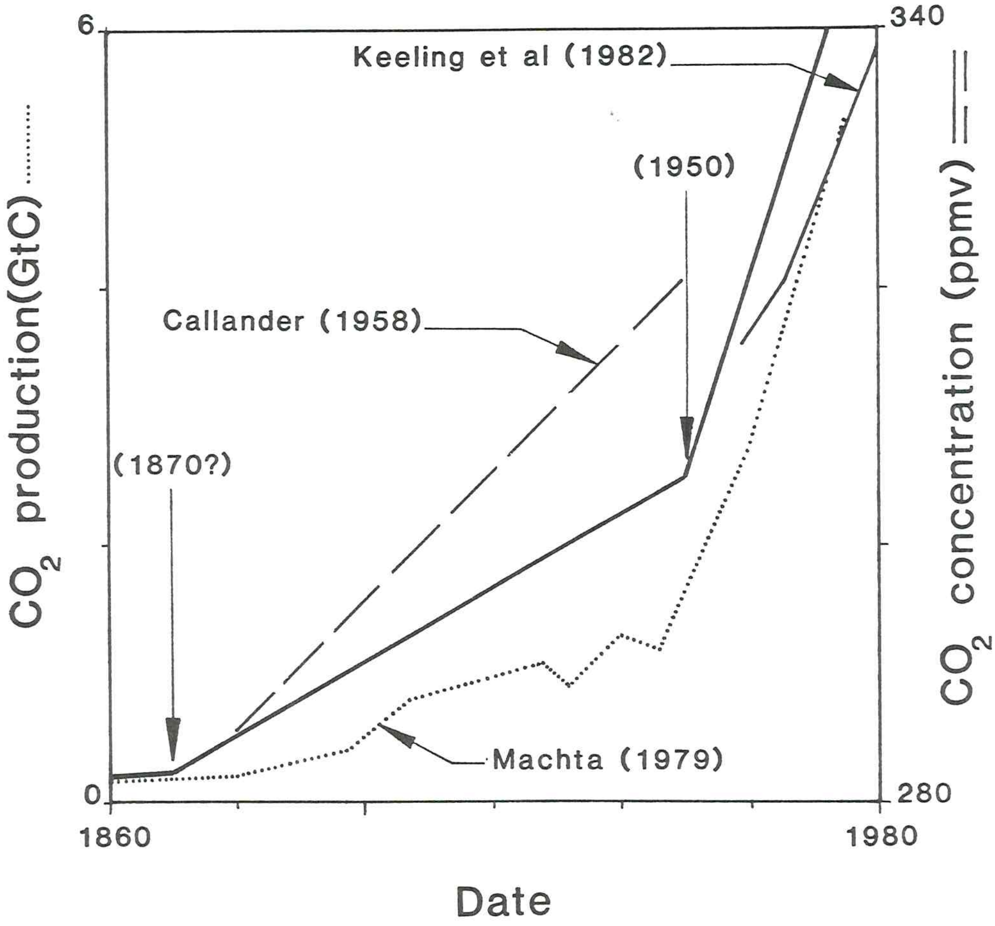

Figure 7. Acceleration of global CO$_2$.

hurricanes and other weather phenomena are thought to be less significant in the long term.

Albeit that sea level has fallen as well as risen in the past, we are here concerned with a future in which only a sea rise seems likely from both greenhouse effect and natural climate components of global temperature change forecast by the geophysical model, first published in the present context by Denness (1984 a), are set to increase from the late 1980's into the twenty first century. As the twentieth century has so far seen a close match of sea level change with global temperature (both from observation and from the model) it is entirely logical to expect a resumption and acceleration of eustatic sea level rise in the very near future.

Historical aspects of the geography of drought in relation to global temperature change and its description by the natural component of the geophysical model have been discussed in Section 3.1. Figure 5 was invoked to describe precipitation changes that can be expected from the rising global temperature that is expected from both the greenhouse effect and natural change over the coming decades. Among the areas forecast to become drier are the mid-west of the U.S.A., Kazakhstan in the U.S.S.R., and parts of north-west Europe, between them producers of most of the world's grain. If the decreasing precipitation approaches drought proportions the outcome is clear; already drought has afflicted the U.S. as expected.

4.1.2. *Socio-economic and Political Implications.* The socio-economic and political consequences of rising sea level and drought are likely to be widespread and serious. Although they cannot all be itemised in detail some are already clear. An example is the need to divert resources into coastal protection or to abandon coastal areas in response to sea level rise: the choice will depend largely on the scale of the existing investment, the political influence of the afflicted nation and the degree of confidence in forecasts of future rises. The scale of diversion of resources from elsewhere in the global economy will be immense, probably exceeding the proportion currently spent on defence.

Another example, relating to drought, is the future of Western Europe and the so-called Superpowers, the U.S.A. and U.S.S.R. in relation to the developing world. As these parts of the developed world, accustomed as they are to policing the less developed, find themselves economically constrained and with contingent social problems it is interesting to muse upon their likely reaction to the emergence of major powers from the burgeoning developing world, much of which will be enjoying far mor clement climatic conditions.

4.2. PREVENTION/MITIGATION OF CLIMATE-DRIVEN PROBLEMS

There is a variety of ways in which the greenhouse effect (already underway) can be mitigated: its extension could be prevented by simple politico-economic decisions in the developed world followed by similar moves in the developing world.

