ENTROPY MAN

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Front Cover: Getty Images.

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Preface

The seeds for this book were sown in the 1970s, four decades ago, when I was then working as group economist for the engineering corporation Babcock International Plc. At that time the group employed about 30,000 people in subsidiaries spread all around the world, engaged in the design, manufacture and installation of capital plant for a variety of industries, including nuclear & conventional power generation, coal mining, gas, chemicals & petroleum, steel, automotive, cement, construction and environmental engineering. Prior to that, my formal university education had included a degree in engineering at University of Bath and a Masters in management science, allied to student sandwich experience with Amalgamated Power Engineering *[now a subsidiary of Rolls Royce]* and ASEA Brown Boveri, Switzerland, followed by working for SKF, the Swedish bearing manufacturer, often considered to be a bell-weather of world economic output.

From the 1980s onwards I worked as director of a consultancy, and subsequently also as an expert witness to the Courts, which roles I continue to the present day. These experiences have taught me to maintain an enquiring, dispassionate and impartial mind regarding the complex workings of human endeavour, the natural world and changes arising thereof.

My particular research interests in those early years concerned the parallels between the disciplines of economics and thermodynamics *[the science of energy & heat]* and how they relate to each other, as a result of which I published two peer-reviewed papers on the subject in *Energy Economics [1979 & 1982]*. Subsequent to these I gave presentations to international gatherings of government ministers, energy industry executives and academia.

Not being based at a university however, and with no research grant at my disposal, my main thrust had been to make a living from consultancy and therefore, until more recently, opportunities to spend time on research were few. Nevertheless, by the turn of the millennium I was able to find time to return to some research and published another peer-reviewed paper in the *International Journal of Exergy [2007]*, followed up by several working papers on monetary aspects and energy models. Subsequently in 2009 I wrote a technical book on the subject, to bring together all the facets of the work into a coherent whole: *'Thermoeconomics – a thermodynamic approach to economics'*. The book was subsequently revised, corrected and added to, up to a third edition *[2012]*, covering topics such as production and consumption processes, employment, money, interest rates and bonds, energy resources, climate change and sustainability, and including more up to date statistics. It has now been superseded by this book.

Whilst not being tied to a university, government agency, industrial enterprise or other organisation has disadvantages in terms of recognition and time available for research, it does nevertheless have the advantages of freedom to investigate and pursue a course of enquiry of one's own choosing and of drawing conclusions independent of those that pay the piper or who may have pre-set agendas, however well-intentioned these may be.

The nature of the subject requires significant proof for economists and scientists to accept that similarities between thermodynamic and economic phenomena might imply more than just a passing analogy or isomorphism, and relations between the two disciplines have rarely been comfortable, with scientists sometimes having scant regard for the work of economists; and many economists believing that science has little to offer their discipline which, by its nature, can be thought of as anthropocentric rather than eco-centric. One eminent energy scientist advised me that he did not know of an economist who could follow a thermodynamic argument. Certainly a concept such as entropy means very little to most economists, still less to the man in the street – money is their language of communication. The latter is not, however, the language that Nature and the environment converse in.

This book is intended for a mixed readership of scientists, economists and those of an enquiring mind. It is a challenge therefore to convey the nub of the argument in terms that all can appreciate, with particular reference to the effects of potential problems such as 'peak resources', humankind's effect on the ecosystem and the maelstrom that would ensue should resource failure or climate change ever come about to a significant degree.

While some chapters, notably chapters 4 through to 8, do contain some mathematical expressions, explanatory points are included to guide non-mathematicians onwards. Formal proofs and derivations have been relegated to the notes on each chapter.

Although economic man may currently have the ascendency, he does not actually *'own'* the Earth. He is there on sufferance, and the Earth would quickly forget him along the ecological timescale, should human civilisation fail or spoil the proceedings.

I am indebted to my wife Alison for all her support and for providing me with an atmosphere conducive to my research.

John Bryant

CHAPTER 11 THE ATMOSPHERE, OCEANS & CRYOSPHERE

More than anything else on Earth, the physical movements and changes in the atmosphere, oceans and cryosphere are vivid examples of entropy in action. High intensity *[short wavelength]* heat flux arrives from the Sun at a total solar irradiance rate of about 1361 W/m^2 *[Kopp et al 2005],* averaging out at about 340 W/m^2 across the surface of the Earth, but varying a little with solar and orbital cycles. Some of the heat flux is absorbed by the atmosphere, some is reflected back to space by the clouds/atmosphere and by the Earth's surface *[depending upon the relative albedo]*, and the rest is absorbed at the surface, ultimately providing energy for life forms to flourish, and heat to warm the air and evaporate water, the latter rising to form clouds which turn to precipitation as latent heat is removed. In addition, low intensity *[long wavelength]* heat flux is radiated directly from the land and oceans out into space, and to the atmosphere, some of latter of which is radiated back by clouds and greenhouse gases, and some is then radiated onwards to space. The greenhouse gases, through their selective blocking of parts of the spectrum of the outgoing long-wave radiation, enable the temperature at the Earth's surface to be maintained at an average, bearable level of about 15ºC. In the absence of these gases, the temperature would be quite a bit colder, at about -18 ºC on average, which would not be conducive to life forms.

Because the heat flux from the Sun impacting on the Earth varies with intensity, from a high level between the Earth's tropics to a very low level around the poles, and according to daily, seasonal and other movements as the Earth rotates about its' axis and orbits the Sun, the atmosphere is constantly in motion, having large-scale, localised, convective and chaotic elements. The directions of winds north and south of the Equator are also influenced by the Coriolis Effect as the Earth rotates. The winds help to re-distribute energy potentials from the tropics towards the poles, and have a significant impact on ocean waves and the circulation of ocean waters around the Earth. The whole process involves continuous degradation of the Sun's energy flux and net production of entropy, as Earth systems forever strive to proceed towards equilibrium states. This brings to mind the Le Châtelier principle which we met at the beginning of this book. Nature is never in balance.

