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EARTH SYSTEM FUNCTIONING IN THE ANTHROPOCENE: HUMAN IMPACTS ON THE GLOBAL ENVIRONMENT

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> Hurt not the earth, neither the sea, nor the trees.
> *Revelation* 7:3, the Holy Bible

> Most Gracious is Allah, Who reveals Himself
> In the Qur'an, in man's Intelligence
> And in the nature around man.
> Balance and Justice, Goodness and Care,
> Are the Laws of His Worlds...
> Summary from *Surah* 55, the Holy Qur'an

> Without the willow, how to know the beauty of the wind.
> Lao She, Buddhist monk

> We're only here for a short amount of time to do what we've been put here to do, which is to look after the country. We're only a tool in the cycle of things. ... (we) go out into the world and help keep the balance of nature. It's a big cycle of living with the land, and then eventually going back to it ...
> Vilma Webb, Noongar People, Australian Aborigines, from:
> *Elders: Wisdom from Australia's Indigenous Leaders*

1. *The Earth's Environment as a System*

Through the ages, humans have recognized two important features of the planet that we inhabit. First, the Earth is a single system that provides a hospitable environment for humans. Second, humans are an integral part of Earth itself, and not an outside force perturbing an otherwise pristine, natural world. Words and phrases such as 'balance', 'cycles', 'care ', 'hurt not the earth' and 'looking after the country' recognize the nature of the Earth System and important aspects of the human-environment relationship.

Modern science has added much detail and a quantitative underpinning to the notion that the Earth operates as a single, interlinked system. In the context of contemporary environmental change the term *Earth System* has come to mean the suite of interacting physical, chemical and biological global-scale cycles and energy fluxes that provide the conditions necessary for life on the planet (Oldfield and Steffen, 2004). Several features of this definition of the Earth System are important. First, the forcings and feedbacks *within* the Earth System are as important as the external drivers of change, such as variability in solar energy input. Second, biological/ecological processes are an integral part of the functioning of the Earth System and not merely the recipient of changes in physico-chemical systems. Finally, the functioning of the Earth System exhibits many modes of natural variability; human-driven changes interact with this natural variability in complex and sometimes mutually reinforcing ways.

The most well-known evidence for the behavior of the Earth as a single, interlinked system comes from the Antarctic ice core data. The Vostok ice core record (Petit *et al.*, 1999) provides convincing evidence for the systemic nature of the planetary environment, with properties and behavior that are characteristic of the system as a whole. In particular:

– The variation of climate, as represented by a proxy for local temperature (the oxygen isotope ratio, $\alpha^{18}O$), and of atmospheric composition, as represented by the concentration of the trace gases carbon dioxide (CO_2) and methane (CH_4) trapped in air bubbles in the ice, are closely coupled throughout the record (Figure 1, see page 401).

– The main maxima and minima of temperature and trace gas concentrations, which mark the alternation between glacial and interglacial conditions, follow a regular, cyclical pattern through time, each cycle spanning approximately 100,000 years. The smooth changes in the eccentricity of the Earth's orbit act as the pacemaker for the observed periodicity but internal mechanisms within the Earth System drive the changes in climate and atmospheric composition.

– The range, over which isotopically inferred temperature and trace gas concentrations vary, is tightly limited. Throughout all four cycles, each interglacial gives rise to similar peak values; each glacial culminates in comparable minima. This points to a high degree of self-regulation within the Earth System over the whole of the time interval recorded in the Vostok ice core.

The recent publication of the ice core data from the Dome Concordia site (EPICA community members, 2004) extends the Antarctic record back to 740,000 years. The data from the later part of the core confirm the Vostok record, while the earlier data show some intriguing differences. For example, the interglacial periods were not as warm then, but the Earth spent more time in the warm mode. Also, the main mode of periodicity was not so clear in the earlier part of the record, having features of both the 40k yr periodicity of the pre-900k Quaternary period and the pronounced100k yr periodicity of the Vostok record. In terms of the tight coupling between greenhouse gas concentration and climate, and the clear upper and lower bounds on temperature and gas concentrations, the Vostok and Dome C data are in good agreement.

The amplification and modulation of the external forcing of solar variability by the complex array of feedbacks and forcings within the Earth System is crucial for maintaining Earth's life support system. For example, without the greenhouse gases that naturally occur in the lower atmosphere, the Earth's surface temperature would be about 30°C lower than it is now, and much more harmful ultraviolet radiation would penetrate to the Earth's surface without the layer of ozone in the stratosphere. However, there is now strong evidence that the growth in the numbers and activities of people – the burgeoning 'human enterprise' – has created a geophysical force of global scale that is beginning to interfere with the internal forcings and feedbacks within the Earth System (Andreae *et al.*, 2004).

2. *The Human Enterprise from an Earth System Perspective*

Human-driven environmental change has operated largely at the local scale for nearly all of human history. This situation changed with the Industrial Revolution in the late eighteenth century. The introduction of fossil fuel-based energy systems transformed economic systems, the structure of human societies and the human capacity to affect the planet. The new energy system increased our capacity to extract, consume, and produce (Grübler, 1998), triggering a sharp and sustained rise in the global population, from just under one billion people in 1800 to a projected nine billion by 2050 (UN Population Division 2000 and Lutz, this volume). In addition, changes in lifestyle and consumptions patterns in most societies around the world have led to a global escalation in both total and per capita demands for Earth's resources, including fish stocks, inert materials, freshwater, and prime agricultural soils (Dicken, 1992; Tolba and El-Kohly, 1992). The resulting impacts on the Earth System are both *cumulative* – changes that occur on a local scale but are so ubiquitous around the planet that when aggregated have a global-scale effect (e.g., Turner *et al.*, 1990) – and *systemic*, such as changes in atmospheric composition and climate. Historically, cumulative changes have had more impact on the environment, but systemic changes are expected to accelerate through this century.

