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SEA TURTLES AND THE GREENHOUSE EFFECT

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INTRODUCTION

For more than three decades scientists have predicted that global warming ("the greenhouse effect") will follow from Man's accelerating industrial and agricultural activities. In the past couple of years increasing confidence of prediction (stemming from sophisticated computer modelling) has combined with media attention to stimulate high level political interest, even though clear *direct* evidence of warming is still lacking.

Briefly, the greenhouse effect is caused by rising levels of the so-called "greenhouse gases"; carbon dioxide, methane, chlorofluorocarbons (CFCs – which also damage the ozone layer) and nitrous oxide (in descending order of importance). These gases allow the passage of short wave length radiation more readily than long wave radiation. Since solar energy reradiated from the Earth is of longer wavelength than incoming energy, the gases act to retain heat, so shifting the average global temperature upwards. Carbon dioxide accumulation is associated with the burning of fossil fuels and the destruction of forests. The causes of methane increases are more obscure, but rising areas of rice paddies, intensive rearing of belching ruminant cattle, the fermenting waste tips of rich countries and even enhanced numbers of termites which release methane as a bye-product of wood digestion have all been invoked (Pearce, 1989). CFCs and nitrous oxide are produced as a result of industrial activities, particularly in refrigeration and road transport.

At present carbon dioxide is the most important greenhouse gas, and it is the capacity of the world ocean for buffering or absorbing carbon dioxide that explains the lack of observed greenhouse effect so far. Carbon dioxide is "fixed" biologically at the sea surface, either as calcium carbonate in skeletal systems, or as living carbon which is eventually lost to deep water by death or defaecation. Transfer of atmospheric carbon to sea sediments has created a lag between the increased output of greenhouse gases following from the industrial, public health and agricultural revolutions of the past two centuries, and its expression in the form of increased temperatures. However, it is now agreed that the next 50-100 years will see an increase in average global temperature of some 2-6 deg. C. This will inevitably be accompanied by rises in sea level as ice melts and rainfall patterns change. Less consensus is as yet available concerning the likely extent of sea level rises. Estimates for increases by the year 2100 generally range from 0.5 to about 3.5 metres, though a few more alarming predictions have suggested rises of as much as 6 metres, which would involve substantial melting of the Antarctic and Greenland icecaps.

Global warming, with its associated changes in patterns of weather and oceanic circulation will have profound effects on the world's vegetation and animal life, so why should attention be particuarly focussed upon sea turtles? Although sea turtles are individually mobile, in that they travel hundreds or thousands of kilometres in a year, they have features of their reproductive strategy which would, *a priori*, make them particularly vulnerable. Firstly, they lay their eggs on sandy beaches to which they are apparently extremely faithful. The evidence for this fidelity has been derived almost exclusively from the tagging of adult female turtles which return to the same beach each time they breed. It is generally assumed that hatchling turtles return as adults to the beach of their hatching (Carr, 1967), but direct evidence to support this hypothesis is still lacking, mainly because no tagging system has yet allowed hatchlings to be identified as adults. Mistakes in maternal homing behaviour do occur, and presumably have allowed colonization of new habitats in the past (Bowen *et al*, 1989), but such colonization is apparently slow, since none of the Caribbean habitats which were fished out by European seafarers in the 16th, 17th and 18th centuries have been reinvaded despite protection and attempts at reintroduction over the past 40 years. It would appear, therefore, that turtles will be essentially limited to their present breeding sites during the course of the development of global warming.

Secondly, in the decade since Yntema and Mrosovsky (1979) showed that the sex of Loggerhead Turtle *(Caretta caretta)* hatchlings was determined by incubation temperature rather than genetically, it has become apparent that sex is environmentally determined in all sea turtle species, with as little as 4 deg. C making the difference between a wholly male and a completely female clutch.

Thirdly, turtles are long lived animals which are particularly slow to mature. In this respect the Green Turtle *Chelonia mydas* has been best studied. Females may take 30-50 years to reach sexual maturity in the wild and survive for a similar period thereafter. Much of the development of the greenhouse effect may therefore take place during the lifetime of turtles hatching on beaches around the world at present.

The rest of this paper consists of an attempt to evaluate the likely impact of various features of the greenhouse effect upon populations of sea turtles, bearing in mind the antiquity of living species, all of which appear to have lived throughout the Quaternary era (*ca* 2 million years ago to the present), with at least the Green and Leatherback turtles *(Dermochelys coriacea)* having origins in the Tertiary period which started 60 million years ago and ended with the start of the Quaternary (Gaffney, 1984; Bowen *et al*,1989). The long duration of individual turtle species (which contrasts strongly with the much more rapid speciation of birds and mammals) can be combined with current palaeoclimatological knowledge to give some idea of turtle species' past resilience when faced with environmental change.

