Chapter 4

Planetary Engineering on the Earth

We are as much gainers by finding a property in the old earth as by acquiring a new planet.

Ralph Waldo Emerson

4.1 A Planet-Shaping Species

As a subject for serious investigation, terraforming suffers, as much as it benefits, from the grandeur of its vision. It deals with human manipulation of energy and matter on so huge a scale that the normal initial reaction to such ideas is to dismiss them as impractical. Proponents of terraforming find themselves continually having to justify that planetary engineering will ever be possible and have to base their speculations on somewhat arbitrary assumptions of the abilities of future civilizations. However, these doubts about the future can be considerably softened by looking into the past, in particular at mankind's increasing ability to reshape the face of the Earth [1].

Reflecting its out of equilibrium nature, a planetary biosphere must always be in a continual state of flux, over whatever period it is observed. Over the expanse of geological time, we would expect to note substantial fluctuations of climate and changes in geomorphology; during the timescales characteristic of biological evolution, life would go on, but its composition of forms would change as new species evolved and uncompetitive species became extinct. By any yardstick however, the transformation that the Earth has seen over the past 10000 years has been remarkable. One single species, *Homo sapiens*, has come to dominate the planet, its associated phenomenon of civilization rivalling, in its ability to harness energy and move material, some of those very biogeochemical cycles in which life both partakes and on which it depends.

Ten thousand years ago, an observer from space would have noted that the Earth had emerged from a glacial period and that it looked similar in aspect to the previous interglacial and the one before that. Yet, if he was to return now, the changes observable would be dramatic. He would find 10% of the land surface covered with artificially maintained ecosystems containing a small number of species, selected and bred for just one consumer. Forty percent of the land would show some overt sign of conscious management or influence, from forests reserved for timber, lands impoverished through over-use, to sprawling, reef-like, cities that live on the import of material from many miles away. Remarkably, these influences would be visible over most of the globe — transcending the normal biogeographical boundaries that restrict species to certain regions. Changes in geomorphology would therefore be widespread: chunks carved out of mineral-rich mountainsides or holes in the ground; new lakes gathered behind dams, or lands dyked, drained and reclaimed from the sea; and many landforms of an entirely novel form — linear, or geometrical in shape. Points of light would be visible on the dark hemisphere of the planet, arranged in clusters and other half-ordered patterns. Analysis of the atmosphere would reveal the presence of several gases that did not exist at all before and, far from the planet cooling as a prelude to the next ice age, measurements would show it to be heating up. However, our visitor's most extraordinary observation would be that he might find his spacecraft sharing an orbit with one built by some of the creatures responsible for the transformation of the planet below.

It is a truism that life expands to fill the space available to it and that species compete to fill the niches available to within this space. Adaptation to new conditions or opportunities is by biological evolution — a relatively gradual process with a timescale of thousands to millions of years. The difference with *Homo sapiens* was that it evolved an ability to develop *technology* and *culture* — new inventions freeing it from many previous constraints. Technology allowed humans to exploit *extra somatic energy sources* (see Table 4.1) and tools to use that energy to rearrange the environment, diverting its resources into improved habitability and the support of increased numbers [2]. Fire was the first extra somatic energy source to be exploited which provided warmth, night-time illumination and assisted in protection from predators, hunting and the preparation of food. The additional work of domestic animals and the tapping of energy in wind and water powered the great classical and medieval cultures, whilst the huge growth in human civilization since the industrial revolution was made possible by the large-scale use of fossil fuels. A space-based civilization (the sort that might attempt a terraforming project) will have potential access to extrinsic energy sources dwarfing those hitherto available — only ~ 4.5×10^{-10} of the Sun's power of 3.9×10^{26} W is interrupted by the Earth.