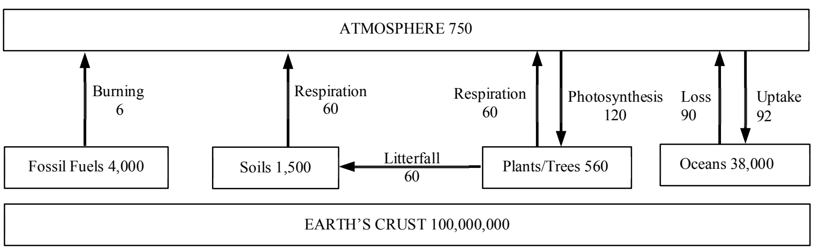
The Earth's systems and climate have been the subject of a number of researchers *[Paltridge (1975), Lorenz (2001), Ozawa (2003), Jenkins (2004),* *Goody (2007), Kleidon (2009), Pascale et al (2009), and others]*, concluding that a variety of irreversible processes are taking place continuously, which are described by the entropy production rate. Ozawa et al *[2003]*, reviewing the maximum entropy production principle, have calculated a global entropy budget for the Earth *[see table 11.1]*, based on in-coming and out-going radiative energy fluxes, and on the temperatures at the surface of the Sun, at the top of the Earth's atmosphere and at the surface of the Earth.

	$WK^{-1}m^{-2}$
Solar short-wave radiation absorbed by the Atmosphere	0.367
Solar short-wave radiation absorbed at the surface of the Earth	0.469
Convection and turbulent processes in the Atmosphere	0.046
Long-wave radiation from the Earth's surface absorbed by the Atmosphere	0.018
Total	0.900

[$WK^{-1}m^{-2}$ Watts per degree Kelvin, per metre squared of area]
Source: Ozawa et al 2003, American Geophysical Union
Table 11.1 Global Entropy Budget for the Earth.

Clearly, at the global level, entropy production and change constitute the natural state of affairs, and one might hazard that this would percolate in some way towards and among the sub-systems of the Earth – atmospheric, hydrologic, geologic, carbon and biotic cycles.

In respect of life, the carbon cycle is vitally important. The diagram at figure 11.1 sets out a very simple summary of the stocks and flows of carbon, circa 1990.

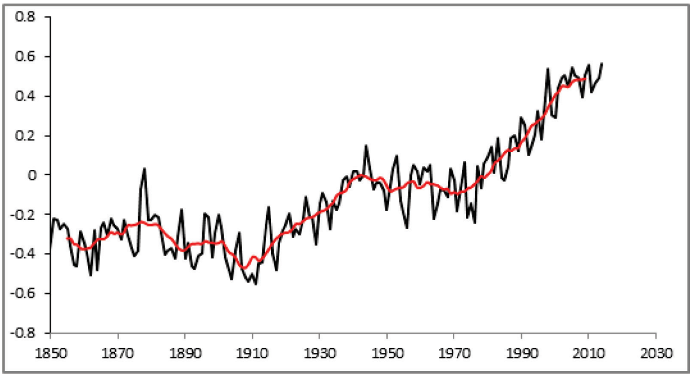


[Not shown: Volcanoes 0.1, deforestation/land use 0.9, rivers 0.8 and sediments 0.1]
Data source: University New Hampshire
Figure 11.1 Simplified carbon cycle circa 1990. GtC [for stocks], GtC p.a. [for flows].

Anthropogenic emissions apart, exchange of carbon through respiration, litterfall and photosynthesis for soil and vegetation, and through losses and uptake of the oceans, is approximately in balance, but subject to changes in solar and other activity. Continuing anthropogenic emissions, however, throw the system significantly out of balance, with the atmosphere initially accumulating the excess carbon in the form of carbon dioxide, unmatched by an immediate sink to reduce the level back down again. One might expect that the Earth's subsidiary systems would each react in some individual, unspecified way to meet the position over time, transferring some of the carbon elsewhere within the Earth's ambit, such as the oceans. Figures of Global Carbon Budget 2014 *[Le Quéré, R et al]* indicate that fossil fuel and cement carbon emissions have risen further, from 6.1 GtC p.a. in 1990 to 9.9 GtC p.a. in 2013, adding to the atmosphere.

The last two decades have seen an escalating interest in the effects of climate change as summarised by IPCC *[Intergovernmental Panel for Climate Change]*, and by the Stern Review *[2006]*. It is not the place of this book to supplant the work done, though it is relevant to set out the main trends to date, while keeping an open mind concerning man's understanding of the way processes work and the directions in which matters may progress; in particular, the potential for climate change to act as a constraint on economic activity, in the manner described at chapter 6 concerning production and consumption, and the potential effects of climate feedbacks such as water vapour, the albedo, land carbon, methane hydrates and permafrost *[methane]*.

Probably the single most important indicator encapsulating the effects has been the rise of more than 0.8ºC in the global average surface temperature *[HadCRUT4 combined land and ocean]* from the mid-19th century to the present day *[see figure 11.2]*, which rise appears to be continuing, though there have been some periods of decline or flattening *[late 19th century, immediate post world war II]* Figures of the Met Office Hadley Centre *[HadCRUT4]*, indicate that the temperature anomaly continues to climb, reaching a peak in 2014 of 0.563ºC.



Source: Metoffice.gov.uk, cru.uea.ac.uk.

Figure 11.2 HadCRUT4 global annually averaged surface temperature anomalies 1850-2014 ºC, relative to 1961-90, with a centred 11-year moving average inserted.