The generation of energy from fossil fuel or wood is the most serious contributor to the greenhouse effect. Yet it is only the bad building and transport habits of the developed world in temperate climates, accustomed to cheap and harmless energy, that is responsible for much of this problem. Insulation is poor, energy is not conserved and waste ensues causing the unnecessary generation of more energy and releasing more CO_2. Switching to renewable energy resources from wind, waves, the sun and so on volunteers a long term communal solution. So does the introduction of endothermic space and water heating: this basically involves reversing the household refrigerator principle by taking heat from the outside to warm the inside of a dwelling - at about a quarter of the cost of a conventional heating system and little more installation cost, i.e. it does not require communal decisions but is available to the individual. Universally used this proven system could alone achieve all the greenhouse targets of the developed world for the next 20 years without curtailing industry at all.

It is certain that countermeasures to solve greenhouse problems will themselves, generate largely unanticipated spin-off problems. One thinks, for example, of the obvious need for energy insulation in buildings in temperate climates (a need incidentally that was sparked off by the energy crises of the early 1970's politico-economic event but has lived on into the "greenhouse concern age") which caused major condensation problems. These problems may in themselves be trivial but will deter democratic people from responding wholeheartedly and urgently to governmental anti-greenhouse schemes as necessary unless they too can be solved readily, as has the condensation problem by a simple cheap device that does not create a third generation problem, for example.

5. Conclusions

A deterministic geophysical model has been developed to describe the variation of natural global temperature over all timescales. The model can incorporate a greenhouse component over the last century or so and by so doing replicates measured global temperature for that period better than any other model known to the writer.

The geophysical model matches past sea level changes via its global temperature representation and forecasts significant rise in the near future. It also explains the variation of economic progress on national and global bases over historical and recent timescales via an agricultural link and forecasts imminent global depression.

Preventative and mitigating measures to combat the greenhouse effect are within the capacity of existing technology. Whether genuine encouragement of their introduction is within the capacity of existing political machinery remains to be seen.

6. Acknowledgments

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APPENDIX: POPULATION GROWTH ACCELERATION AND ITS RELEVANCE TO THE GREENHOUSE EFFECT

A.1 Synopsys

The youthful growth stages of individual animals and plants exhibit expansion according to the cube of time. Extending earlier work which has shown marked consistency between growth rates for individual plants and animals and whole communities, it can be shown that the human population has grown in a series of accelerating expansion phases separated by steps of cultural evolution with their attendant technological revolutions, each phase exhibiting a cubic-time growth pattern.

The relation between technological progress and population growth is analysed here for the population as a whole and the archaeological and historical record is examined to substantiate the association of the beginning of cubic-time growth phases with technological revolutions . It is shown that the historical growth record for which reliable population estimates are available, i.e., since the fifteenth century, corresponds closely with the theoretical pattern which, if uninterrupted, would culminate in an infinite population by 2030 AD. However, it is concluded that such an expansion could equally well be transformed into the steady and rapid cultural evolution of a stable population able to depend on several technological revolutions in the individual lifetime and contain the greenhouse effect by so doing.

A.2 Introduction

Homo sapiens derives his very name from his most distinguishing characteristic, wisdom. Wisdom is born of intelligence, the intellectual skill which enables the growth of a knowledge base from step-by-step learning, reasoning and remembering. One of the ways in which man has employed intelligence is reflected in the historical record of the growth rate of the overall population. Every time he has conceived a sufficiently bright idea to lead to a technological revolution he has invested the material rewards flowing from it upon procreation; population growth has accelerated every time.

This is the generalised embodiment of the notion behind Malthusianism, an essentially laissez-faire philosophy which sees the technology-population link as inevitable. However, the analytical framework for the entire growth pattern is more confusing.

First it is necessary to consider the growth of a population which is not beneficiary of intelligence, one which does not therefore engage in cultural evolution or generate technological revolutions. By invoking the Gaia concept, which sees the whole of the biosphere as one living entity so that a whole population is to the biosphere as an individual is to the population or a cell within the individual is to the host, we can investigate the possibility that each size unit, such as an individual or a population, shares the same growth pattern; Gaia was described at length by Lovelock (1979).

Individual animals, including humans, exhibit a growth pattern according to the cube of time during their youthful stage as illustrated by Tanner (1978). Therefore, we might expect that the total population of an animal species would also grow according to the cube of time during this expansion phase if the Gaia concept should apply here and if the intelligence element were excluded. The converse is not necessarily true, i.e., the demonstration of cubic-time population expansion does not prove the existence of Gaia as noted by Denness (1986 a).

After exploring the possibility of simple cubic-time population growth, without leaning too heavily on the Gaia hypothesis, the impact of intelligence can be added. This then leads to a theoretical model which mirrors almost exactly the actual growth record of mankind especially since accurate estimates could be made.