TABLE 4.1 EXTRASOMATIC ENERGY SOURCES AVAILABLE TO CIVILIZATIONS AT VARIOUS STAGES OF DEVELOPMENT

	Hunter / Gatherers	Agriculturalists	Industrialism	Nuclear Age	Space based Civilization
Fire	✓	✓	✓	✓	✓
Domestic Animals		✓	✓	✓	✓
Wind		✓	✓	✓	✓
Water		✓	✓	✓	✓
Fossil Fuels			✓	✓	✓
Nuclear				✓	✓
Space Solar					✓

Culture allowed the body of accumulated knowledge to be transmitted to future generations. It permitted behavioural adaptation to the environments humanity had created for itself — short-circuiting the more lengthy process of biological adaptation. It also permits the pre-planned mobilization and coordination of human work on a very large scale and contains a degree of negative feedback too, in the sense that conscious beings can try to hold back from the brink of a disaster that they can foresee, but which has not yet happened. Most importantly perhaps (and as emphasized by Vernadsky), culture has enriched the biosphere with new flows of *extra somatic information* exterior to the genome of individual organisms.

Homo sapiens has therefore been following the great imperative of life, faithfully, and according to natural ability. *Purposeful environmental modification, from a personal to regional scale, is thus a quintessentially human activity*. Although change of a global kind has happened unintentionally, as a consequent effect of ubiquitous, but smaller-scale activity, it nonetheless suggests that a latent capacity in true planetary engineering already exists. It is not surprising therefore that human beings are making their first forays into space — virtually as soon as the technology was developed to permit it. If the sustained settlement of space ever happens (and it is natural that it should) then the evidence provided by history makes it logical to suppose that extraterrestrial locales will be engineered to make then fit for human-containing ecosystems. Terraforming should therefore not be a foreign or unlikely notion at all — but a normal outcome of our outreach into the larger Universe.

There is no doubt that prehistoric man, through the use of fire, was able to change the distribution of the flora and fauna about him. Agricultural and early industrial civilizations had a much more profound impact on their surroundings — the study of which was pioneered by early environmentalists such as George P. Marsh and R.L. Sherlock. However, whilst it is wise not to underestimate the environmental engineering capacity of past civilizations, it is not appropriate to review it here (the subject having been dealt with most admirably elsewhere [3,4]). Human activities that are most relevant to terraforming are to be found within the present day global economy which uses energy and materials on a scale dwarfing that of only 100 years ago. In this chapter therefore, we will examine some examples of the planet-shaping abilities of modern civilization and will follow this with a review of geoengineering proposals — mostly ideas for purposeful intervention on a planetary-scale to counter the inadvertent changes wrought so far.

4.1.1. Manipulation of the Earth's Surface

There are two ways human activities affect the Earth's geomorphology: *directly*, by such exertions as excavation, construction, dumping and hydrological interference; and *indirectly*, via consequent effects, such as accelerated erosion and sedimentation, subsidence and slope failure. It is instructive to compare some of these processes with the mass moving capacity of nature and we concentrate here on excavation.

The amount of sediment carried in rivers annually is ~ 24 billion tonnes and represents the amount of rock and soil carried off the land surfaces by the natural processes of weathering and erosion [5]. Published figures for the annual movement of soil and rock by global civilization vary, but even the lower estimates exceed the natural mobilization rate. A recent Worldwatch Institute paper [6] reports that > 30 million tonnes of non-fuel minerals are dug out of the ground each year, much of this being sand and gravel to be used as fillers for concrete. In his book <u>The Human Impact on the Natural Environment</u> [3], Oxford University geographer Andrew Goudie quotes the annual movement of soil and rock for the purpose of all mineral extraction, including tailings and overburden, to be as high as a staggering 3000 billion tonnes (a figure derived originally from Russian work in the 1970's). This estimate may seem too large to be credible — and yet when determining total human action, one also has to take into account material moved in construction, dredging, and reclamation, as well as many indirect imprints caused by human exposure of the land surface. A figure nearer to the larger of the two values above therefore seems likely.