Warmer atmosphere, land and ocean surfaces, affecting latent heat and thermal expansion, imply that changes in sea level and the extent of ice in the cryosphere may also occur. IPCC report that it was very likely the mean rate of rise of global average sea level was 2mm per year between 1971 and 2010, which rate has escalated more recently. However, between 1979 and 2012, while the annual mean Arctic sea ice extent very likely decreased by 3.5-4.1% per decade, that for the Antarctic area increased by 1.2-1.8% per decade. Even so, IPCC report that over the last two decades both the Greenland and Antarctic ice sheets have been losing mass, glaciers have continued to shrink almost worldwide, the extent of Northern Hemisphere snow cover has decreased since the mid-20th century and permafrost temperatures have increased in most regions since the early 1980's. It is thought that if all the ice in Greenland melted then sea level could rise by about 7m. The equivalent figure for Antarctica is over 60m. A follow on effect of a reduction in ice and snow cover is a reduction in the albedo or reflective effect, increasing the amount of solar radiation absorbed at the Earth's surface, with a consequent effect on surface temperature.

The generally accepted origins of the rise in temperature which has occurred are those of radiative forcings, measuring the influence of factors that alter the balance of incoming and outgoing energy *[in W/m^2]* of the Earth-atmosphere system. Contributing factors include changes in energy flux from the Sun, volcanic activity, changes in the concentrations of greenhouse gases and others, including human activity.

In respect of human activity, the predominant influences must be those impacting on changes in the atmosphere and in land use; in particular, anthropogenic emissions to the atmosphere of carbon dioxide *[CO_2]*, methane *[CH_4]* and nitrous oxide *[N_2O]*, and deforestation, the latter affecting the level of photosynthesis and hence the removal rate of CO_2 from the atmosphere. Greenhouse gases, *once accumulated*, by their nature tend to linger in the atmosphere for a number of years, CO_2 up to 200 years, CH_4 about 12 years and N_2O about 110 years. Water vapour on the other hand has a short lifetime in the atmosphere – of the order of hours to a week or so on average. Historic figures indicate that atmospheric concentrations of CO_2, CH_4 and N_2O have risen significantly, and at increased rates since 1960. As at September 2014 the level of CO_2 in the atmosphere stood at 395.9 ppmv.

	CO_2	***CH_4***	***N_2O***
Year	*ppmv*	*ppbv*	*ppbv*
1850	285.1	801	275.4
1960	317.1	1263	291.4
2014	395.9	1792	326.5

Sources: NASA GISS, CSIRO Cape Grim (September 2014)
Table 11.2 Atmospheric concentrations of greenhouse gases.

Table 11.3 is instructive of the mass of carbon dioxide now in the Earth's atmosphere:

	Concentration	***Mass***
Year	*ppmv*	*$GtCO_2$*
1850	285.1	2229
2014 (CSIRO September)	395.9	3096
Net Increase 1850-2014	110.8	867

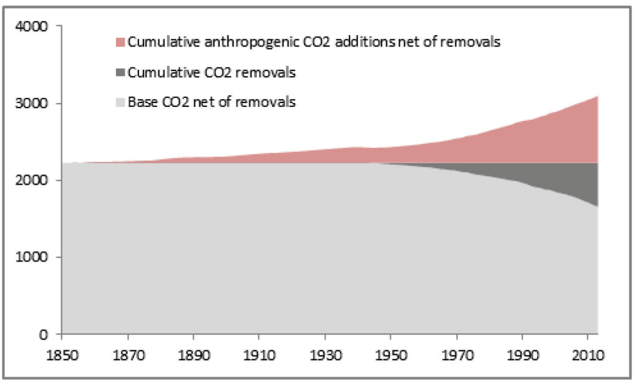
Assumptions:
Mass of Atmosphere: 5.148 x 10^6 Gtonnes [Trenberth, Smith 2005]
Mass/Volume adjustment CO_2/Air 44.001/28.97 = 1.519
Table 11.3 Mass of CO_2 in the atmosphere.

The net mass of 867 $GtCO_2$ added to the atmosphere between 1850 and 2014 can be compared to the gross cumulative mass of annual anthropogenic CO_2 generated from fossil sources for the period 1850 – 2013 inclusive *[see figure 2.2 at chapter 2]*, which amounted to 1,439 $GtCO_2$. Thus only 572 $GtCO_2$ *[1439 – 867]* or 39.7% has been re-absorbed so far at the Earth's surface *[mostly by the oceans]* over the 164 years that have passed.

Archer et al *[2009]* confirm that the time required to absorb anthropogenic CO_2 depends upon the total amount of emissions.

The chart at figure 11.3 summarises the mass of CO_2 in the atmosphere over time. Changes in land use have not been included. CO_2 removed has been equated to the gross anthropogenic emissions added to the atmosphere less the net rise in atmospheric CO_2.

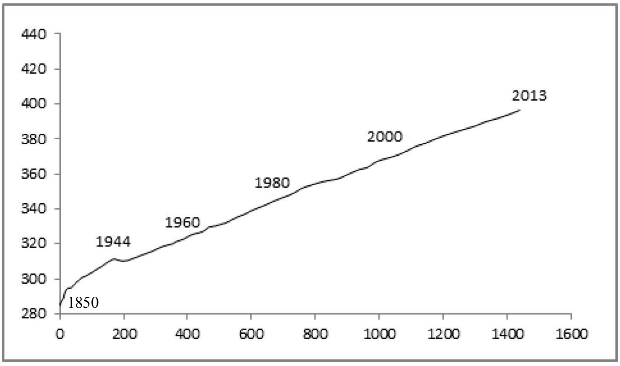
Amounts of anthropogenic CO_2 began to accumulate in the atmosphere from the late 19th century onwards, but it was not until post world war II that some of these began to percolate downwards, the latter principally to the oceans, altering ocean acidity and chemistry, and thereby creating a ripple effect onwards to the marine biotic system. According to Oceana.org, particular species that may be affected include plankton, sea snails, sea urchins, squid, and life forms that depend upon calcification to survive.