TEMPERATURE INCREASE

Superficially, temperature-dependent sex determination would appear to make turtles appallingly vulnerable to the greenhouse effect. Surely if the average global temperature rose by as much as 6 deg. C. then a single sex would be produced on all breeding beaches (with beach fidelity preventing an escape to cooler latitudes) and all turtles would disappear a few decades later after a fruitless search for mates? Several factors deny such finality. Firstly, the various greenhouse models all agree in this respect; though average temperatures may rise, the increases are *not* evenly distributed across the globe. The more extreme of current models which predict an average rise of 5-6 deg. C involve increases of 10-12 deg. C at the poles, but only 1-2 deg. C at the equator. Less extreme models involve proportionally smaller equatorial increases. A high proportion of turtle breeding beaches are in or near the tropics, so although sex ratios might be somewhat skewed, it is most unlikely that temperatures would rise sufficiently to abolish a sex. The situation for warm temperate breeding areas (e.g. the Mediterranean, south eastern U.S.A.) is less encouraging.

Secondly, as may be seen from the discussion of Mrosovsky (1980), incubation temperature is strongly affected by nest site selection and the timing of egg laying during the breeding season. We do not know how much (if any) control the female has over incubation temperature. Under warmer conditions, might females be more prone to lay eggs earlier in the season, seek shadier nesting sites, or dig deeper (= cooler) nests? Also, not enough is known about the flexibility of the pivotal temperature range over which the hatchlings' sex is controlled). Most turtle species breed over a fair latitudinal range, particularly the Loggerhead, *Caretta caretta.* Presumably the populations breeding in cooler latitudes have rather lower pivotal temperatures (again, evidence is lacking), but are latitudinal differences in pivotal temperature genetically or phenotypically determined? If there is a phenotypic component it is feasible that the thermal history of an adult female may affect the pivotal temperature of her clutches, so that a female exposed to a warmer environment might lay eggs with a higher pivotal temperature.

Palaeoclimatology (which relies on a battery of techniques, including measurement of ^{16}O; ^{18}O ratios in the shells of fossil foraminiferans, study of palaeomagnetism and fauna/flora analysis) gives similarly conflicting messages. Broadly speaking, information about climate during the Quaternary is good and rapidly improving, but most data have been obtained for middle latitudes (currently cool temperate in nature). More attention is now being paid to the Tertiary, but inevitably detail is more difficult to obtain the further back in time investigation is pursued.

During the Tertiary, global temperatures were apparently stable and high, peaking in the Eocene (40-50 million years before present) at about 22°C, but steadily falling thereafter to a value of around 12.5°C at the beginning of the Quaternary (Nilsson, 1983). The Quaternary has been characterized by pronounced fluctuations in global temperatures. These changes are now known to be driven by the Croll/Milankovitch astronomical cycles which reflect:

a) changes in the shape of the earth's orbit (96,000 year periodicity)
b) changes in the earth's axis tilt from 21.5° to 24.5° and back (42,000 year periodicity).
c) equinoctial precession ("wobble") (21,000 year periodicity)

These cycles control the amount of solar energy reaching the earth's surface and, during the Quaternary, have interacted to produce cold glacials ("ice ages") and warm interglacials. During glacials the amount of ice at the poles rises, sea levels fall and so do atmospheric carbon dioxide levels (for reasons which are not yet clear). A reverse sequence of events takes place during interglacials, so the greenhouse effect is likely to produce a "super interglacial" and delay the onset of the next ice age. The longest periodicity of the Milankovitch cycles appears to be most important and intervals between ice ages have been about 100,000 years. During glacials, global average temperatures have dropped below 0°C; currently we are close to the end of an interglacial with a global average surface air temperature of about 9°C (it must be remembered that such averages integrate the atmospheric temperatures of all latitudes and all seasons). Global averages must be interpreted with care; equatorial temperatures have varied much less than the global average. However, Emiliani (1972) reported that Caribbean surface sea temperatures have been as much as 1 deg. C warmer in the past 500,000 years than the present 27°C (as well as 5 deg. C colder!) and this implies air (and presumably turtle nest) temperatures several degrees higher than at present. Even within the present interglacial, temperatures have apparently been at least 2 deg. C higher in the Mediterranean area (ca. 7,000 years ago). On balance it seems probable that sea turtles have previously encountered temperatures at least as high as are likely to be caused by the greenhouse effect. It is even more certain that they have encountered lower temperatures during ice ages without suffering extinction through production of one-sex egg clutches! It might be argued that the temperature increases induced by the greenhouse effect will occur more rapidly than any previous alterations encountered by turtles. However, the realization in recent years that volcanic eruptions and meteorite impacts can affect climate suddenly, profoundly and for substantial periods make such arguments relatively weak.