There is thus little doubt that manipulation of the Earth's surface by people and their machines is on the same, or greater, scale to that of natural forces. Anybody who has been impressed by a visit to the Barringer Meteor Crater in Arizona (1200 m across, 180 m deep) might appreciate this by looking at Fig. 4.1. Here, this natural impact structure is compared with cross sections of two anthropogenic landforms — the Sedan Crater (370 m across, 100 m deep), produced by a 100 kt nuclear explosive buried at optimum cratering depth, and the extraordinary Bingham Canyon open-pit copper mine in Utah (7.21 km^2, 774 m deep). Bingham makes Barringer look like a dimple and is one of the world's largest man-made landforms, involving the removal of > 3 billion tonnes of rock, seven times the amount shifted to clear the Panama Canal [3]. There are of course many ancient impact craters on Earth bigger than this, the eroded remnants of which have been discovered in many regions, however none have formed in the lifetime of the human species.

The expansion of civilizations is often accompanied by the construction of massive anthropogenic landforms, such as the enormous dyke systems which reclaimed half of the present surface area of Holland from the sea (see Plate 4.1). Perversely, the opposite activity of attempting to destroy civilizations in warfare also leaves its mark on the Earth's surface. In seven years of the Vietnam War, "carpet bombing" produced over 26 million craters excavating over 2.6 million m^3 of earth [7]. The ultimate in such activity would be a nuclear war (fortunately, now unlikely). A "severe" exchange, according to standard scenarios would have a total yield of 10,000 Mt, comprising approximately 16,000 individual explosions of average yield of ~ 625 kt, 63% of them being surface bursts [8]. This would produce about 10,000 craters of average diameter ~ 252 m and depth ~ 63 m, ejecting a total volume of ~ 16 billion m^3, a mass of about 50 billion tonnes. This would be only about six times the amount mobilised in the Vietnam War, but since a nuclear exchange might only take about half a day, the rock mobilization *rate* exceeds that of conventional warfare by a factor of ~ 31,000, natural erosion by a factor of ~ 1500 and that of the global earth-shifting activities of civilization by a factor of ~ 12 - 1200.