Data sources: GISS CDIAC

Figure 11.3 Global mass of CO_2 in the atmosphere $GtCO_2$ 1850 – 2013.

The chart at figure 11.4 illustrates the relationship between the concentration of CO_2 in the atmosphere *[by volume]* and *cumulative* anthropogenic additions of CO_2 to the atmosphere from fossil sources *[by mass]* from 1850 to the present time. The relationship appears to be almost linear, affected only by some removals to the Earth.



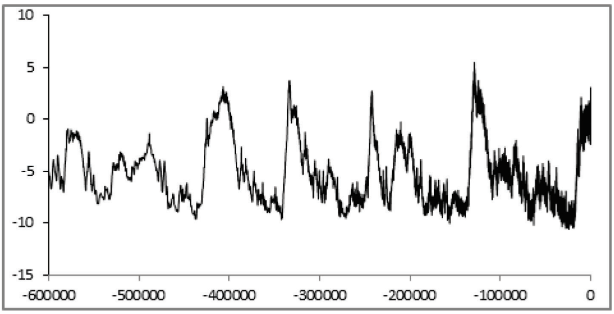
Data sources: GISS CDIAC

Figure 11.4 Global mean atmospheric concentration of CO_2 ppmv [y-axis] versus gross cumulative anthropogenic additions of CO_2 to the atmosphere from fossil sources $GtCO_2$ [x-axis] 1850 – 2013.

Should the human race reduce drastically, and irrevocably, its emissions of CO_2, one might expect the curve to flatten off gradually, and eventually to turn down, though possibly hundreds of years in the future. As yet there is little sign that this will occur.

A note of caution should be sounded with regard to the measurement of CO_2 in the atmosphere. From 1958 onwards accurate measurements were made possible via an analyzer at the Scripps Institute, Mauna Loa and from flask samples from other sites *[The Keeling Curve]*. Prior to that, only sporadic measurements had been made, with gaps of some years between each. To fill the gaps in older periods many researchers rely on data from ice-cores *[Etheridge et al 1996]* which themselves have gaps of 6-7 years or more between each measurement. Thus annual figures going back before 1958 rely on averaging between each point, which could lead to hiding some short term trends.

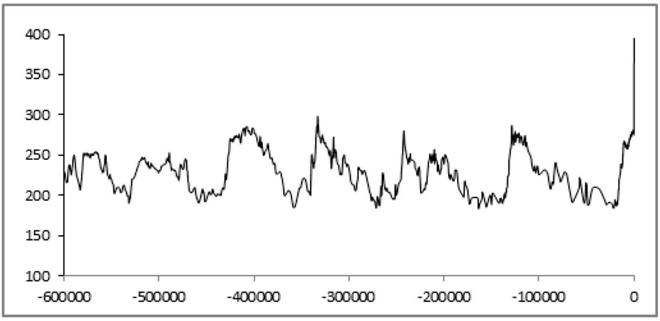
For longer timescales, it is well-known that past changes in atmospheric temperature and the concentrations of greenhouse gases can be deduced with a high degree of confidence from polar ice-core paleo-climate records; temperature being related to the relative presence of isotopes, either of oxygen *[$\delta^{18}O$]* or of deuterium *[D or ^2H]* in the water, and greenhouse gases to samples from the air bubbles trapped in the ice-cores. Figure 11.5 shows the variation in the temperature anomaly measured from the ice-core data obtained from the Dome C site of the European Project for Ice Coring in Antarctica *[EPICA]* in East Antarctica. The original core, measuring 3,190 metres deep, covers a period from the present back to about 800,000 years ago. Data are not evenly spaced *[physically or in terms of time]* down the core; much of the temperature data for instance is concentrated in the first 200,000 years before the present, which might explain the crowding of the line towards the right in figure 11.5. The temperature anomaly has varied in cycles, around 100,000 years in length, over a range of up to 15ºC. The more recent paleo-climate record indicates that the temperature anomaly may be at or about the upper end of a cycle.



Source: NOAA. EPICA Dome C Ice Core Temperature Estimates Jouzel, J., et al. 2007

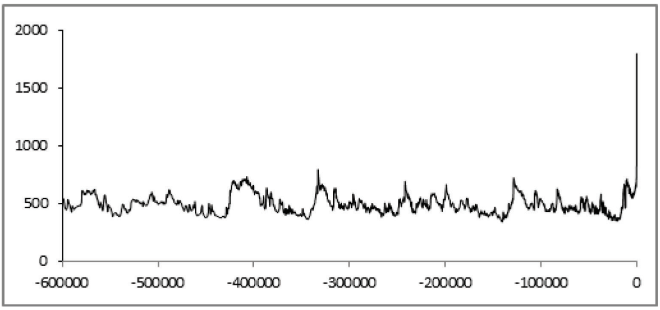
Figure 11.5 Estimate of temperature anomaly ºC years before 1950 [relative to the average of the last 1000 years].

Figures 11.6 and 11.7 show the concentrations of carbon dioxide and methane over the same period. The last record of the ice-core indicated concentrations for CO_2 at 280.4 ppmv and CH_4 at 907 ppbv respectively. Figures for the current concentrations of the gases have been added by the writer to illustrate the recent large jumps, to 395.9 ppmv and 1792 ppbv respectively.



Source: NOAA. EPICA Dome C Ice Core 800KYr Carbon Dioxide Data Lüthi, D., et al. 2008

Figure 11.6 Estimates of atmospheric carbon dioxide concentration ppmv.



Source: NOAA. EPICA Dome C Ice Core 800KYr Methane Data Lüthi, D., et al. 2008

Figure 11.7 Estimates of atmospheric methane concentration ppbv.