A.3 Simple Cubic-Time Population Growth

Let us consider a population in which the average mass of the individual is constant; this implies the reasonable assumption that over the long term the population contains the same proportion of individuals at all stages of development. In an expanding population the number of individuals grows. Therefore, for a given environment of fixed energetics constraints the volume of the cumulative (and interactive for mobile species) exclusion zones of all individuals grows in order to postpone competition as long as possible; the exclusion zone is that space surrounding the individual required to provide it with sufficient sustenance. This is the most energy-efficient system as the avoidance of conflict reduces its potential energy to a minimum. After competition ensues, following the exhaustion of available free space, subsequent population expansion requires either a change in energetics or is subject to the constraints of the -3/2 law of distribution and growth as previously applied to plants by Shinozaki and Kira (1956), Todaki and Shidei (1959), Yoda et al. (1963), White (1981) and Whittington (1984) and to animals by Hayton (1984) and Denness (1986 b).

Davidson (1985) showed that for three nations of humans, USA, Brasil and Australia, each until recently being able to expand into sparsely occupied territory within its own boundaries to avoid internal competition, the full available historic records exhibit a general population expansion according to the cube of time. Denness (1986 c) provided theoretical reasoning for this observation for the simple case in which the impact of cultural evolution is unnecessary to avoid competition or is otherwise absent. Such cubic-time growth runs counter to the common, but demonstrably erroneous, assumption of exponential expansion. However, the popular "exponential" assumption appears to owe less to mathematical exactitude than to literary licence, which allows its use to imply merely "at a great rate".

The population of mankind as a whole has not experienced the freedom from competition enjoyed by these relatively recently colonised nations whose initial growth rates ran ahead of the rest in unfettered expansion. The overall population has not expanded continuously according to the cube of time. For the growth of the whole population the impact of cultural evolution has been more evident.

A.4 The Influence of Cultural Evolution on Growth Rate

By applying intelligence the changing of energetics constraints becomes possible, i.e., the species that can learn from its experiences or from inspiration can improve its efficiency at that most critical of its basic functions, reproduction. It seems reasonable to assume that the chance of a community producing a worthwhile idea within a given time is proportional to the number of individuals within it who are available for thinking; in other words, the time taken to produce an idea is inversely proportional to the population. Therefore, as an intelligent population expands the time taken for it to produce knowledge reduces so that it is more frequently able to enhance its reproductive efficiency if that is the way it chooses to apply that growing knowledge reservoir.

It might be assumed that an intelligent species such as man would recognise what it is doing and thereby interrupt this sequence to divert its knowledge reservoir into activities other than procreation. However, Malthus, the notable eighteenth century economic philosopher, well reported by Flew (1957), believed it inevitable that the rewards of each technological revolution, an expression of a step in cultural evolution, would be absorbed by a consequent increase of population thus preventing any rise in the general standard of living (or, in ecological terms, an improvement in energetics efficiency). Let us now examine the facts.

Population statistics tend generally to be somewhat scattered through partisan national literature and to depend heavily on subjective interpretation prior to the recent historical record. However, McEvedy and Jones (1978) provided a convenient and broadly founded compendium from which the world population figures used here are taken: these are summarised graphically in Figure A1. McEvedy and Jones derived figures for early man based on analogy with the distribution of equivalent modern primates followed by estimates from archaeological and historical reconstructions and finally modern census abstracts.

For cubic-time growth we can anticipate an early linear relationship between population and time at a slope of 3 on a double logarithmic graph until man had his first constructive idea. Thereafter, for each step in knowledge acquisition leading to a technological revolution, the graph should reveal a step to a more efficient population growth rate, i.e., faster expansion denoted by a transfer of the relation of gradient 3 to the left. Each time this happens is equivalent to starting the population growth afresh at a faster pace and from a pre-existing base equal to that at the end of the previous phase.

On the purely graphical presentation in Figure A2 the essential feature is that all the data points from Figure A1 have been included and the steps in the plot are the result of ensuring that they all fall on lines at a slope of 3. The steps therefore differentiate successive growth stages from man's earliest intellectual progress to the most recent advances, moving from bottom right to top left in Figure A2. No attempt has been made to control the position of the steps so that they are the natural outcome of assuming the growth stages are constrained to cubic-time expansion. It thus seems appropriate to examine whether any anthropological or historical significance can be attributed to the points at which the growth rate changed gear; according to the above reasoning these should represent major technological advances.