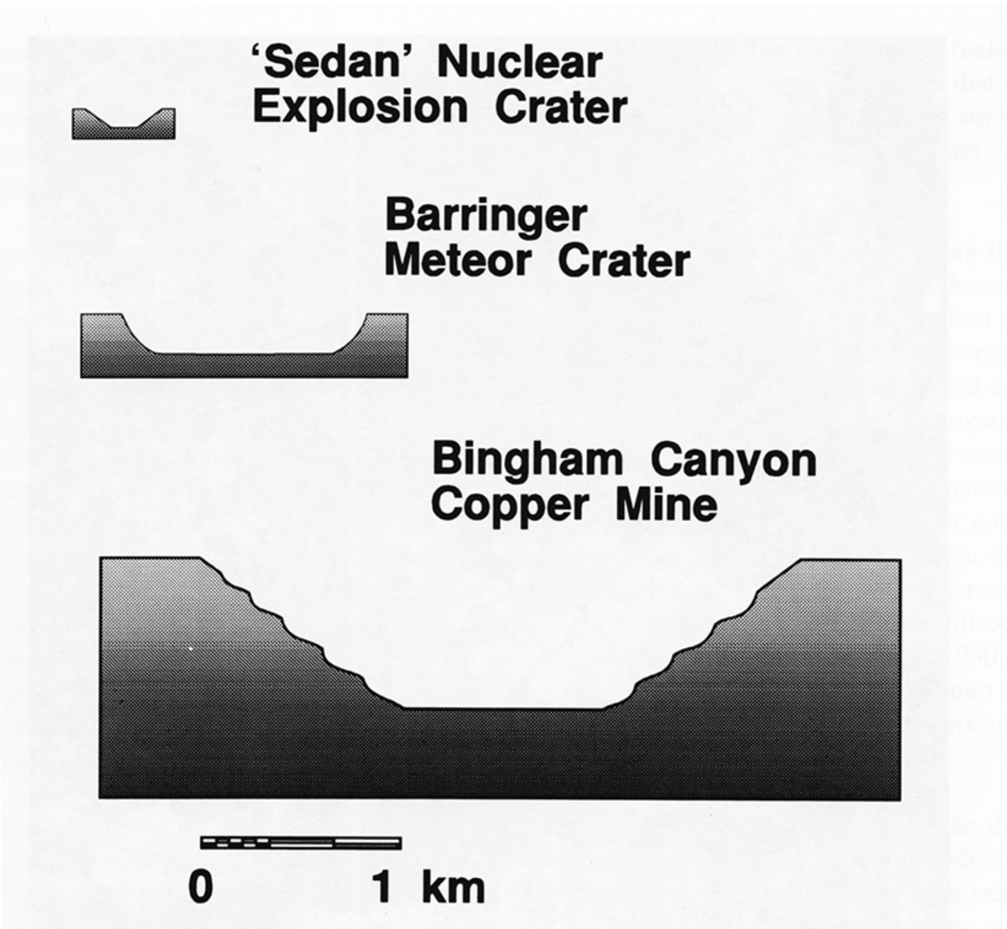

Figure 4.1 *Approximate cross-sections of three large excavations. Only the middle one is natural.*

It is this question of mass mobilization rates that is therefore crucial when considering planetary engineering. For while natural processes can build entire mountain chains and erode them into the sea, it takes millions of years. In his comparatively brief history on the Earth, and especially in areas of concentrated activity, man has overtaken nature as being the dominant force in re-shaping the land. This has been further reinforced by the discovery of the explosive release of nuclear energy which has been extensively studied (although never employed) for civil engineering, as well as military use.

Plate 4.1 *The polder of Flevoland, Holland, is seen as the flat farmland in the upper two-thirds of this Space borne Imaging Radar image. Polders are dry land reclaimed from the sea and this is a recent example, having been created this century from what is left of the Zuider Zee (South Sea). The city of Harderwijk is seen on the southern (lower) shore of the canal that separates Flevoland from mainland Holland. (Photo courtesy of NASA.)*

4.1.2 Alteration of the Earth's Atmosphere

It used to be thought that human influence on the composition of the Earth's atmosphere was still too minor to show any detectable effect on its two bulk constituents, nitrogen and oxygen. However, recent measurements have demonstrated a tiny, but sustained decrease in the quantity of oxygen that is commensurate with consumption in the combustion of fossil fuels [9]. The rate of reduction (~ 2.1×10^{13} kg/yr) is minute compared with the enormous mass that is present (~ 1.2×10^{18} kg) and, if sustained (which it won't be), would not deplete the atmosphere of all its O_2 for ~ 56,000 years. Nonetheless, geologically speaking, this timescale for the bulk transformation of a planetary atmosphere is short.

A much more significant human impact on the atmosphere is apparent by examining the fluxes of its minor constituents which, although only present in trace quantities, can have a large influence on climate and habitability. Many of these are by-products of civilization, as well as natural processes, and contribute to the greenhouse effect through their infrared opacity and to the albedo by the formation of aerosol particles. The key gases in this regard are listed in Table 4.2, alongside their pre-industrial and present concentrations, and a comparison of the annual anthropogenic and natural production. The causes of anthropogenic emissions are given in Table 4.3, and it is apparent that in all cases they rival or exceed the natural flux of these gases. Their net concentration is building up in the atmosphere at lower rates than given in Table 4.2, but the fact that accumulation is occurring demonstrates that the natural sinks for these compounds cannot absorb the excess over the time period observed. The magnitude of this build up is estimated in Fig. 4.2 for carbon dioxide, methane, nitrous oxide and CFC-11 — it is striking how their rate of accumulation rises sharply after 1950 [10]. Particularly interesting is the recent appearance of chlorofluorocarbons (CFCs), a group of compounds used as refrigerants and fire retardants, which have no natural counterparts and which have great potential for creating environmental change in low concentrations.