Considering only the CO_2 data of the paleo ice-cores *[i.e. excluding the data added to the chart at figure 11.6 by the writer]*, then a significant coupling of temperature level with the concentration of CO_2 in the atmosphere can be seen, as over the long-term they appear to follow similar cyclical paths.

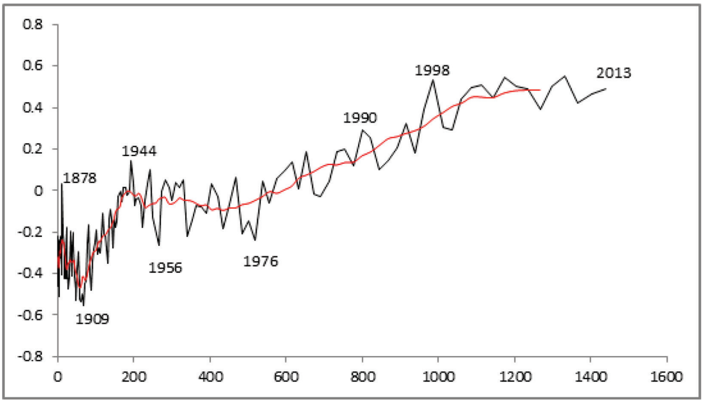
A number of observers, however, have pointed to specific parts of the data which appear to show that temperature changes *lead* those of the CO_2 concentrations – by as much as a thousand years – whereas one might have expected the reverse if greenhouse gases are presumed to be the agents of temperature rise.

Parrenin et al *[2013]* have revisited the ice-core data in an attempt to resolve this problem. In an ice-core, temperature and CO_2 concentration are not read off at the same levels of the core. The researchers developed a different method to measure different ages of gas and ice, by reference to the presence of a nitrogen isotope *[$\delta^{15}N$]* in the core. They could find no significant asynchrony between gas concentrations and temperature data, indicating that Antarctic temperature did not begin to rise hundreds of years before the concentration of atmospheric CO_2, as was suggested by earlier studies. Nevertheless, in the writer's view, more research in this area would be of great value to add confidence to any conclusion.

Tripati et al *[2009]* confirm that atmospheric CO_2 is closely coupled with both temperature and sea-level, though for periods earlier than 800,000 years the position is much less certain. They estimate that during the middle Miocene *[around 11-16 ma]* CO_2 levels were similar to those of the present time; temperatures were 3-6ºC warmer and sea level was 25-40 metres higher than at present.

With regard to more recent trends, a paper of Lockwood & Fröhlich *[Proc.R.Soc.2007 463]* concluded that while the Sun has been a significant influence on both pre and post-industrial climate changes, the observed rise in global temperature after 1985 cannot be ascribed to solar variability. Svensmark and Friis-Christensen *[Danish National Space Centre],* however, reply to the Lockwood & Fröhlich paper by the use of an inversion of cosmic ray flux as an index of solar activity, and consider that the Sun still appears to be the main forcing agent in climate change. The author defers to experts in the field as to the weight to be attached to the Svensmark and Friis-Christensen reply.

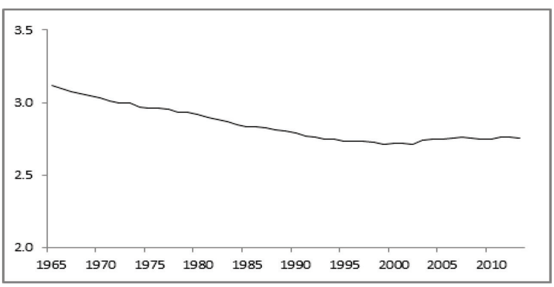
From all of the foregoing, it is apparent that from 1850 to the present time there has been a coupling between the concentration of CO_2 in the atmosphere and cumulative anthropogenic emissions of CO_2 arising from burning fossil fuels *[see figure 11.4]*. Further, that an increase in atmospheric temperature occurred over the same period which, for more recent periods, cannot be explained purely by solar variance. It is reasonable to conclude that anthropogenic emissions of CO_2 do have some relation to, and influence on, the level of atmospheric temperature. Figure 11.8 illustrates the relationship *[A similar chart is presented at figure SPM10 of the IPCC WGIAR5 summary for policymakers, but including only decadal points]*.



Data Sources: Metoffice.gov.uk, cru.uea.ac.uk, CDIAC

Figure 11.8 Global temperature anomaly ºC [y-axis] as a function of cumulative anthropogenic emissions of CO_2 to the atmosphere $GtCO_2$ [x-axis] 1850 – 2013, with a centred 11-year moving average inserted.

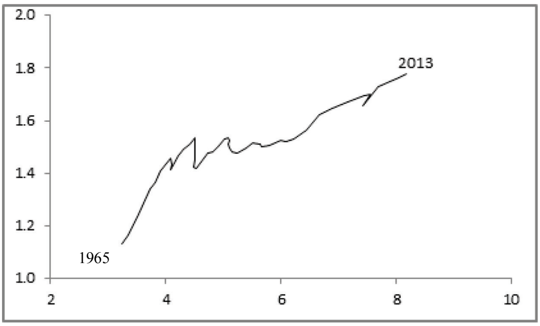
Continuing further, readers may note first, from the charts at figures 2.3 and 2.4 chapter 2, that anthropogenic CO_2 emissions have followed a very similar path to that of the rapidly escalating rise of world primary energy consumption, though subject to any changes in fuel mix, in particular towards renewable energy. The International Energy Agency *[World Energy Outlook 2013]* report however that as of 2013 the share of fossil energy in the global mix was 82%, the same as it was in 1988, 25 years previously. On this basis it is reasonable to conclude that emissions of CO_2 are still strongly related to primary energy consumed. Figure 11.9 summarises changes in the ratio of world CO_2 emissions to primary energy consumption. The ratio declined to about year 2000, but thereafter has increased a little.