Global warming will not only affect the breeding phase of sea turtle life history. With the exception of the Leatherback turtle, living sea turtles are limited to waters of about 18-19°C or higher; when temperatures fall below these levels they either retreat to warmer waters, become torpid (Felger *et al*, 1976; Carr *et al*, 1980), and cease feeding (Davenport, *et al*, 1989). The greenhouse effect is likely to expand the potential foraging areas open to sea turtles (though whether Man allows enough turtles to survive to take advantage of this opportunity is less certain!). The Leatherback, almost certainly an endothermic ("warm blooded") animal when living in cool waters (Pritchard, 1969; Friar *et al*, 1972; Greer *et al*, 1980), currently forages for jellyfish as far north as Labrador, the U.K. and Western Norway in warm summers. Global warming should permit more frequent appearances in northern waters, but again this must be set against the decline in Leatherback numbers due to Man's more direct influences.

RISING SEA LEVEL

Much information is now available about past sea levels, interpretation being based upon geological studies of fossil coral reefs in areas thought to have avoided geologically recent glaciation and tectonic activity (e.g. New Guinea), combined with analysis of ^{16}O; ^{18}O ratios in the shells of fossil foraminiferans (which allow estimates of the relative volumes of water in the sea and in ice sheets). Sea levels have varied greatly during the past 160,000 years, from as much as 120 metres below present levels, during a glacial period (Shackleton, 1987), to 6 metres above current sea level. Clearly turtles have tolerated sea level changes greater than those predicted for the next 50-100 years. Sandy beaches are mobile, dynamic structures, especially surf-built beaches exposed to oceanic swells. Material can be added or subtracted rapidly, so a beach can easily move inland as sea level rises – but only if the land is not itself covered by the rise! Some turtle breeding beaches on low islands may disappear, but overall it seems improbable that predicted sea level changes will be as damaging as hurricanes or developers.

CHANGES IN OCEANIC CURRENTS

Ocean currents are important to turtles. Hatchlings of some species probably spend much of their early life drifting in oceanic gyres as part of weedline communities (Carr, 1987), while Archie Carr long ago suggested that adult turtles (particularly *Chelonia mydas)* might navigate their way to their natal beaches by following chemical cues ("smells") brought to them by currents. Surface oceanic currents owe much of their direction and strength to wind patterns. Winds, in turn, are strongly affected by temperature gradients. Global warming is likely to reduce wind velocities and thereby gradually slow oceanic currents, conceivably disrupting the life history of the more oceanic species (Green, Leatherback), but probably having less influence on the coastal species (e.g. Loggerhead and Hawksbill, *Eretmochelys imbricata).* Effects on turtle species are difficult to predict, not least because so little is known of their methods of navigation. As well as the possibility of olfactory navigation mentioned above, solar, celestial and geomagnetic mechanisms have all been suggested. None of the clues which such navigation methods rely upon are entirely stable; the Earth's magnetic field changes strength and direction over quite short time scales (<100 years), and even reverses frequently by geological or evolutionary standards (reversals happen every 10,000-100,000 years and take ca. 2000 years to complete). The star map shifts over the centuries, and even the sun's position in the sky varies with the Milankovitch cycles. However, of all likely navigation aids, the oceans' currents are probably the most labile, changing noticeably through natural causes during the life of a single turtle generation. Unless currents are totally altered by the greenhouse effect it seems unlikely that consequence to turtles will be critical.

CONCLUSIONS

In a hypothetical world unaffected by Man, a warming of the globe by 1-2 deg. C at the equator and perhaps 6 deg. C. in middle latitudes would almost certainly be beneficial to sea turtles. In a sense turtles are relict species, survivors of a warm Tertiary era, confined to the tropics by the unstable climates of the Quaternary. Prolongation of the present interglacial could only help them.

However, in the past few centuries Man has had a considerable impact on turtle populations. Many have been destroyed by fishing, by the introduction of predators (e.g. dogs, rats, pigs), by egg collection, by beach development, by incidental capture in fishing nets or by pollution (particularly plastic garbage – Carr, 1987). While conservation legislation and initiatives have burgeoned, so have the pressures of exploitation; nowhere is it possible to point to a growing sea turtle population. The Kemps Ridley *(Lepidochelys kempi)* is probably the only species in imminent danger of extinction, but the recent crash of the Trengganu Leatherback rookery (due to unremitting egg collection), and the continued massive kills of Hawksbills and Green Turtles in the Far East (e.g. Davenport, 1988) give little encouragement to conservationists.

Much of the resilience of sea turtle populations in the past has probably relied upon the existence of large numbers of relatively separate populations around the warmer regions of the globe, each containing substantial numbers of breeding animals. Such populations relied on high egg and hatching numbers to sustain recruitment (effectively the high numbers saturated the appetite of natural predators during the vulnerable nesting, hatching and swimming frenzy stages of the life history). Man's activities have removed whole populations and continue to reduce the size of those that remain. The genetic material on which selection could act to alter responses to environmental conditions has been much depleted. In these circumstances it is probable that the greenhouse effect will have detrimental consequences (particularly to populations furthest from the equator), but it seems doubtful whether it will be possible to discern such consequences against a background of continued human improverishment of sea turtle environments.

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