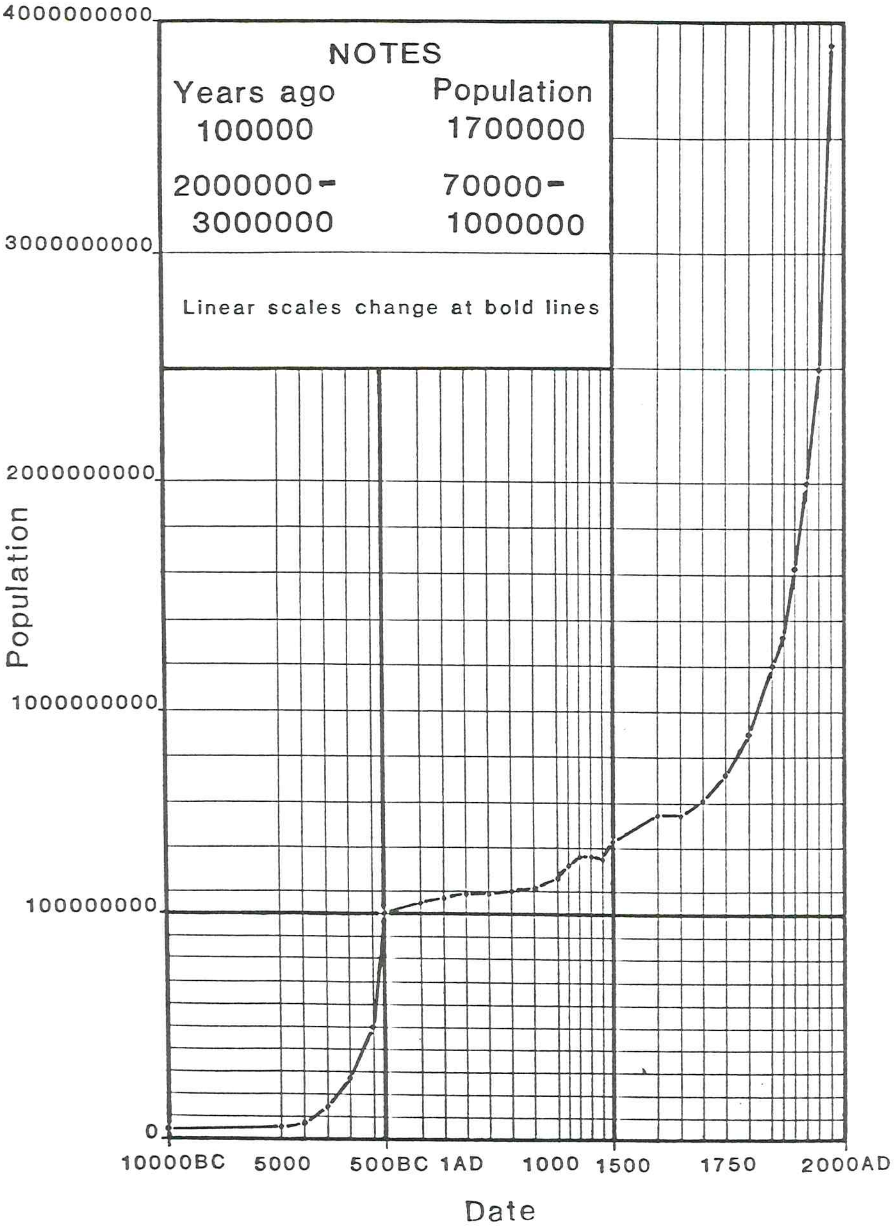

Figure A.1. World population growth

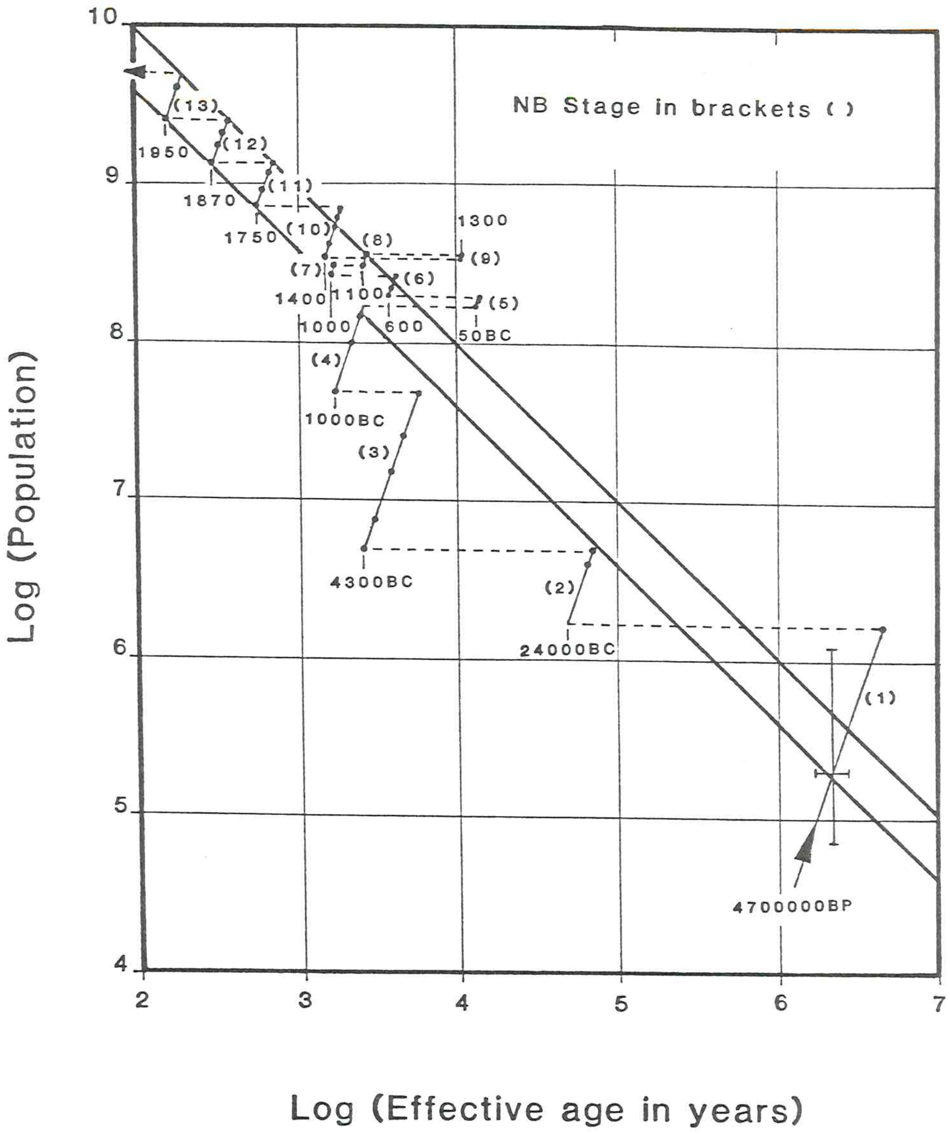

Figure A.2. World population growth steps (log-log)