Figures 2 and 3 (Steffen *et al.*, 2004b) capture graphically the profound transformation of the human enterprise and its growing impact on the Earth System. The change in the human enterprise over the past few hundred years is shown in Figure 2. The temporal scale begins before the start of the Industrial Revolution and the spatial scale is global. Although this masks important regional differences in trends, from the perspective of the Earth System, global-scale indicators are appropriate. Figure 3 shows the impacts of the changing human enterprise on the structure and functioning of the Earth System.

These two sets of plots together represent what is often called *global change*. Figure 2 shows the human component of global change, while Figure 3 depicts the environmental component; the latter is often called *global environmental change*. In reality, these two components are strongly coupled and indeed are parts of the same system – the Earth System. A further important distinction is between environmental change at the global scale and regional and local changes to the environment. This distinction will be made clearer via specific examples later in the paper.

Several features of Figures 2 and 3 are noteworthy. First, nearly all of the indicators in Figure 2 either began to change around 1950, or changed their rate significantly at that time. Clearly the human enterprise underwent a profound reorganization and acceleration after the end of the Second World War. Many of these socio-economic changes are associated with the phenomenon of *globalization*. Second, the human imprint on the Earth System is discernable in every component of the planet – oceans, coastal zone, atmosphere, land. Third, the implications of this human imprint go far beyond the well-known effects on climate to impact on a wide range of Earth System functions, including the hydrological cycle, the cycles of important chemical elements and the dynamics of the marine and terrestrial biospheres. Global change is more than climate change.

Figures 2 and 3 suggest that the *rates* of the human-driven changes to the Earth System are as important as their *magnitudes*. Figure 4, showing the rise in atmospheric CO_2 concentration, is a good example of this comparison. The Vostok ice core data (Petit *et al.*, 1999) show that the CO_2 concentration has varied naturally in the past and has shown rapid

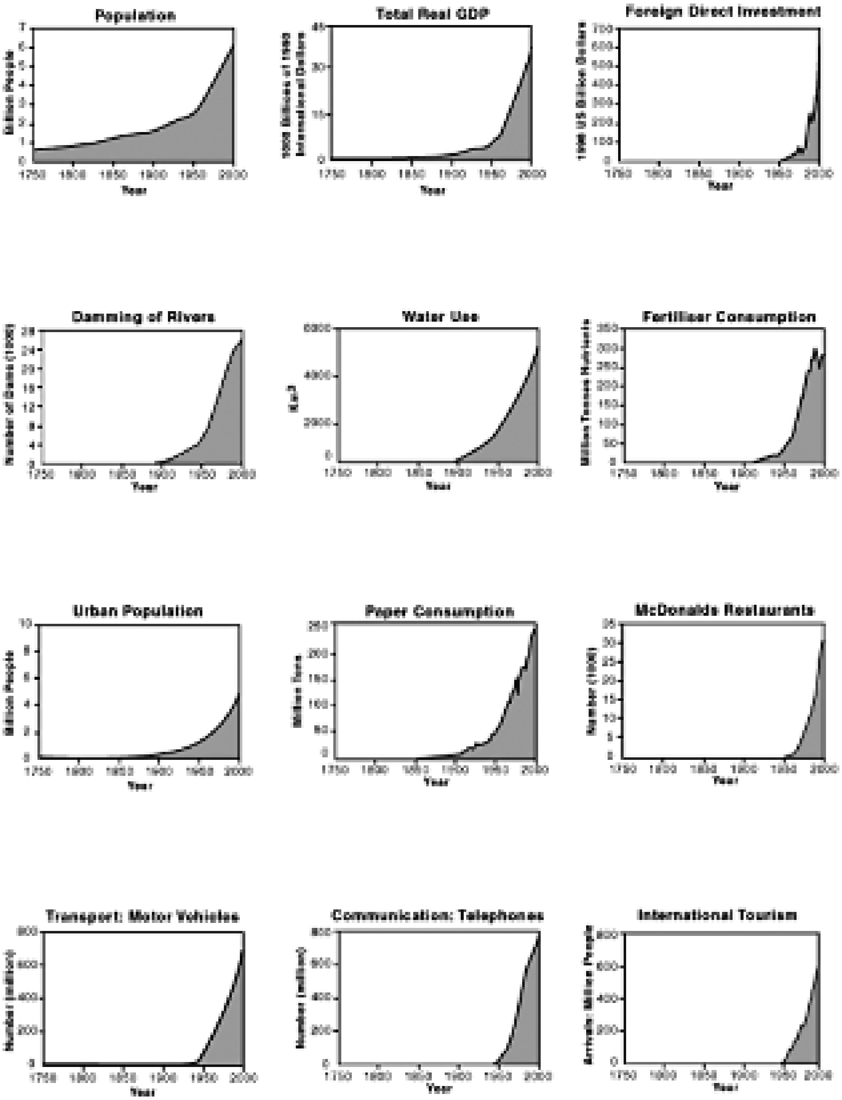

Fig. 2. The increasing rates of change in human activity since the beginning of the Industrial Revolution (Steffen *et al.*, 2004b). Significant increases in the rates of change occur around the 1950s in each case and illustrate how the past 50 years have been a period of dramatic and unprecedented change in human history. (US Bureau of the Census, 2000; Nordhaus, 1997; World Bank, 2002; World Commission on Dams, 2000; Shiklomanov, 1990; International Fertilizer Industry Association, 2002; UN Centre for Human Settlements, 2002; Pulp and Paper International, 1993; MacDonalds, 2002; UNEP, 2000; Canning, 2001; World Tourism Organization, 2002).