Source: BP Statistical Review

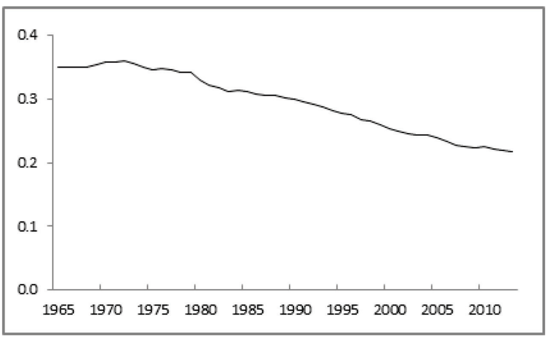
Figure 11.9 Ratio global emissions CO_2 $GtCO_2$ p.a. to primary energy consumption Gtonnes p.a. oil equivalent 1965 – 2013.

Second, energy consumption is also related to GDP through changes in energy intensity of use *[primary energy consumption per $ of GDP]*. Figure 9.1 at chapter 9 illustrates declining energy intensities for the developed economies, but offset by fairly level energy intensities for developing countries, with the result that, overall, world primary energy consumption per head of human population continues to rise, as shown in figure 11.10. Should developing countries subsequently emulate the developed countries in reducing their energy intensity ratio, then one might expect the curve in the chart to curl further to the right. Figure 11.11 shows the net effect to date on the global energy intensity ratio.



Sources: BP Statistical Review,
Angus Maddison, OECD Development Centre Studies:
"World Economy – A millennium perspective", CIA, UN

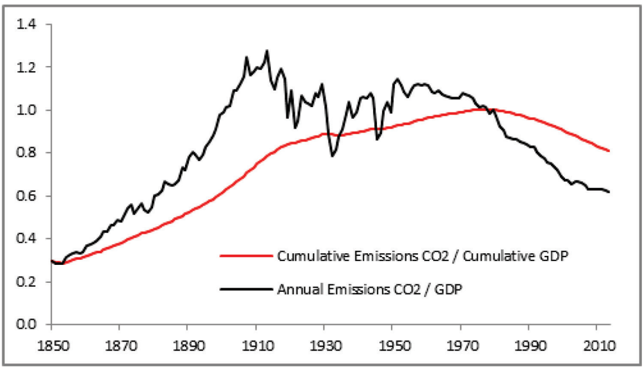
Figure 11.10 Global primary energy consumption per capita tonnes oil equiv p.a. [y-axis] as a function of world GDP per head $000 p.a. at 1990 prices [x-axis] 1965 – 2013.



Sources: BP Statistical Review, Angus Maddison,
OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

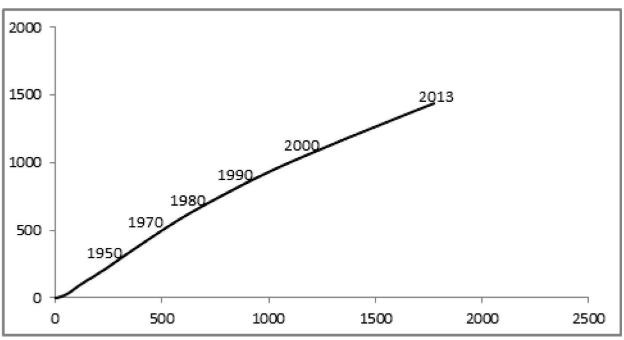
Figure 11.11 Ratio global primary energy consumption to GDP Kgoe/$ [1990 prices] 1965 – 2013.

Combining all the effects of figures 11.4, 11.9, 11.10 and 11.11, then figure 11.12 shows the trend of the world annual and cumulative emissions intensity ratios kgCO_2 per $ GDP *[1990 prices]* 1850 – 2013, and figure 11.13 shows the relationship of *cumulative* emissions of CO_2 to *cumulative* world GDP 1850 – 2013. The Maddison study from which the GDP figures are taken provides only four estimates of world GDP prior to 1950, when GDP *[at 1990 prices]* was then $5,336 billion. For the purposes of the charts, annual GDP figures in between each of the pre-1950 Maddison GDP estimates *[1940, 1913, 1900 and 1870]* were approximated on an interpolated basis. This was a reasonable procedure to take, as the pre-1950 figures for cumulative world GDP were small, relative to those after 1950, and do not significantly affect the accuracy of the longer-term trend.



Sources: CDIAC, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

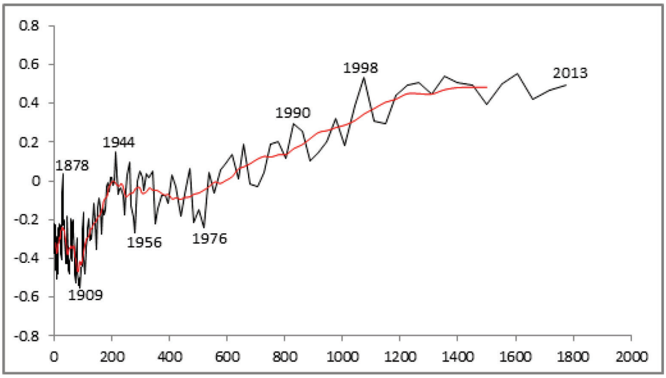
Figure 11.12 World emissions intensity ratio kgCO_2 / $ GDP 1990 prices 1850 – 2013.



Sources: CDIAC, Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

Figure 11.13 Cumulative global emissions CO_2 $GtCO_2$ [y-axis] as a function of cumulative world GDP $ trillion 1990 prices [x-axis] 1850 – 2013.