TABLE 4.2 ESTIMATED FLUXES OF KEY CLIMATE MODIFYING TRACE GASES

Species	Pre-industrial Atmospheric Concentration (ppm)	Present Atmospheric Concentration (ppm)	Natural Production (million tonnes / year)	Anthropogenic Production (million tonnes / year)	Ratio of Anthropogenic to Natural Production
CO_2	280	353	375 †	26000	70
CH_4	0.8	1.72	200	300	1.5
Sulphur Compounds	§	§	60 ‡	90	1.5
N_2O	0.29	0.31	20	6	0.3
CFCs	0	0.001	0	1	∞

§ Sulphur compounds are common precursors of aerosol particles and are thus short-lived in the atmosphere and concentrated over industrial regions. No long-term measurements outside built-up areas are available, but anthropogenic emissions have increased by more than a factor of 20 since 1860.
† Average of upper and lower estimates of natural CO_2 production by volcanic out gassing.
‡ Expressed in millions of tonnes/year of sulphur.
Compiled from data in Ref. [10].

Man's influence on the carbon cycle is very important, as it is a crucial component of the dynamic of the biosphere, as well as being influential in short and long-term climatic stability. About 200,000 million tonnes of carbon dioxide are cycled through the biosphere each year, without net effect on the atmosphere, consumption by photosynthesis being balanced by respiration and decay (see Section 2.5.2). However, chemical weathering of silicate rocks to form carbonates produces a potential deficit in the carbon cycle which is compensated for by volcanic out gassing of ~ 265-485 million tonnes of CO_2/yr [11]. Anthropogenic production of CO_2, from fossil fuel burning, cement production etc., amounts to ~ 26,000 million tonnes/yr, only ~ 10% of the amount cycling through the biosphere, but ~ 70 times the flux involved in the geochemical loop of the carbon cycle. Thus, carbon dioxide too is accumulating in the atmosphere, having increased in concentration by 30% over the past 125 years. Yet civilization's grip on the carbon cycle is actually greater than these figures suggest, since about 40% of continental net primary productivity (NPP) is used or diverted by human beings (see Table 2.9). This is equivalent to 27% of the global NPP, or a manipulation of an additional annual flux of ~ 54,000 million tonnes of CO_2 [4].

TABLE 4.3 ORIGIN OF ANTHROPOGENIC TRACE GAS EMISSIONS

CO_2	• Fossil fuel combustion • Cement production • Biomass burning
CH_4	• Rice paddies • Cattle herds • Gas drilling/coal mining • Landfills
Sulphur Compounds	• Fossil fuel combustion • Biomass burning
N_2O	• Combustion • Biomass burning • Fertilizer
CFCs	• Industrial synthesis