A.5 The Archaeological and Historical Record

The earliest stage of development (Stage 1) started with the appearance of the first hominid, **Australopithecus** who is commonly known to have appeared in Africa about 5 million years ago with a cranial capacity of about 600 cc - little more than that of a gorilla. By analogy with modern chimpanzee and gorilla populations his successor, **Pithecanthropus**, numbered between 70,000 and well over 1,000,000 between two and three million years ago by which time his cranial capacity had expanded to 900 cc. From Figure A2 that nevertheless appears to have been insufficient to result in the long overdue breakthrough that eventually came, according to the data from McEvedy and Jones, about 24,000 BC, somewhat after the final increase in cranial capacity to the 1450 cc average of **Homo sapiens** who appeared about 100,000 years ago and is considered to have numbered about 1.7 million. In passing it is interesting to note that the origin of the earliest stage of expansion - the non-intellectual stage - appears, by applying the cubic-time expansion model to the mean of McEvedy and Jones estimates, to have been about 4.7 million years ago; this is remarkably close to the commonly accepted date of 5 million years.

Stage 2, the second recognisable from the estimates condensed by McEvedy and Jones, took the sluggish population of 24,000 BC and expanded it to three times its previous size within about 20,000 years. Whatever the invention that allowed that progress its impact on man, beleaguered as he was by the depths of the last ice age, was immense and resulted in his population growth rate, seen in the light of ecological energetics, taking its greatest single step.

To continue the cubic expansion requires changing to Stage 3 in about 4300 BC, which is consistent with the general onset of the Neolithic agricultural revolution. That appears to have been the second most substantial advance in man's evolution and also that leading to the greatest proportional increase of population (tenfold) of his intellectual period. Within that steady cubic-time expansion the Bronze Age came and went without apparently registering its impact. Not so the Iron Age, however; about 1000 BC man embarked on Stage 4 equipped with durable tools. However, a millennium of progress in this new ecological niche was evidently too much for him. There followed a series of alternating recessions and recoveries, including one actually retrograde period, before the expansion entered the uninterrupted series of stages leading to the renowned "population explosion" of the second half of the present century.

About 50 BC, according to Figure A2, there began a 650 year recession during which growth proceeded more slowly than during the Neolithic period several thousand years before. Here termed Stage 5, this corresponds to the so-called Dark Ages normally attributed in some measure to the fall of the Roman and Han Empires as political unifiers leaving the field open to relative anarchy as society lost its structure throughout about half the world's population. However, let us now explore a possible ecological explanation as an alternative to this social rationâle. Figure A2 describes a general stepwise trend from bottom right to top left at an overall gradient of -1, a theoretical explanation for which is given later. Although Stage 1 had overshot this boundary while awaiting the development of sufficient cranial capacity to generate a technology the succeeding Stages 2, 3 and 4 had gone ahead of the general trend. Therefore during these three stages the population had acquired a potential beyond the capacity of this development model. Seen in that light the Dark Ages are but a dissipation of that overdeveloped potential; as is common to most physical systems the subsequent relaxation resulted in rebound beyond the general trend before homing in on it again.

Stage 6 brought a measure of recovery starting about 600 AD, effectively resuming the Iron Age progress. Then about 1000 AD comes the next real step, perhaps rooted in the development of effective shipping in Europe and agricultural advances in China. This Stage 7, was relatively short-lived, however, as the subsequent Stage 8 followed on within a century illustrating the fragility of the Stage 7 accomplishments. Stage 8 reverted yet again to similar progress to that in the Iron Age.

Then the bad news. The Black Death swept through Europe shortly after China succumbed to waves of Mongols. Each lost about one third of its population to a force beyond its influence. In each case the source was the same - Mongolia. The Bubonic Plague was certainly beyond human control and whatever possessed the Mongolian Khans was equally remarkable as the Chinese outnumbered the Mongols by about 150:1. The resultant Stage 9 of the fourteenth century marks the only recorded decline in global population and the last time at which there was a significant departure from the bounds of the general stepwise trend.

About 1400 the world began the steady stepwise progress of the modern population era. Stage 10 was heralded by the invention of guns and marked improvement in ships to enable discovery and colonisation of pastures new. With the speeding up of technological advances contingent on population number the next phase, Stage 11, was not long in following. In that case it was the second agricultural revolution, seen from Figure A2 to have become effective about 1750. Hot on its heels came Stage 12, coincident with the industrial revolution, here seen to influence population growth (and of course the greenhouse effect) globally from about 1870.