Given that cumulative global anthropogenic emissions of CO_2 appear to be significantly correlated with cumulative world GDP, and that the world annual emissions intensity ratio, though falling, is beginning to level off, it is not unreasonable to replace the base line of the chart at figure 11.8 *[cumulative emissions]* with cumulative GDP, while acknowledging that the emissions intensity ratio will fall further. Figure 11.14 sets out such a relationship.

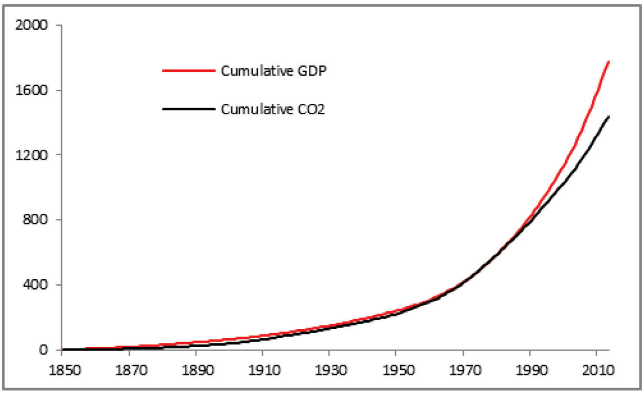


Sources: Metoffice.gov.uk, cru.uea.ac.uk,
Angus Maddison, OECD Development Centre Studies: "World Economy – A millennium perspective", CIA

Figure 11.14 Global temperature anomaly ºC [y-axis] as a function of cumulative world GDP $ trillion 1990 prices [x-axis] 1850 – 2013, with a centred 11-year moving average inserted.

A number of observations are pertinent. First, the temperature anomaly appears to have a similar relation to cumulative GDP as it does to cumulative anthropogenic emissions of CO_2, though it has been stretched out in recent years because cumulative GDP is growing faster than cumulative CO_2 *[see figure 11.13]*. Readers should not however be beguiled into thinking that the temperature anomaly will not escalate further. Figure 11.2 indicates that levelling of this sort has occurred two or three times in the world's industrial past. As long as GDP remains dependent upon fossil energy to power its base, and GDP is able to advance further, then the temperature anomaly might be expected to continue rising, and for some while, even after a levelling or decline in GDP. It will be a matter of evidence as to how far the emissions intensity ratio will eventually fall, through changes in efficiency and switches to non-fossil energy, such as to divorce emissions from GDP.

Second, because the world's energy consumption rate is still increasing significantly in order to fuel a growing anthropogenic appetite for GDP, for a given increase in cumulative GDP *[and thereby cumulative CO_2 emissions]*, the number of years between the starting and finishing points is reducing, and the situation is escalating as the years go by. Figure 11.15 illustrates the apparently inexorable rises in cumulative anthropogenic emissions of CO_2 to the atmosphere and cumulative world GDP 1850 – 2013. On current trends, cumulative emissions to the atmosphere could double in the space of two decades or so and rapidly escalate thereafter, *assuming that energy consumption and GDP are able to continue growing*.



Data Sources: GISS CDIAC,
Angus Maddison, OECD Development Centre Studies:
"World Economy – A millennium perspective", CIA

Figure 11.15 Cumulative world emissions CO_2 $GtCO_2$, and cumulative world GDP $ trillion1990 prices, 1850 – 2013.

Extrapolations of the trend lines at figure 11.15 correspond approximately to the higher end scenario ranges set out by IPCC *[Representative Concentration Pathways RCP6.0 and RCP8.5, Table TS1 WGIIIAR5]*, with cumulative emissions between years 2011-2100 approaching 3620 – 7010 $GtCO_2$, along with a temperature anomaly range of 3.1 - 4.8ºC *[relative to 1850 – 1900]*, though IPCC indicate that with appropriate actions to mitigate climate change *[RCPs 2.6 and 4.5]* the temperature anomaly might be reduced to a range 1.5 – 2.9ºC. They indicate, however, that this would require a significant reduction in the level of projected cumulative world emissions to the atmosphere between years 2011-2100, to a range of 630 – 3340 $GtCO_2$.

Figure TS.7 IPCC WGIII AR5 technical summary sets out variations of four main factors linking to carbon production: world *[human]* population, GDP per capita, energy intensity of GDP and the carbon intensity of energy consumption. Superimposed on these factors are divisions by main geographic area, and subdivisions by energy sector and by consumer, such as transport, residential and industry, with a projection of emissions of each of the gases *[CO_2, CH_4 N_2O]* into the future. The exercise was carried out by several agencies, and included scenario variations such as conventional or abundant gas and many others. In all, more than 160,000 projections were made. In respect of population, the projected variants reflected much of what is set out at chapter 10 of this book with regard to UN estimates of human population growth. With regard to estimates of future GDP per capita, however, the majority of the IPCC model projections made are of the exponential kind, forever into the future, albeit with varying growth rates assumed, generally in a range of 1 - 2½% compound, against a historic trend of 1.4%, implying world GDP per capita in 2100 in the range 2½ - 8½ times the level in 2013.

Some of the models in the IPCC projections *[Pik and IIASA]* make use of Cobb-Douglas and Augmented Solow models *[see chapter 5]*, which project forward exponentially only the capital and labour/human capital cost components of GDP, and make no reference to the productive contribution of the resources consumed *[other than the ratio of energy consumed per unit of GDP]*. It will be recalled from chapter 5 however that the work of Ayres and Hümmel showed that traditional economic theory explained very little of growth compared to natural resource energy, with around two-thirds of productivity in fact arising from energy consumption and only a small percentage from human labour.