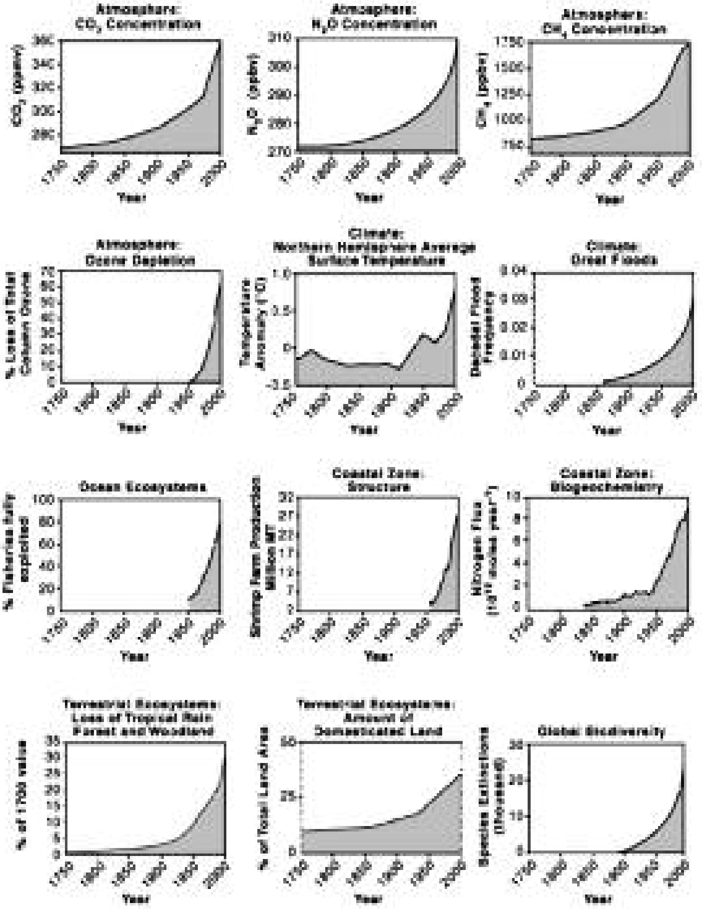

Fig. 3. Global-scale changes in the Earth System as a result of the dramatic increase in human activity (Steffen *et al.*, 2004b): (a) atmospheric CO_2 concentration (Etheridge *et al.*, 1996); (b) atmospheric N_2O concentration (Machida *et al.*, 1995); (c) atmospheric CH_4 concentration (Blunier *et al.*, 1993); (d) percentage total column ozone loss over Antarctica, using the average annual total column ozone, 330, as a base (Image: J.D. Shanklin, British Antarctic Survey); (e) northern hemisphere average surface temperature anomalies (Mann *et al.*, 1999); (f) decadal frequency of great floods (one-in-100-year events) after 1860 for basins larger than 200,000 km^2 with observations that span at least 30 years (Milly *et al.*, 2002); (g) percentage of global fisheries either fully exploited, overfished or collapsed (FAOSTAT, 2002); (h) annual shrimp production as a proxy for coastal zone alteration (WRI, 2003; FAOSTAT, 2002); (i) model-calculated partitioning of the human-induced nitrogen perturbation fluxes in the global coastal margin for the period since 1850 (Mackenzie *et al.*, 2002); (j) loss of tropical rainforest and woodland, as estimated for tropical Africa, Latin America and South and Southeast Asia (Richards, 1990; WRI, 1990); (k) amount of land converted to pasture and cropland (Klein Goldewijk and Battjes, 1997); and (l) mathematically calculated rate of extinction (based on Wilson, 1992).

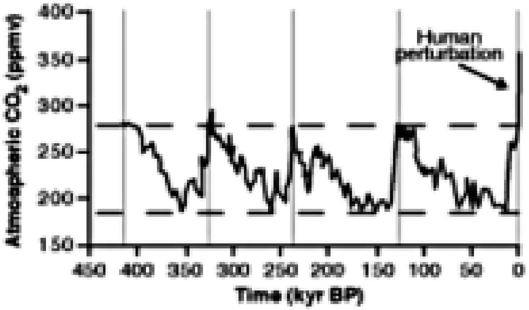

Fig. 4. Atmospheric CO_2 concentration over past 420,000 years from the Vostok ice core with the recent human perturbation superimposed (Petit *et al.*, 1999; Keeling and Whorf 2000).

changes in concentration on the geological timescale. However, within the limits of resolution of the ice-core records, the current concentration of 380 ppm appears to have been reached at a rate at least 10 and possibly 100 times faster than increases of CO_2 concentration at any other time during the previous 420,000 years (Falkowski *et al.*, 2000). Many other human-driven changes to the Earth System show similarly rapid changes compared to the pace of natural variability.

The remainder of this paper focuses on the extent of human impacts on the global environment over the past few centuries. We focus first on the transformation of the land surface; this is critically important for human well-being, as it is our primary source of food and provides the immediate environment in which we, as terrestrial creatures, must live. We then summarize the human impacts on the Earth System's two great fluids – the atmosphere and the ocean – before considering human-driven changes to climate and the hydrological cycle. We also consider the possibility of abrupt changes in major aspects of Earth System functioning, changes that are rapid on both geological and human timeframes and that could have catastrophic impacts on human societies.

3. *Transformation of the Land Surface*

Ever since humans have controlled fire and domesticated plants and animals, they have cleared forests to wring higher value from the land. About half of the ice-free land surface has been converted or substantially modified by human activities over the last 10,000 years. Undisturbed (or wilderness) areas represent 46% of the earth's land surface (Mittermeier *et al.*, 2003). Forests covered about 50% of the earth's land area 8000 years ago, as opposed to 30% today (Ball, 2001).

Concerns about transformations of the land surface emerged in the research agenda on global environmental change several decades ago with the realisation that land surface processes influence climate. Land-cover change modifies surface albedo and thus surface-atmosphere energy exchanges (Otterman, 1974; Charney and Stone, 1975; Sagan *et al.*, 1979); terrestrial ecosystems are sources and sinks of carbon and thus affect the global climate via the carbon cycle (Woodwell *et al.*, 1983; Houghton *et al.*, 1985; Ruddiman and Carmichael, this volume); and land cover controls the contribution of local evapotranspiration to the water cycle (Eltahir and Bras, 1996). A much broader range of impacts of land-use/cover change on ecosystem goods and services have now been identified. Of primary concern are impacts on biotic diversity worldwide (Sala *et al.*, 2000), soil degradation (Trimble and Crosson, 2000), and the ability of biological systems to support human needs (Vitousek *et al.*, 1997). Land-use/cover changes also determine, in part, the vulnerability of places and people to climatic, economic, or sociopolitical perturbations (Kasperson *et al.*, 1995). When aggregated globally, land-use/cover changes significantly affect central aspects of Earth System functioning, and thus are truly components of global environmental change, in addition to their local and regional impacts. All impacts are not negative, however, as many forms of land-use/cover changes are associated with continuing increases in food and fiber production, in resource use efficiency, and in wealth and well-being.

