The ever-changing global environment: not a reason for complacency

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Politicians, scientists and the news media have much to say about current changes in our environment, and especially on climate change. This contribution considers current environmental change in the context of past changes in the Earth's environment, and current views of this change in relation to the changing scientific perceptions of how the Earth's environment has changed in the past.

Evolution and revolution in geological and biological thought. Starting in the eighteenth century, developments in the natural sciences led to the development of a 'Uniformitarian' view of the history of the Earth, and of the methods by which this history should be studied, in contrast to the cluster of views that were termed 'Catastrophism'. These terms were coined by Whewell in 1832, and crystallised the views of Lyell, who interpreted past events by studying present-day events, and of the contrasting perceptions of Cuvier and Sedgwick among others who believed that the geological changes revealed by stratigraphy occur by processes which are not happening today, e.g. diluvialism which attributed many phenomena observed in geology to the biblical flood [1]. A part of catastrophism is directionalism, whereby the Earth's components have undergone a directional change [1]. This was especially seen in the fossil record of animals 'ending' (for the moment) with *Homo sapiens.* It must be emphasised that both of these views allow for change with time in the Earth's surface and its fossil components, i.e. are evolutionary in the sense of change with time.

Lamarck, and Darwin and Wallace, accepted biological evolution, i.e. change with descent as opposed to origin (creation) without subsequent change, but differed in the mechanism involved. The Darwin-Wallace perception of evolution by natural selection of heritable variation, as opposed the Lamarckian inheritance of characters which changed in direct response to environmental challenges, is, of course, the current view [2]. The uniformitarian versus catastrophist views of Earth history have echoes in the recent controversies over the punctuated equilibrium as opposed to the gradualist view of evolution by natural selection [2]. Regardless of the extent of a relatively constant rate of change as opposed to episodic changes during biological evolution, it is clear that there were major extinction events at intervals throughout the last 650 million years for which the fossil record is adequate to yield evidence of the extent of biological diversity. Thus, regardless of the time course (gradual, or by punctuated equilibrium) of change in lineages of organisms through the time between mass extinctions, the mass extinctions represent 'catastrophes' which can be broadly contrasted with essentially uniformitarian changes in the intervening periods following evolutionary radiation after the extinction event [2].

The causes of these mass extinctions is a matter of current debate, as indeed is what qualifies as a mass extinction, and thus how many such events there have been since the fossils in the stratigraphical record became adequate to record them. Five major extinction events have been recognised at or near the end of the Ordovician, Devonian, Permian, Triassic and Cretaceous epochs at, respectively, 443, 354, 248, 206 and 65 million years ago. These mass extinctions involved the loss of at least 65% of species, and they have been related to major environmental changes on Earth, such as large-scale vulcanism, or a meteorite impact, both of which have been suggested as a cause of the end-Cretaceous mass extinction which included the demise of dinosaurs. Weaker, because less mechanistically plausible, arguments for the causes of these Phanerozoic mass extinctions have involved changes in climate and in sea level [2].

One process which must have had a major effect on biota was the gradual oxygenation of the Earth which occurred starting about 2,300 million years ago[3,4]. This build-up of oxygen was not contemporaneous with the evolution of oxygen-producing photosynthesis in cyanobacteria, since there were inorganic reductants which consumed the oxygen which would otherwise accumulate when the organic carbon produced in parallel with the oxygen was buried rather than re-oxidised in respiration.