It will be a matter of evidence therefore as to the extent to which world GDP per capita will be able to grow in the face of an escalating effect from first, climate change, impacting on the ability of the eco-system and humanity to cope with the changes, and second, potential limits on the amounts of resources that will be available *[energy and other forms]* that have been highlighted in this book; the evidence of trends in world human population growth alone indicating, perhaps subconsciously, a potential ceiling in about 2050. Exponential growth in a finite and dynamic world cannot be assumed. A discussion of this prospect is set out in the final chapter of this book.

IPCC have set out an analysis of major areas in specific parts of the world expected to be affected by climate change, which analysis the author would not challenge. The areas included:

- Physical systems:
  - Glaciers, snow and ice
  - Rivers, lakes, flooding and drought
  - Sea level and coastal erosion
- Biological Systems:
  - Terrestrial ecosystems
  - Marine ecosystems
  - Wildfire
- Human & managed systems:
  - Food production
  - Livelihood and health
  - Economics

Specific effects include:

- Reduced glacier mass and forest cover
- Reduced crop yield – particularly wheat and maize
- Increased precipitation towards the poles
- Increased drought in temperate zones
- Increased flooding in tropical zones and low lying lands
- Movement and displacement of some species to track climate change
- Under-nutrition
- Food & water-borne infections
- Extreme weather events
- Mental health and violence
- Increased insecurity, nationally and internationally
- Conflict, land grabs and resettlements

On the evidence to date, further significant rises in global air temperature and water levels will occur, which ultimately will cause a reduction in output to some if not many economies through a loss of agricultural farming capacity, loss of habitation located in low-lying areas liable to sea flooding, and entail a consequent large-scale write-off of capital stock. Of more concern, however, is the effect on the eco-system, which humankind has previously mostly ignored, and which will affect the quality and quantity of natural capital, which in turn will impact on sustainability.

There is of course nothing initially to prevent world economies continuing along a *'same as usual'* path, with governments endeavouring to satisfy their populace by delivering economic growth and the wherewithal to service debt, but in the absence of concerted action among the international community to reduce fossil energy consumption, ultimately the Earth will do it for us, in ways that individually may not seem fair to humankind, and with a lasting effect. On present trends, it appears likely that action at best may be of a delayed, iterative kind in response to accumulating environmental disasters, affecting individual areas and countries in the world.

Table 11.4 summarises current and cumulative emissions by major country, along with figures of population, GDP and primary energy consumption, and the ratios connecting all these variables. It is reasonable to assert that countries with high emissions, currently and historically, are those more likely to be impacting on anthropogenic contributions to global warming. Sixteen countries, headed by China and USA, account for 76% of current global emissions *[2013]*, 71% of cumulative emissions *[1965-2013]*, 75% of primary energy consumption *[2013]* and 70% of world GDP *[2013]*, but only 59% of population *[2013]*. On a cumulative basis, Poland, South Africa, Australia, Ukraine and the Netherlands have also been high emitters; and Saudi Arabia, USA, Canada and South Korea currently have very high emissions per capita.

It is perhaps inevitable that some countries may be less committed to change than others, and some may feel that their response should be less than others by virtue of history and their relative economic development. Nature, however, makes no such distinction.

Country	CO_2 Output	Cumulative CO_2 1965-2013	CO_2/Hd	Carbon Intensity CO_2/PEC	Primary Energy Consumption	Energy Intensity Energy/GDP	GDP PPP	Population	GDP/Hd	PEC/Hd	Emission Intensity CO_2/GDP
	$MtCO_2$ pa	$MtCO_2$	tCO_2 pa	ratio	mn toe pa	Kgoe/$	bn $ pa	mn	$ pa	toe pa	Kg/$
China	9524.3	149550	7.02	3.339	2852.4	0.1765	16158	1357.4	11904	2.101	0.5894
USA	5931.4	266979	18.76	2.618	2265.8	0.1349	16800	316.1	53148	7.168	0.3531
India	1931.1	34309	1.54	3.246	595.0	0.0878	6774	1252.1	5410	0.475	0.2851
Russia	1714.2	53287	11.95	2.452	699.0	0.2020	3461	143.5	24118	4.871	0.4953
Japan	1397.4	54548	10.98	2.948	474.0	0.1025	4624	127.3	36324	3.723	0.3022
Germany	842.8	48020	10.46	2.593	325.0	0.0930	3494	80.6	43350	4.022	0.2412
South Korea	768.1	15539	15.30	2.831	271.3	0.1630	1664	50.2	33147	5.404	0.4616
Saudi Arabia	632.0	12150	21.94	2.776	227.7	0.1469	1550	28.8	53819	7.906	0.4077
Iran	630.6	12167	8.15	2.585	243.9	0.2021	1207	77.4	15594	3.151	0.5225
Canada	616.7	24166	17.52	1.853	332.9	0.2189	1521	35.2	43210	9.457	0.4055
Brazil	541.1	12645	2.70	1.905	284.0	0.0943	3012	200.4	15030	1.417	0.1796
Indonesia	523.3	9008	2.09	3.102	168.7	0.0706	2388	249.9	9556	0.675	0.2191
UK	513.4	30286	8.01	2.567	200.0	0.0862	2320	64.1	36193	3.120	0.2213
Mexico	499.4	13616	4.08	2.656	188.0	0.0933	2014	122.3	16468	1.537	0.2480
Italy	383.1	19934	6.41	2.412	158.8	0.0774	2052	59.8	34314	2.656	0.1867
France	385.6	21314	5.84	1.552	248.4	0.1019	2437	66.0	36924	3.764	0.1582
Rest of World	8259.9	321253	2.85	2.585	3195.5	0.1053	30352	2893.4	10490	1.104	0.2721
World	35094.4	1098771	4.93	2.757	12730.4	0.1250	101828	7124.5	14293	1.787	0.3446

Source: BP Statistical Review, World Bank

Table 11.4 CO_2 output, Primary energy consumption, GDP and Population 2013