The area of cropland has increased globally from an estimated 300-400 million ha in 1700 to 1500-1800 million ha in 1990 (Ramankutty and Foley, 1999; Goldewijik, 2001), a nearly five-fold increase in three centuries and a 50% net increase just in the 20th century. The area under pasture, the estimates for which are more uncertain than for cropland, increased from around 500 million ha in 1700 to around 3100 million ha in 1990 (Goldewijk and Ramankutty, 2003). Forest area decreased from 5000-6200 million ha in 1700 to 4300-5300 million ha in 1990. Steppes, savannas, and grasslands also experienced a rapid decline, from around 3200 million ha in 1700 to 1800-2700 million ha in 1990 (Ramankutty and Foley, 1999; Goldewijk, 2001).

The Global Forest Resources Assessment 2000 (FAO, 2001b) estimated that the world's natural forests decreased by 16.1 million hectares per year on average during the 1990s; that is a loss of 4.2% of the natural forest that existed in 1990. However, some natural forests were converted to forest plantations. Gains in forest cover arose from afforestation on land previously under nonforest land use (1.6 million hectares per year globally) and the expansion of natural forests in areas previously under agriculture, mostly in western Europe and eastern North America (3.6 million hectares per year globally). The net global decrease in forest area was therefore 9.4 million hectares per year from 1990 to 2000 (FAO, 2001b). The total net forest change for the temperate regions was positive, but it was negative for the tropical regions. Between 1990 and 1997, 5.8 ± 1.4 million hectares of humid tropical forest were lost each year (Achard *et al.*, 2002). Forest regrowth accounted for 1.0 ± 0.32 million hectares. The annual rate of net cover change in humid tropical forest was 0.43% during that period. A further 2.3 ± 0.7 million hectares of forest were visibly degraded. This figure does not include forests affected by selective logging.

The driving forces for tropical deforestation vary between the regions (Figure 5, see page 402). In Latin America, large-scale forest conversion and colonisation for livestock-based agriculture is prevalent, whereas cropland expansion by smallholders dominates in Africa. In Asia, intensified shifting agriculture, including migration into new areas, gradual change of existing areas toward more permanent agriculture, and logging explain most of the deforestation (FAO, 2001b; Achard *et al.*, 2002; Geist and Lambin, 2002). Within these regions, deforestation is largely confined to a few areas undergoing rapid change, with annual rates of deforestation from 2% to 5% (Figure 6, see page 402).

Historically, humans have increased agricultural output mainly by bringing more land into production. However, the amount of suitable land now remaining for crops is very limited in most developing countries (Young, 1999; Döös, 2002), where most of the growing food demand originates. Where there is a large surplus of cultivable land, land is often under rain forest or in marginal areas. The period after 1960 has witnessed a decoupling between food production increase and cropland expansion. The 1.97-fold increase in world food production from 1961 to 1996 was associated with only a 10% increase of land under cultivation, but also with a 1.68-fold increase in the amount of irrigated cropland, and a 6.87- and 3.48-fold increase in the global annual rate of nitrogen and phosphorus fertilisation (Tilman, 1999). In 2000, 271 million ha were irrigated (FAO, 2001a). Globally, the cropland area per capita decreased by more than half in the 20th century, from around 0.75 ha per person in

1900 to only 0.35 hectare per person in 1990 (Ramankutty *et al.*, 2002). The mix of cropland expansion and agricultural intensification has varied geographically (FAO 2001a).

In 2000, towns and cities sheltered more than 2.9 billion people, nearly half of the world population (UN Population Division, 2002). Urban population has been growing more rapidly than rural population worldwide, particularly in developing countries. Urban form and function have also changed rapidly. Built-up or paved-over areas are roughly estimated to occupy from 2% to 3% of the Earth's land surface (Young, 1999; Grübler, 1994). Urbanisation affects land in rural areas through the *ecological footprint* of cities, that is, consumption of prime agricultural land in peri-urban areas for residential, infrastructure, and amenity uses.

Other forms of rapid land-cover change that are thought to be widespread are still poorly documented at the global scale. Local- to national-scale studies, however, demonstrate their importance and ecological significance. Prominent among these are changes in the (sub)tropical dry forests; forest-cover changes caused by selective logging, fires, and insect damage; drainage or other forms of alteration of wetlands; soil degradation in croplands; changes in the extent and productive capacity of pastoral lands; and dryland degradation, also referred to as desertification.

Land-use change is always caused by multiple interacting factors originating from different levels of organisation of the coupled human-environment systems. The mix of driving forces of land-use change varies in time and space, according to specific human-environment conditions (Lambin *et al.*, 2001). Land-use change is driven by a combination of the following fundamental high-level causes (Lambin *et al.*, 2003): (i) resource scarcity leading to an increase in the pressure of production on resources; (ii) changing opportunities created by markets; (iii) outside policy intervention; (iv) loss of adaptive capacity and increased vulnerability; and (v) changes in social organisation, in resource access, and in attitudes. These changes are the product of multiple decisions resulting from interactions between diverse agents, who act under certain conditions, anticipate future outcomes of their decisions, and adapt their behaviours to changes in external (e.g., the market) and internal (e.g., their aspirations) conditions (Lambin *et al.*, 2003). Climate-driven land-cover modifications do interact with land-use changes. Slow and localized land-cover conversion takes place against a background of high temporal frequency regional-scale fluctuations in land-cover conditions caused by climatic variability, and it is often linked through positive feedback with land-cover modifications.