When these inorganic reductants had been exhausted, oxygen built up locally in the surface ocean and the atmosphere and only subsequently in the deep ocean [4-6]. This 'oxygen revolution' had a major influence on biota. Before oxygen build-up began the organisms had not been exposed to oxygen, and the interaction of oxygen with redox reactions yields toxic, mutagenic, oxygen radicals. The main source of these oxy-

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gen radicals in cells before the advent of free oxygen was the photochemical influence of ultraviolet radiation. More significantly, ultraviolet radiation is absorbed by, and damages (chemically changes) informational macromolecules. While oxygenation increased the potential for damage by oxygen free radicals, the photochemical (involving ultraviolet radiation) production of ozone in the stratosphere forms an ultraviolet-absorbing shield which limits the ultraviolet flux to the surface of the ocean and to the land surface, and this restricts ultraviolet damage to cells. Oxygenation thus had very great effects on the potential for damage to informational macromolecules, increasing effects from oxygen free radicals but reducing damage from ultraviolet radiation.

Oxygen also had a very important effect on biota by providing an electron acceptor for respiration which permits the greatest quantity of useful energy to be obtained from oxidation of a given substrate molecule. The increased oxygen level, and increased oxygen:carbon dioxide ratio, in the atmosphere and much of the rest of the surface biosphere impacts negatively on the primary productivity of photosynthetic organisms via effects of the core carboxylation enzyme ribulose bisphosphate carboxylase-oxygenase. Other biological influences of oxygen include a decrease, by oxidation to the less soluble ferric form, in the availability of iron, and hence of phosphorus by the binding of phosphate to ferric iron compounds; these effects are probably major feedback controls, via changes in primary productivity, on the oxygen content of the biosphere. These examples show that oxygenation of the biosphere had a very great biological impact. The fossil record does not permit quantitation of the impact on speciation and extinction, but it was probably of a magnitude which compares with the subsequent 'big five' extinctions [4].

Returning to changes in our understanding of the age of the Earth and changes in its environment over the last century and a half, the age of the Earth was deduced to be less than 100 million years in the nineteenth century on the assumption that the Earth had been steadily cooling since it formed as a molten body, with heat, ultimately derived from gravitational energy, transmitted radially within the Earth purely by conduction. The discovery of radioactivity and its decay at the end of the nineteenth century gave another significant source of heat for the Earth, and also permitted radiometric dating showing that the Earth is some 4.5 billion years old [2]. Radioactive heating is also now known to be the ultimate driving force for plate tectonics, suggested by Wegener in the early twentieth century on the basis of a wide range of lines of evidence as continental drift, but without an obvious mechanism [2].

Another consideration is the temperature at the Earth's surface, which is a essentially a result of the temperature needed for black body radiation by which long-wavelength radiation dissipates energy from the Earth's surface at the same rate as that at which it arrives as short-wave radiation from the sun. In the early nineteenth century Fourier, and Tyndall, pointed out that polyatomic (more than two atoms) atmospheric gases, such as water vapour and carbon dioxide, absorb radiation in the wavelength range of the black body radiation from the Earth, and are important in maintaining the Earth surface temperature higher than that if there were no such 'greenhouse gases' [7]. At the end of that century Arrhenius made accurate calculations of the extent of this greenhouse effect, and it is now known that the Earth's mean surface temperature of 288 K would only be 256 K in the absence of 'greenhouse gases' [2].

The role of the greenhouse effect in maintaining the Earth's surface in the temperature range at which liquid water could occur continuously over the last 3.8 billion years was further emphasised when it became known that the sun has increased its output of electromagnetic energy by more than 20% over that time. There must have been a decrease in the greenhouse effect over time to account for the known Earth surface temperatures over the last 3.8 billion years. The surface temperature of the Earth is also controlled by its albedo, a function of cloudiness and ice cover. Ice cover is in part dependent on the extent of heat transfer from the tropics to poles, which is in part a function of the distribution of land and sea as a result of plate tectonics in the long-term Wilson cycle. Over most of the last 3.8 billion years we now know that the Earth spent more of its time in a hot-house state, with little or no ice, rather than in an ice-house state[2].