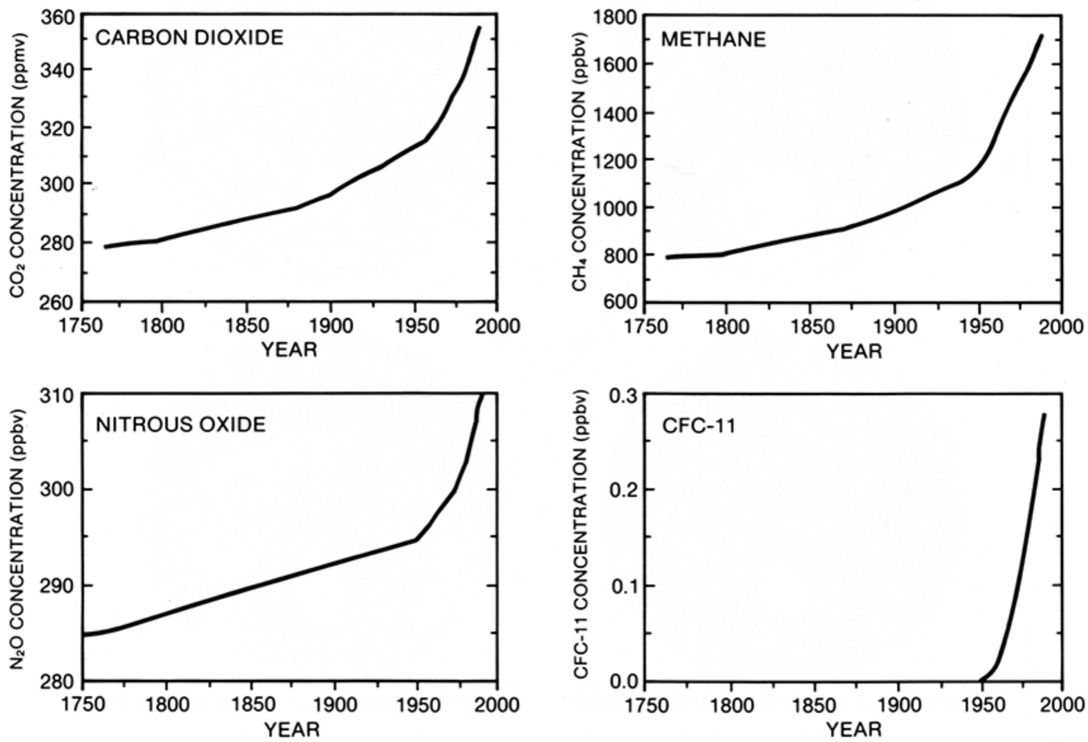

Figure 4.2 *The rising concentrations of the four most important greenhouse gasses. The rate of increase has accelerated in the late 20th century. (Reproduced with permission from Ref. [10].)*

As well as directly adding to the quantity of certain trace gases, civilization can also indirectly remove others. By far the most *consequential* is stratospheric ozone which performs the vital function of protecting the surface from ultraviolet radiation (see Section 3.4.1). It has long been suspected that human activities have been instrumental in eroding the ozone layer and possible confirmation of this came in 1985 with the observation of the so-called "ozone hole" over Antarctica [12]. Since then it has proved to be a regular annual feature, appearing in Austral Spring for about two months and characterised by a reduction in column mass of ozone to < 50% of normal, most of the loss happening at altitudes of 15 - 25 km (see Plate 4.2).

Modelling the dynamics of the ozone layer is a complex problem and a detailed treatment would require taking into account ~ 50 chemical species, ~ 200 photochemical processes and chemical reactions occurring on the surfaces of aerosol particles. Inevitably therefore, we must simplify the account here. The simplest photochemical cycle that produces ozone is the pure oxygen Chapman scheme [13]:

$$\begin{aligned} O_2 + h\nu &\rightarrow O + O \\ O + O_2 + M &\rightarrow O_3 + M \\ O_3 + h\nu &\rightarrow O + O_2 \\ O + O_3 &\rightarrow O_2 + O_2 \end{aligned} \tag{4.1}$$