Finally (to date) we have the current population explosion of Stage 13 which has been underway since 1950. Not surprisingly that date is representative of the twentieth century communications revolution.

At this state it is appropriate to emphasise that each of the steps in Figure A2 is simply the result of applying the ecological cubic-time expansion model to the world population data given by McEvedy and Jones. That those steps are then seen to be coincident with commonly agreed technological revolutions is to be expected from the innovation rate hypothesis introduced earlier and developed further as follows. Were that hypothesis not available, the coincidences would be totally inexplicable.

A.6 An Analytical Growth Model

Figure A3 describes a small generalised part of the stepwise trend developed in Figure A2. At the beginning of the n^{th} growth stage the population is P_{bn} and its effective age is t_{bn}; at the end of the stage the values are P_{en} and t_{en} respectively. Similarly for the $(n+1)^{th}$ stage, etc. Let the intercepts on the Log P axis at zero on the log t axis be respectively

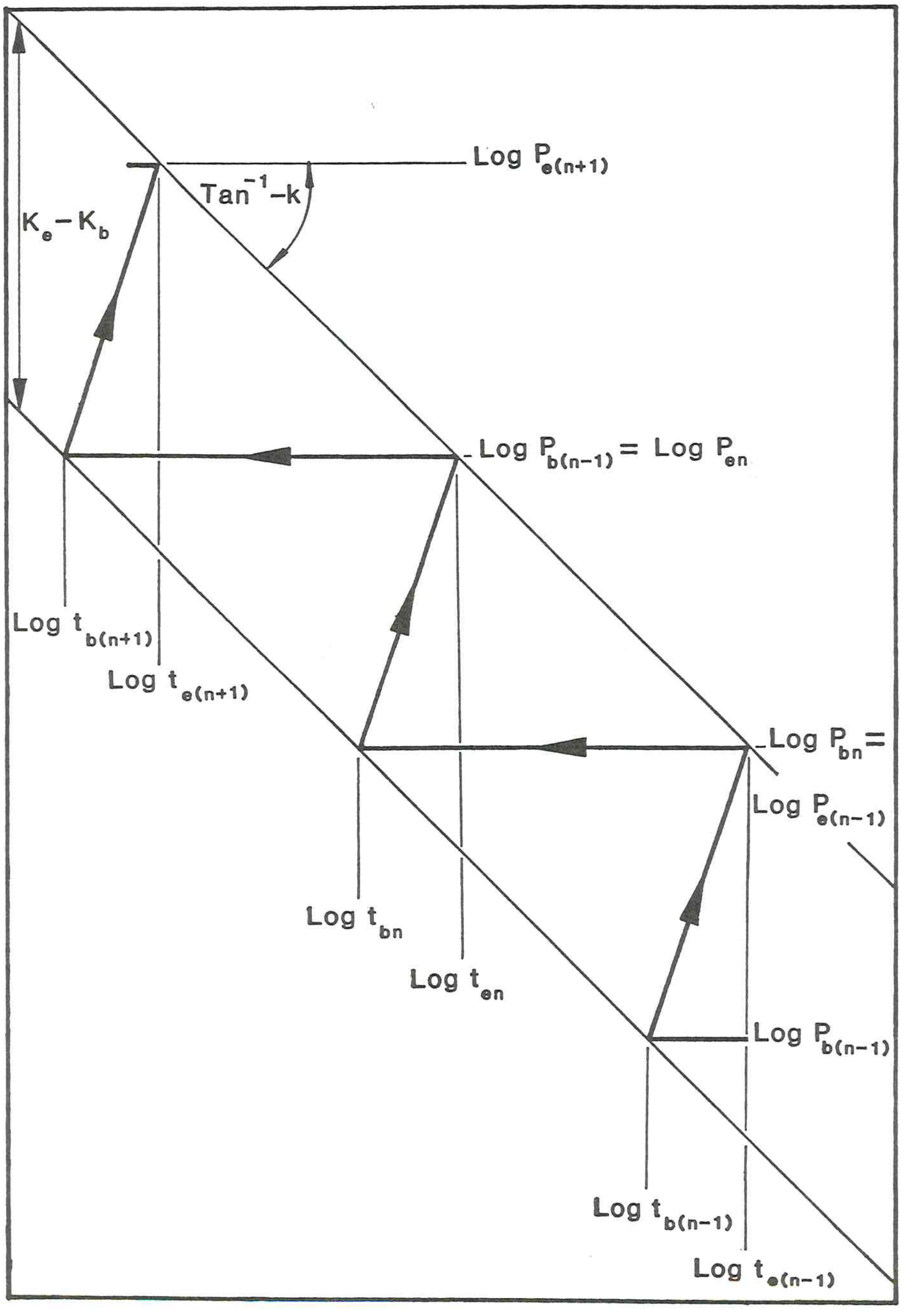

Figure A.3. Schematic representation of three typical growth steps.