4. *Human Impacts on the Atmosphere and Ocean*

While the human imprint on the terrestrial surface of the planet is relatively easy to discern, the evidence for human impact on the two great fluids of Earth – the atmosphere and the ocean – is harder to visualize but nevertheless real and important. The human imprint on the atmosphere began millennia ago; there was clear evidence of enhanced atmospheric concentrations of lead, copper and other trace metals by the time of the Greek and Roman Empires, as shown by ice core data from Greenland (Hong *et al.*, 1994) and in lake sediments (Renberg *et al.*, 1994) and peats (Lee and Tallis, 1973; Livett *et al.*, 1979; Shotyk *et al.*, 1996, 1998; Martínez-Cortizas *et al.*, 1999) from Europe. Since then, the human imprint on the atmosphere has remained measurable and has grown strongly in the last two centuries.

The best known of the human impacts on atmospheric composition concerns the concentration of greenhouse gases (IPCC, 2001). Compared to their pre-industrial upper limits of about 280 ppm, as shown in the Vostok (Fig. 1) and Dome C ice cores (Petit *et al.*, 1999; EPICA TEAM, 2004), the concentration of CO_2 has now increased to nearly 380 ppm. This represents a doubling of the entire operating range of CO_2 between glacial and interglacial states. The increase in CH_4 concentration has been even more dramatic and rapid, with the current concentration of 1700 ppb nearly three times that of the pre-industrial era (670 ppb). A third major greenhouse gas, N_2O, has risen in concentration more modestly, from 285 to more than 310 ppb. For all three of these gases, the evidence is very strong that human activities are responsible for the observed increases (IPCC, 2001).

Less well known, but perhaps as important as the change in greenhouse gas concentrations, has been the sharp rise of aerosol particles in the atmosphere (Andreae *et al.*, 1995, 2005). Aerosols are defined as atmospheric mixtures containing liquid or solid particulates of various sizes and compositions suspended in carrier gases. The most studied of the aerosol particles is sulphate, which began to increase in the North Atlantic region from the start of the 20th century (Mayewski *et al.*, 1990; Legrand *et al.*, 1997). Since the 1960s, however, concern about local and regional air pollution has led to measures to curb sulphate emissions and atmospheric concentrations of sulphate in the region have steadily decreased from the 1980s. At the same time, the concentration of sulphate particles in the atmosphere in Southeast, South and Temperate

East Asia are increasing steadily (Fu *et al.*, 2002). Globally, anthropogenic sources of oxidized compounds of sulphur are more than double the natural sources, indicative of the large human influence on the atmosphere's aerosol particle burden.

Carbonaceous particles (soot) from the combustion of fossil fuels and from biomass burning are other sources of aerosol particles in the atmosphere (Kanakidou *et al.*, 2005). Although biomass burning is a natural part of the dynamics of some ecosystems, extensive deforestation and the use of fuel wood by humans has led to an estimated 30-50% increase over the last century in aerosol production from fires (Scholes *et al.*, 2003). Globally, the amount of soot in the atmosphere due to human activities has increased by about 10-fold over natural sources (Brasseur *et al.*, 2003). Mineral dust arising from arid regions is a third important type of aerosol particle. Like carbonaceous particles from burning, dust particles also arise to some extent from natural sources. However, due to human-driven land-cover change, the atmospheric loading of dust has increased over the last couple of centuries, perhaps by as much as 30-50% (Heintzenberg *et al.*, 2003). Global distributions of aerosol particle loading as characterized by the aerosol optical depth are shown in Figure 7 (see page 403).

Aerosols are a good example of an environmental problem that has grown in scale from local and sometimes regional to one that is now undeniably global. The rapid geographical expansion of anthropogenic sources of aerosols coupled with intercontinental atmospheric transport have generated global distributions of many important aerosol particles. This rapid expansion of aerosol particles has impacts on air quality in places far removed from their source and is also significant for climate, both directly through their radiative properties, and indirectly through their effects on cloud physics and their interaction with the hydrological cycle.

The amount of oxidizing gases, often called photo-oxidants, in the atmosphere has also increased due to human activities. The most important of these is ozone, which is harmful in the troposphere, in contrast to its role in the stratosphere (Crutzen, 1995). Tropospheric ozone is not produced directly by human activities, but rather is the result of chemical reactions involving precursors that are produced by human activities. The degree of increase in tropospheric ozone is difficult to determine, but measurements at mountain sites in Europe suggest that it has increased by a factor of four or so during the last century (WMO, 1999). As for aerosols, the increase in emissions, coupled with atmospheric transport, has elevated oxidizing gases from a local air pollution problem to a global change issue.

One of the most prominent changes in atmospheric composition observed over the past decades has been the decrease in stratospheric ozone over the southern high latitudes owing to the emission of chlorine- and bromine-containing gases of industrial origin (primarily the so-called chlorofluorocarbons). Peak ozone loss has approached 60% at the South Pole – the so-called 'ozone hole'; ozone loss in the stratosphere over the mid-latitudes, although much less, is still measurable. Total column ozone during the period 1997-2001 was 3% less than the pre-1980 value for the northern mid-latitudes and 6% less for the southern mid-latitudes (UNEP/WMO, 2002).

The human imprint on the marine environment is most strongly expressed in the coastal zone, as more than 50% of the human population lives with 100 km of a coast (Kremer and Crossland, 2002) and even more use the coastal zone for recreational activities. Humans alter the coastal zone most directly via geomorphological changes through the construction of shoreline engineering structures, ports and urban developments. Other direct impacts include the conversion of natural ecosystems to managed systems designed for food production, for example, the conversion of mangrove forests to prawn farms. Globally, approximately 50% of mangrove systems have been converted to other uses as a result of human activities (Kelleher *et al.*, 1995; WRI, 1996, 2000; Naylor *et al.*, 2000). Coastal ecosystems have also been modified by the direct or inadvertent introduction of non-indigenous species, which can alter the structure and functioning of coastal ecosystems.

One of the most important roles of the coastal zone in terms of Earth System functioning is the transport and transformation of materials from the land to the ocean. These include the flow of water itself, sediments suspended in the water and a large range of chemical species dissolved in the water. Human activities have altered all of these functions.