Another very significant insight into the control of surface temperature of the Earth's surface came from Milankovich. His work involved mathematical analysis of the changes in eccentricity of the Earth's orbit, the changes in obliquity (the inclination of the axis of the Earth's rotation to the plane of the orbit), and the precession of the equinoxes. These astronomical phenomena alter the solar radiation reaching the Earth, and their periodicities of about 96,000 years (eccentricity), 41,000 years (obliquity) and 21,000 (precession) have been related to changes in aggregate ice volume in the recent (Pleistocene) glacial-interglacial cycles [2]. There is also the likelihood that these periodicities have influenced climate over much longer time periods.

The atmospheric gas composition, dust deposition and surface temperatures have been determined for the last 420,000 years, including the last four glacial episodes, by analysis of the Vostok ice core in Antarctica [8]. Temperature and dust deposition, with temporally restricted atmospheric gas composition, data are available for the last 740,000 years for the Dome C ice core [9]. These analyses have shown that the glacial periods have lower atmospheric levels of the greenhouse gases carbon dioxide, nitrous oxide and methane than the warmer interglacial periods. More recent work has demonstrated a greater parallelism of the temperature changes and the greenhouse gas changes than was found in earlier analyses [10]. The available time resolution does not show whether the greenhouse gases change before, in precise parallel with, or after, the change in temperature. Even if the greenhouse gas changes do precede the temperature changes, a reason for the greenhouse gas changes must be sought if they are to be considered as at least a partial cause for the temperature changes.

One suggestion is that the increased atmospheric dust content, as also recorded in the Vostok ice core, in glacial episodes increased carbon dioxide drawdown from the atmosphere into the surface ocean through greater primary productivity and sedimentation of the resulting organic carbon. An increase in marine primary productivity, which is supported by some but by no means all independent evidence from the natural abundance of stable isotopes in marine sediments [11], is proposed to have been caused by iron in the dust which relieved the constraints on primary productivity in the high nutrient, low chlorophyll areas with low pigment content (biomass of primary producers) and primary production, yet relatively high nitrate and phosphate concentrations. Today the largest of these regions is the Southern Ocean. There are still doubts about this suggestion. Regardless of a causal effect of changes in greenhouse gas concentrations in producing temperature changes, the greenhouse gas changes could amplify changes in temperature as a result of, for example, changes in solar energy input via the Milankovic cycles [8,9].

These environmental changes, and especially the Pleistocene glaciations and the cooling which preceded them following the Late Palaeocene Thermal Maximum, have had profound influences on biodiversity, biogeography and biogeochemical cycles. However, as far as global speciation and extinction are concerned the Pleistocene did not have major influence until the last 50,000 years or so when human influences are probably at least partly responsible for, as an example, the loss of many large, and other slowly-reproducing, mammals from cooler parts of the world [12-14].

These considerations show that there have been very great environmental changes in the past which gave rise to mass extinctions and subsequent evolutionary radiation. The question that we now address is whether we are currently in the sixth, anthropogenically induced, mass extinction event if there have already been five (the Big Five) mass extinctions [15].

Present and Future Environmental Change: Impact on Biota. It is generally believed that there has been a significant increase in the temperature at the Earth's surface over at least the last century. The atmospheric concentration of the greenhouse gases carbon dioxide, methane and nitrous oxide has increased at an accelerating rate since about 1750, in parallel with increasing industrialisation and changed land use [16]. In the last few decades increases in these three naturally occurring greenhouse gases have been paralleled by increases in the purely anthropogenic chlorofluorocarbons [16]. A causal relationship between the increased concentration of greenhouse gases and the increase in the mean global temperature is logically defensible and is much more likely to be true than not [17,18]. However, there are feedback mechanisms which could counter, or amplify, the effect of increased greenhouse gas concentrations on global temperatures [16]. The possibility of such effects has led some policy-makers, especially in the United States, to use such uncertainties to delay action which could mitigate warming.