K_b and K_e for the parallel lines bounding the beginning and end of the growth stages. Finally let the slope of those boundary lines be $\tan^{-1} -k$.

$$\therefore \log P_e = K_e - k \log t_e$$
$$i.e.\ t_e = \left(\frac{10^{K_e}}{P_e}\right)^{1/k} \tag{1}$$

Now let the innovation stage

$$t_e - t_b = t_i \tag{2}$$

According to the cubic-time expansion model:

$$3(\log t_e - \log t_b) = \log P_e - \log P_b \tag{3}$$

But from Figure 3,

$$\log P_e - \log P_b = (K_e - K_b) - k(\log t_e - \log t_b) \tag{4}$$

Putting (4) in (3):

$$3(\log t_e - \log t_b) = (K_e - K_b) - k(\log t_e - \log t_b)$$
$$i.e.\ (3 + k)(\log t_e - \log t_b) = K_e - K_b$$
$$\therefore \log \left(\frac{t_b}{t_e}\right) = \frac{K_b - K_e}{3 + k} \tag{5}$$
$$\therefore t_b = t_e \,.\, 10^{\frac{K_b - K_e}{3 + k}}$$

Introducing (5) into (2):

$$t_i = t_e\left(1 - 10^{\frac{K_b - K_e}{3 + k}}\right) \tag{6}$$

Substituting t_e from (1) in (6):

$$t_i = \left(\frac{10^{K_e}}{P_e}\right)^{1/k} . \left(1 - 10^{\frac{K_b - K_e}{3 + k}}\right) = \left(\frac{1}{P_e}\right)^{1/k} . \left(10^{\frac{K_e}{k}} . \left[1 - 10^{\frac{K_b - K_e}{3 + k}}\right]\right) \tag{7}$$

$$i.e.\ t_1 = A\left(\frac{1}{P_e}\right)^{1/k} \tag{8}$$

$$where\ A = 10^{\frac{K_e}{k}}\left(1 - 10^{\frac{K_b - K_e}{3 + k}}\right) = constant$$

Returning to the concept of intelligence leading to technological revolution, we have already seen the reasonable argument that the chance of a population producing a worthwhile idea in a given time is proportional to the number of thinking individuals within it. If we assume that the proportion of thinking to non-thinking individuals remains constant this is equivalent to the time taken to produce a worthwhile idea being inversely proportional to the population.

The time taken to produce a technologically significant idea in terms of population growth stages is t_i (FigureA3), i.e. the duration of one steady state, cubic-time expansion step. The population at the time the idea is produced is P_e, i.e. that when the revolutionary step is made at the end of the stage. Therefore,

$$t_1 = \frac{B}{P_e}$$ (9), where B is constant.

Dividing (9) by (8):

$$1 = \frac{B}{A} . P_e^{-(1 - \frac{1}{k})} ;\ i.e. P_e^{(1 - \frac{1}{k})} = \frac{B}{A} = constant \tag{10}$$

As P_e is a variable, (10) has a singular solution:

$$k = 1 \tag{11}$$

That is to say the slope of the boundary lines on Figure A3 is at a gradient of -1. Boundaries at this theoretical slope have been superimposed on Figure A2 and are seen to be almost exactly consistent with the observed stepwise-cubic progress of world population growth in the modern era (since about 1400 AD) and generally in keeping with it since **Homo sapiens** arrived on the scene.

With k = 1 from (11), then from Figure A3:

$$\begin{gathered} \log t_{bn} - \log t_{b(n+1)} = \frac{3}{4}(K_e - K_b) \\ \therefore t_{b(n+1)} = \frac{t_{bn}}{10^{\frac{3}{4}(K_e - K_b)}} \end{gathered} \tag{12}$$

But from (5) and (11):

$$t_e = t_b \, . \, 10^{\frac{K_e - K_b}{4}} \tag{13}$$

And (13) in (2):

$$t_i = t_b\left(10^{\frac{K_e - K_b}{4}} - 1\right) \tag{14}$$

$$\therefore t_{i(n+1)} = t_{b(n+1)}\left(10^{\frac{K_e - K_b}{4}} - 1\right) \tag{15}$$

Putting (12) in (15):

$$t_{i(n+1)} = \frac{t_{bn}}{10^{\frac{3}{4}(K_e - K_b)}} \, . \left(10^{\frac{K_e - K_b}{4}} - 1\right) \tag{16}$$

But from (14):

$$\begin{gathered} t_{in} = t_{bn}\left(10^{\frac{K_e - K_b}{4}} - 1\right) \\ \therefore t_{bn} = \frac{t_{in}}{\left(10^{\frac{K_e - K_b}{4}} - 1\right)} \end{gathered} \tag{17}$$

Putting (17) in (16):

$$t_{i(n+1)} = \frac{t_{in}}{\left(10^{\frac{K_e - K_b}{4}} - 1\right)} \cdot \frac{\left(10^{\frac{K_e - K_b}{4}} - 1\right)}{10^{\frac{3}{4}(K_e - K_b)}} \tag{18}$$

$$= \frac{t_{in}}{10^{\frac{3}{4}(K_e - K_b)}} = \lambda t_{in}, \textit{ where } \lambda < 1$$