Perhaps the most profound change has been the flow of water itself, described in more detail in the next section on changes in the hydrosphere (see also Meybeck, this volume). The flow of suspended material from upland areas is important for maintaining the structure of the coastal zone as sediments provide the building material for river deltas and for coastal geomorphology more generally. The overall impact of human activities on the delivery of sediments to the coastal zone is difficult to determine due to two opposing effects. In many regions, delivery of sediment to the coastal zone has been decreased through sediment trapping within reservoirs and other pondages upstream. In other areas there have been regional increases in the delivery of sediments to the coastal zone through increased soil erosion driven by construction, mining, forestry and agriculture (Steffen *et al.*, 2004b).

Changes in nutrient flows through the coastal zone are more clear-cut (Andreae *et al.*, 2004). The sharp increase in the delivery of nitrogen to the world's oceans via the coastal zone is typical of the increased flow of nutrients more generally from land to ocean. A synthesis of the current understanding estimates that nitrogen delivery via rivers entering the North Atlantic has increased by a factor of between 3 and 20 (Howarth *et al.*, 1996). Although some of this increased nitrogen flux is due to direct human injection in the coastal zone from urban sewage treatment plants and from industrial activities, much of the nitrogen is derived from fertilizer application to agricultural areas upstream. Additional nitrogen is delivered via atmospheric deposition of NO_x originating from agricultural, industrial or transport activities (Jaworski *et al.*, 1997; Howarth *et al.*, 1996). Phosphorus delivery to the ocean has similarly increased in the last 50 years or so. In addition to nutrients, contaminants such as heavy metals, persistent organic pollutants, various other synthetic chemicals, radioactive materials, bacteria and slowly degrading solid waste like plastics are transported from land to the coastal regions.

The primary direct human impact on marine ecosystems is through fisheries. The total fish catch globally increased steadily through the 20th century but has leveled off during the last decade (Figure 8), probably representing the upper limit that can be attained. Among the major marine fish stocks or groups of stocks for which information is available, about 47-50% of stocks are fully exploited, 15-18% are overexploited and 9-10% have been depleted or are recovering from depletion (FAO, 2000). In terms of impacts of this fish harvest further down the food chain, one recent study estimates that humans ultimately harvest 8% of the primary production of the oceans, with much greater percentages for the upwelling and continental shelf areas (Pauly and Christensen, 1995). Human fisheries cause other changes to marine food webs. For example, commercial fisheries probably influence population characteristics of species incidentally caught in the fishery, as an equivalent of 25% of the annual production of marine fisheries is discarded as bycatch each year (FAO, 2000).

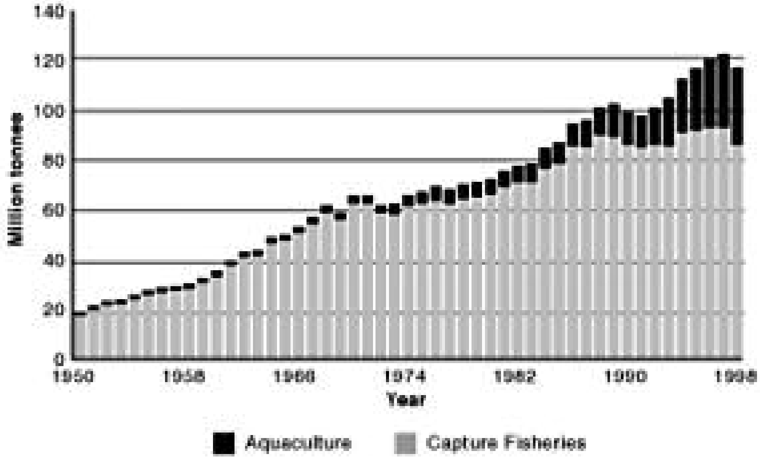

Fig. 8. World capture fisheries and aquaculture production (FAO, 2000).

5. *Changing Hydrosphere and Climate*

Given the central importance of water for human well-being, it is not surprising that the hydrological cycle has been heavily modified by human activities (Meybeck, this volume). The widespread rise of agriculture around 4,000 or 5,000 years ago triggered the start of major human influence on the hydrological cycle through the first development of water engineering works.

More recently, humans have come to dominate continental aquatic systems through a strong increase of activity during the past century. During that period, reservoirs and flow diversions have become both massive in size and widespread around the globe (Figure 9, see page 405). About 45,000 dams over 15 m high are registered in the world and many hundreds of thousands of smaller dams have been built on farms and on rivers. At present about 40% of the total global runoff to the oceans is intercepted by large dams, that is, about 16,000 km^3 yr^{-1} of discharge. Approximately 70% of this discharge flowing through large reservoirs experiences a sediment trapping of 50% or more (Vörösmarty *et al.*, 2003). In the northern hemisphere only 23% of the flow in 139 of the largest rivers is unaffected by reservoirs in one way or another (Dynesius and Nilsson, 1994).

Now that much of the easily accessible surface water has been captured and diverted for human use, the extraction of groundwater is increasing sharply. In many cases, the current extraction of deep groundwater amounts to mining of the resource. For example, in the Chad Basin, Nigeria, the groundwater reservoir has not been fully recharged for thousands of years, with only shallow water recharge near the margins. A similar situation exists in arid areas of the Middle East, where natural recharge of the groundwater is also close to zero so that pumping of groundwater for irrigation of agriculture is equivalent to the mining of fossil water. Extraction of groundwater from the large Ogallala aquifer in the Great Plains area of the United States for agricultural use has led to decreasing water levels in the aquifer and to abandonment of agricultural land (Steffen *et al.*, 2004b).