One argument which can be used to minimize the role of the increased 'permanent gases' in the atmosphere is the complexity of the hydrological cycle which controls the amount of water in the atmosphere. Water is the most quantitatively significant of the greenhouse gases, and accounts for about two-thirds of the present greenhouse effect of the atmosphere. The hydrological cycle also relates to the extent of cloudiness: increased cloudiness increases the Earth's albedo, decreasing the solar radiation reaching the Earth's surface and thus lowering the surface temperature (negative feedback effect), and vice versa [16]. Increased temperature resulting from an increased concentration of the 'permanent' greenhouse gases increase evaporation rates, and hence the extent of the greenhouse effect attributable to water vapour since evaporation (including transpiration from plant canopies) increases to a greater extent than rainfall.

Significant constraints on models of the effects of increased 'permanent' greenhouse gases on climate can be achieved by considering past climate change and atmospheric composition. Modelling the climate at the Last Glacial Maximum some 18,000 years ago shows that Milankovic cycle parameters can not reproduce southern hemisphere glaciations when the carbon dioxide is set at post-glacial concentrations (about 280 molecules carbon dioxide per million molecules of total permanent gas in the atmosphere), but can reproduce them when carbon dioxide is set at the concentrations known to have occurred at the Last Glacial Maximum, i.e. as little as 180 molecules carbon dioxide per million molecules of permanent gas [16]. However, we are now, at some 375 molecules carbon dioxide per million molecules of permanent gas, outside the range of carbon dioxide concentrations found over at least the last 420,000 years, so comparisons with the past to constrain the models of the future environment must go back well beyond 420,000 years[16].

As to biotic effects of the increases in carbon dioxide and in temperature, it is often difficult to tease out the influence of carbon dioxide and temperature from other direct and indirect anthropogenic effects. Before anthropogenic influences on carbon dioxide and temperature there were extinctions of large terrestrial vertebrates over a period of tens of thousands of years toward, and just after, the end of the last glacial episode, some of which may be attributable to human influences [12-14]. Certainly these large animals had survived earlier late-glacial periods. There are certainly very significant extinctions occurring today, for example in Britain [15], which have led to suggestions that we are in the sixth global mass extinction.

It is not clear how much of these extinctions can be attributed directly to anthropogenic environmental change. There are certainly grounds for believing that there are increased disease risks for aquatic and terrestrial organisms as a result of global change [19]. An interaction between global and local changes in the atmosphere involves the photochemical generation of tropospheric ozone using nitrogen oxide radicals, 70% of which are anthropogenic and occur in industrialised areas, and volatile hydrocarbons [20,21]. The production of isoprene, a major tropospheric hydrocarbon, by some plants is inhibited by increased carbon dioxide, so that air quality in terms of a lower ozone concentration may be increased with increasing carbon dioxide [22]. However, it has been shown the build-up of soil organic carbon under increased carbon dioxide, which acts as a negative feedback on the increasing atmospheric carbon dioxide, is inhibited by ozone [23]. Regardless of the effects of ozone on the removal of CO_2 from the atmosphere into long-term (years-decades-centuries) storage, it is clear that tropospheric ozone could also have significant effects on the relative fitness of species of plants and animals.

Conclusions. Current evidence suggests that there has been a significant increase in mean global temperature over the last century, and that the increased greenhouse gas concentration is causally related to this increase. This temperature increase will almost certainly continue over the century and more, and will interact with other components of environmental change and aspects of human activities in altering the potential for ecosystem services for the support of man and other biota and in leading to extinctions. Clearly biota have withstood extreme events in the previous great extinctions, and the extinction of many species of micro-organisms would be very unlikely even as a result of very extreme events [3]. However, this continuity of life, and even of many higher taxa of large organisms, through mass extinctions, should not cause us to think that global environmental change is not a problem. Life survived earlier extreme events, but did not have man's impact to contend with. From an anthropocentric viewpoint environmental change is a significant threat to at least our current way of behaving, and the survival of life through earlier major traumatic events does not mean that our civilisation can survive.

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