So:

$$\sum_{r=n}^{\infty} t_{ir} = t_{in}(1 + \lambda + \lambda^2 + \dots) = \frac{t_{in}}{1-\lambda} \tag{19}$$

where:

$$\lambda = \frac{1}{10^{\frac{3}{4}(K_e - K_b)}} \tag{20}$$

Of special interest here is the case in which $\lambda = 0.5$. Then from (19):

$$\sum_{r=n}^{\infty} t_{ir} = 2t_{in} \tag{21}$$

For this to be so:

$$10^{\frac{3}{4}(K_e - K_b)} = 2 \textit{ from } (20)$$

$$\textit{i.e. } \frac{3}{4}(K_e - K_b) = \log 2 = 0.30103$$

$$\textit{i.e. } K_e - K_b = 0.40137 \tag{22}$$

Let us now return to Figure A2 on which the step boundaries have been superimposed at a spacing considered to be a best fit "by eye" to the extremes of the most recent, and hence best documented and most reliable, steps. The vertical separation of these beginning and ending boundaries, i.e. $K_e - K_b$, is 0.40 within the accuracy of interpretation possible from this graphical representation. Therefore, it would appear that the world human population has, for at least the whole of modern times (since 1400 AD) and possibly before, been expanding in a series of accelerating steps, consistent with equation (21), which can be summed with interesting consequences.

From Figure A2 the last whole step, Stage 12, took 80 years for completion. Therefore, from its beginning in 1870 the sum of the duration of all subsequent steps, according to equation (21), is only 160 years leading to a theoretically infinite population in the year 2030 AD. Among the milestones on the way would be a relatively modest 5 billion in 1990 as observed at the end of current stage, 8 billion by the turn of the century, 20 billion (at present considered to be the maximum supportable with modern technology) by 2020 and instability thereafter.

A.7 Discussion

This is a sobering thought, the immediate reaction to which is the nervous assertion that mankind is not so crazy as to misdirect the rewards of its intellectual achievements solely into extending its procreation-oriented technology which can never quite sustain its numbers (according to Malthusianism). But that might well also have been the reaction several growth stages (and decades or centuries) ago.

This philosophy is not new - only its detailed analysis now receives a high profile. Meyer (1958) first focused upon this mode of global population growth. Meyer and Vallee (1975) drew particular attention to the mode of expansion as $P = 200 \times 10^9(2026 - t)^{-1}$, where P is the global population and t is the date AD (the date BC being a negative AD date). Von Foester et al (1960) almost repeated Meyer's empirical analysis but with less causal sensitivity and Taagepera (1976) developed the same theme further but began to loose touch even more with the real growth mechanism, explained by Denness (1986 d and 1987). It is particularly interesting to note that the expansion mechanism, first empirically observed by Meyer (1958) and theoretically justified by Denness (1986 d) and in more detail here, has described almost exactly the global population growth for about the last 30 years - conventional means of growth estimation have failed to do so (c.f. innumerable United Nation, World Bank and national sources) - and if uninterrupted will lead to an untenable population shortly after 2020 AD according to the expression $P = 2 \times 10^{11}(2030 - t)^{-1}$ using the above definitions (Denness, 1987).

Do we have to wait until it happens before we believe the evidence which **Homo sapiens** has drawn up over the last 100,000 years - indeed, **Homo** since the evolution of **H. habilis** 2.5 million years ago(Dobzhanksy, 1977)? Or can we really justify the term "sapiens" and apply the results of our intellectual agility to the betterment of the way of life of a steady-state population and amelioration of the greenhouse effect, rather than dissipating it on continuing the headlong dash to self-destruction - apparently the only alternative - within the next 40 years?

There is some evidence in recent years of a decline in the overall population growth rate. This is commonly held to imply that expansion is now under control and that the population will level off at perhaps about three times the present size over the next couple of centuries. However, reference to Stage 13 of FigureA2 shows that its cubic-time expansion progressed from an effective age of 150 to 185 from 1950 to 1985; this implies the slowing down of the growth rate from 2.0% in 1950 to 1.6% simply by ageing within one simple cubic-time growth phase consistent with observations. The same was true for all the previous phases and has no implication for the rate of growth after the next universal step of cultural evolution with its attendant technological revolution.

Nevertheless there is abroad today a mood of awareness of man's condition not previously evident in history. There is also on hand the fruits of the last technological revolution, the Communications Revolution. This has equipped modern man with the necessary device to bring the whole population into the global village to hear the words of wisdom from sages regarding the need for procreative restraint, a unifying capability never previously available. It is to be hoped that it is used.

If reason prevails, as surely it must, instead of squandering the rewards of technological revolution on procreation,there will arise the opportunity for a population of constant size to improve its standard of living and eventually quality of life at similar rates to those currently associated with population growth. Extending FigureA2 to Stage 14 between the bold sloping parallel lines would see a population of five billion in 1990 with an effective age of 75 years (for the population **not** the individuals) capable of expanding at a rate of 4.1% per year, slightly less than Kenya already enjoys! Spread across the whole world with an emphasis on the current underprivileged quarters this represents an exciting prospect if channelled into development rather than population growth: if not so channelled, the greenhouse effect is unstoppable.

A.8 Conclusions

It has been shown that the historical record of population growth is closely matched by an expansion model which encompasses cubic-time expansion phases separated by rejuvenation steps. The steps reflect cultural evolution with attendant technological revolutions.

The future appears to hold the options of continuing adherence to the hitherto uninterrupted expansion mechanism leading to an unsupportable number of people in the 2020's or of diverting procreational energies into development consistent with ameliorating the greenhouse effect. The latter would lead to the improvement of the global standard of living at about 4% per year for a stable population of five billion in perpetuity if other environmental issues were also resolved.

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