Water quality has also changed significantly over the last few centuries, but the types of pollutants vary widely in the different regions of the world (Meybeck and Vörösmarty, 1999; Vörösmarty and Meybeck, 2003; Meybeck, this volume). For example, in the developed world agricultural runoff is probably the largest source of pollutants – sediments, nutrients, pesticides and coliform bacteria. According to the US Environmental Protection Agency (USEPA, 1989), 76% of pollution entering rivers and lakes in the United States is from non-point sources, of which agriculture contributes 64%. Most of the chemical pollutants are nitrogen and phosphorus compounds derived from fertilizers, and halo-organic compounds arising from pesticides. In the developing world, much of the water quality problem centers on faecal and organic pollutants from untreated human wastewater, a problem that was eliminated in developed countries a few decades ago. Loading of industrial and urban pollutants on freshwater resources continues to be a major problem in many parts of the world.

Climate change is the most well-known aspect of global change, and is often confused with global change itself. However, at the beginning of the 21st century, climate change probably still has less impact on human societies than the range of other global changes – direct changes to the land surface, atmosphere, coastal zone, and hydrological cycle – described herein. In addition, the recent Millennium Ecosystem Assessment has documented the extent to which human activities have modified terrestrial, coastal and marine ecosystems, and thus affected their ability to provide ecosystem services to support human development and well-being (Reid *et al.*, 2005).

As this century progresses, climate change will almost surely become more important as the climate moves further from its 'operating range' of the last few millennia (IPCC, 2001) and the impacts on a wide range of natural and managed ecosystems become more apparent with increasing consequences of various types (Hare, 2005). Furthermore, the rate of land-cover change, particularly tropical deforestation in South America and Southeast Asia, is projected to slow through this century under most scenarios (Reid *et al.*, 2005). Thus, climate change will likely become relatively more important by mid-century compared to other global changes, and may dominate the other changes in the second half of the century.

The debate on whether climate change is 'real' or not is over; the vast majority of global change scientists accept that the climate is now moving beyond the bounds of natural variability and that human activities play a significant role in observed contemporary climate change (IPCC, 2001). The best-known feature of climate change is the rise in global mean temperature (Figure 10, see page 406), largely due to an increase in the nighttime minimum temperatures rather than an increase in maximum temperature. In terms of geographical variability, the high latitudes of the northern hemisphere and the interior of continents more generally are warming at a faster rate than the rest of the Earth's surface. The evidence for the general warming trend is also clearly discernible in the cryosphere, in both the retreat of most land glaciers around the world and the observed degradation of permafrost (Anisimov, 2004; ACIA, 2004). The response of the terrestrial biosphere to the warming trend is now also unmistakable (Parmesan and Yohe, 2003).

The magnitude and patterns of precipitation also appear to be changing beyond natural variability. For the mid and high latitudes in the northern hemisphere, for example, it is very likely that precipitation increased during the 20th century by 5-10% in many areas (IPCC, 2001). This was predicted, as increasing temperature leads to increasing evaporation from the land surface and a more active hydrological cycle in general. However, there is some debate about whether evaporation is actually increasing, as the preferential increase in nighttime minimum temperatures would not increase evaporation (Roderick and Farquhar, 2004), and in some regions of the world the cooling effect of increased aerosol loading in the atmosphere may dampen evaporation from the land surface (Ramanathan *et al.*, 2001, 2005). In addition, there are some counter-trends in precipitation change, with rainfall decreasing by about 3% on average over much of the sub-tropical land areas (IPCC, 2001).

Extreme events like floods and droughts are particularly important aspects of climate for human well-being. Although there is inconclusive evidence that the incidence of drought has increased globally, there is some evidence that climate change is increasing the number of severe floods around the world. The analysis by Milly *et al.*, (2002), which examines 100-year floods (river discharge that has a probability of 0.01 of being exceeded in any given year) for basins larger than 200,000 km^2 with observations that span at least 30 years, shows that the frequency of extreme flood events is increasing. Only half of the observational record of 2066 station-years was made after 1953, but 16 of the 21 extreme floods occurred after 1953. The observed increase in extreme floods is consistent with the projections of climate models, which suggests that the increase in frequency of extreme floods will continue into the future.

6. *Abrupt Changes in the Earth System*

The palaeo record shows that abrupt changes of various types are a common feature of the behavior of the Earth System, and closer examination of processes across many facets of the Earth System in the contemporary period shows that nonlinear behavior occurs frequently (Rial *et al.*, 2004). The term 'abrupt change', the most common term used to describe nonlinearities, usually refers to changes in major features of Earth System functioning that occur at an unexpectedly rapid rate (Steffen *et al.*, 2004a). The term 'unexpectedly rapid' depends on the perception and time scale considered, human or geological. Here we consider those changes that would be considered abrupt on a geological time scale, but would also be so rapid that they would be discernible within a human lifetime, thus would occur within a decade or, at most, a few decades.

The sudden, unexpected formation of the stratospheric ozone hole over Antarctica, mentioned briefly in Section 4, is an example of an abrupt change that has already occurred (Crutzen, 2004). The rapid and unexpected loss of ozone over the southern high latitudes was first recognized in the mid-1980s through measurements taken over decades by the British Antarctic Survey. The cause of the ozone hole was traced to man-made compounds called chlorofluorohydrocarbons (CFCs), produced as refrigerants and insulators and thought to be completely harmless. Under cold conditions in the stratosphere, the CFCs undergo a complex series of reactions, eventually producing Cl_2, which is photolyzed by sunlight to create Cl radicals. These start a catalytic chain of reactions, leading to the destruction of ozone. The ozone hole is an example of a chemical instability in the Earth System, where a reaction sequence triggered by synthetic compounds caused an abrupt shift in ozone concentration in a large region of the stratosphere.

Instabilities in ocean circulation and regional climate are now attracting much attention as a type of abrupt change that could severely impact on modern civilizations. The focus is on the North Atlantic region; in this area the Gulf Stream transports much heat from the tropical Atlantic Ocean northwards, where the water cools and releases heat that is then delivered by the westerly winds to Northern Europe and Scandinavia. Much of the abrupt change seen in the Greenland ice core records (Bond *et al.*, 1999) is associated with reorganizations of this pattern of oceanic circulation (Rühlemann *et al.*, 1999). The abrupt climate shifts observed in the Greenland ice cores extend well beyond the North Atlantic region, as shown by a range of other synchronous environmental changes observed around the northern hemisphere, indicating that the abrupt changes are at least hemispheric and possibly global in extent (Alverson *et al.*, 2003). This evidence suggests a bipolarity in the states of the Earth System, where the North Atlantic ocean circulation appears to flicker or flip-flop between the two states, triggering extremely rapid and large temperature swings of up to 10°C in a decade (Alley *et al.*, 2001). Such changes, if they occurred now, would have severe consequences for the modern civilizations of the North Atlantic region. Studies show that a weakening of the circulation is possible, and abrupt and irreversible changes in ocean circulation cannot be excluded within the range of projected climate change over this century (Rahmstorf and Stocker, 2004).

The world's coral reefs are undergoing changes now that are the result of both local pressures and systemic global changes. There is a high probability that the combination of such forcings will cause most reefs to cross a threshold and convert them to algal beds sometime in the second half of this century, if not sooner. The global pressures are due to both changes in ocean chemistry and sea surface temperature. Increasing atmospheric CO_2 leads to increased dissolution of CO_2 in the upper ocean layers, changing the acidity of the ocean water and thus the ability of reef organisms to create their calcium carbonate shells (Orr *et al.*, 2005). A doubling of atmospheric CO_2 is estimated to lead to a 30% reduction in calcification rate of reef organisms (Kleypas *et al.*, 1999). The warming of the ocean's surface waters adds another stress on the reefs; the exceptionally warm year of 1998 triggered widespread bleaching of reefs around the world (WRI, 2001). These global-scale forcings affect all reefs, whether they are pristine or under local pressure from human activities (e.g., fishing, tourism, nutrient loading from agriculture on adjacent lands), but where the local and global pressures act together on reefs, they are particularly susceptible to bleaching events and a conversion to algal beds. It is estimated that 58% of the world's coral reefs are currently at medium to high risk of degradation and possible conversion to algal beds as result of changing environmental conditions (Burke *et al.*, 1998), and this proportion will likely increase through this century.

Abrupt changes in human systems are rarely considered in global change studies, but they may be more common than many think and, indeed, could be triggered by gradual changes in the biophysical world. Examples of potential changes in human systems include instabilities caused by large and growing inequalities both within countries and between countries exacerbated by global change; instabilities in the human health system, including pandemics, re-emergence of old diseases and emergence of new diseases; and the possibility that gradual changes in the biophysical world could trigger abrupt changes in the globalizing economic system.

A summary of the potential biophysical part of the Earth System is given visually in the global map of 'switch and choke points' (Schellnhuber, 2002; Figure 11, see page 406). The map is an attempt to identify those areas where change – often abrupt change – at the regional level may lead to significant changes in the way that the Earth System as a whole operates.

7. *Human Health in a Changing Earth System*

The previous sections have described how human activities are affecting the functioning of the Earth System in many different ways. It is clear that the Earth is currently operating in a no-analogue state. In terms of key environmental parameters, the Earth System has recently moved well outside the range of natural variability exhibited over at least the last half million years. The *nature* of changes now occurring *simultaneously* in the Earth System, their *magnitudes* and *rates of change* are unprecedented (Steffen *et al.*, 2004b). The implications of the changing Earth System are complex and potentially serious.

Direct impacts of changing climate and atmospheric composition are probably the most obvious effects of global change on health. The heat wave of 2003 in southern France that killed over 15,000 people is an example of such an impact. Less well-known is an equally severe heat wave in Australia in February 2004. Although Australian society is better equipped than French society to deal with high temperatures, the heat wave nevertheless caused numerous collapses due to heat stress in Adelaide and Sydney as well as a surge in ambulance call-outs in Brisbane, an event described by the Queensland commissioner of ambulance services as '... the most significant medical emergency in the south-east corner (of Queensland) on record'. (Steffen *et al.*, 2005).

Deterioration of air quality due to emissions of a variety of deleterious compounds is another. Originally considered to be a local or regional problem, the long-range transport and transformation of chemical species has now become so widespread that pollution from North America affects Europe, while that from Europe affects Asia and so on. Air pollution has become a global change issue (Brasseur *et al.*, 2003).

In addition to direct impacts, global change affects human health via ecological changes that can affect the transmission of diseases (McMichael, this volume; Confalonieri *et al.*, this volume). One consequence of changing land use, for example, is the change in the prevalence of infectious disease. Vector-borne diseases are particularly sensitive to changes in land cover and land use, because their spatial distribution is restricted by the geographical range of the vector and by its habitat preferences. Research is needed to better understand correlations between land use, specific vector species and disease patterns. Land use change and vector ecology control the interactions between hosts and vectors, given the use of different land parcels by people, the breeding habitats of specific vectors and their dispersal through the landscape (influenced by landscape pattern and heterogeneity). The impact of land use change on vector-borne disease risks can modify the course of land transformation via a feedback mechanism affecting human decisions on land use. By predicting the effects that changes in land use would have on vector-borne disease, public health funds could be allocated more effectively in the prevention and treatment of these diseases. Vector-borne disease is often most effectively combated through vector control measures but, to be effective, the behavior and ecology of the target species must be fully understood.

Whatever biophysically driven impacts of global change on human health can be postulated, it is clear that the differing vulnerabilities of countries or sectors of society will be often be the decisive factor in determining whether a serious infectious disease pandemic, for example, breaks out or not. Therefore, indirect changes in the human component of the Earth System may have the most critical effects on health. Deterioration of public health systems due to an increased need of society to cope with the more direct impacts of global change could ironically leave populations more vulnerable to disease. Populations in the developing world weakened by poor nutrition or poor water quality will be also be more vulnerable to health problems as global change accelerates (Shah *et al.*, this volume). Changes in the biophysical component of the Earth System could promote the reemergence of old diseases or the development of new diseases. As in many aspects of global change, we should expect surprises as the Earth System is subjected to a suite of increasing human pressures. Human health is arguably the most complex of the major types of global change impacts on our societies; understanding how to prepare for the impacts on and improve the resilience of our health systems is surely one of the grand challenges of Earth System science.

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