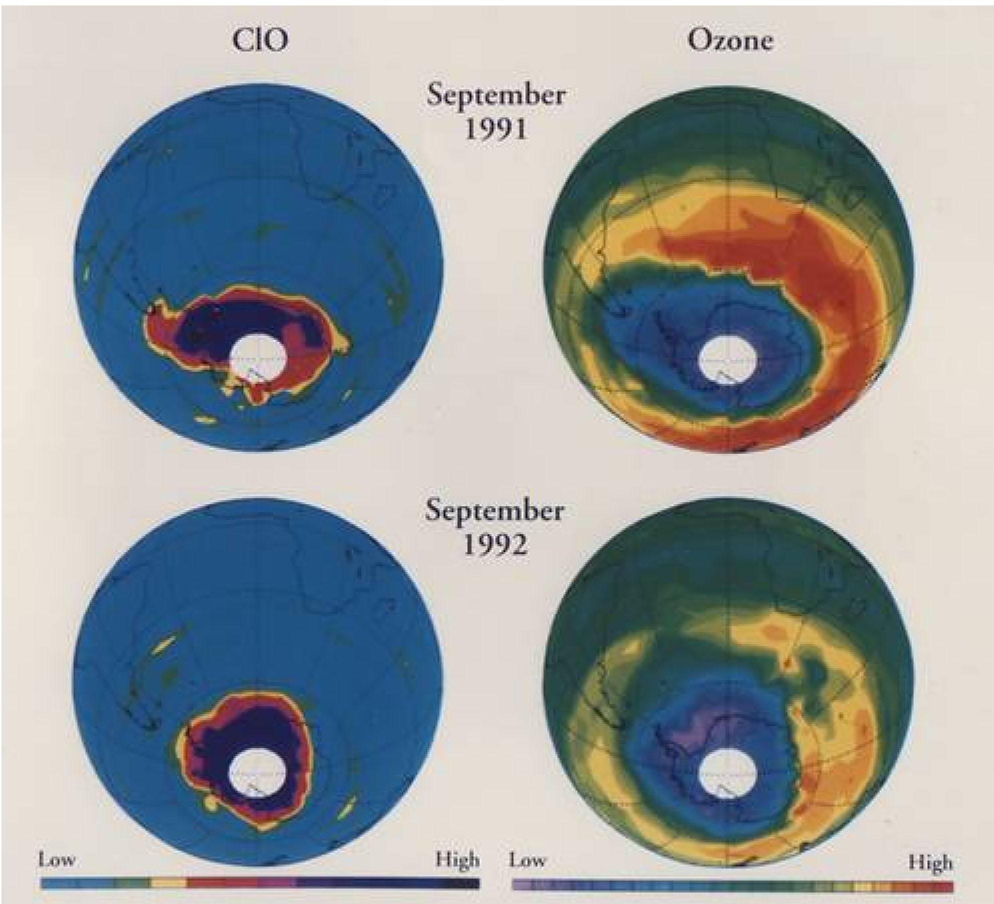

Plate 4.2 *The Antarctic "ozone hole." A plot showing high ClO and low ozone concentrations at high southern latitudes in austral spring for the years 1991 and 1992. (Photo courtesy of NASA.)*

where hν is a photon of appropriate wavelength and M is a third molecule required to balance the energy and momentum of the reaction. The Chapman scheme however predicts an equilibrium level of ozone that is too high and so there are other natural ozone-depleting reactions at work, in particular involving hydroxyl radicals and nitrogen oxides. The former process operates so:

$$\begin{array}{l} OH + O_3 \rightarrow HO_2 + O_2 \\ \underline{HO_2 + O_3 \rightarrow OH + 2O_2} \\ O_3 + O_3 \rightarrow 3O_2 \text{ (net)} \end{array} \tag{4.2}$$

The scheme is catalytic as it regenerates OH to participate in further reactions.

Anthropogenic destruction of ozone is thought to be happening through the build up of CFC gases in the atmosphere. These compounds are quite stable and long lived; however, once they reach the stratosphere, they are vulnerable to photodissociation by UV radiation; e.g. for CFC-11:

$$CFCl_3 + h\nu \rightarrow CFCl_2 + Cl \tag{4.3}$$

Chlorine can then destroy ozone in its own catalytic scheme:

$$\begin{array}{l} Cl + O_3 \rightarrow ClO + O_2 \\ \underline{ClO + O \rightarrow Cl + O_2} \\ O + O_3 \rightarrow 2O_2 \text{ (net)} \end{array} \tag{4.4}$$

In reality the reaction scheme is much more complex than this. It turns out that chemical reactions on the surfaces of droplets within polar stratospheric clouds in Winter are responsible for the appearance of the ozone hole in Spring [14]. At temperatures of < 200 K, stable chlorine reservoir compounds such as $ClONO_2$ and HCl can condense onto the cloud particles and are transformed into compounds such as Cl_2 and HOCl:

$$ClONO_2 + H_2O \rightarrow HOCl(g) + HNO_3 \tag{4.5}$$

$$HOCl + HCl \rightarrow Cl_2(g) + H_2O \tag{4.6}$$

$$ClONO_2 + HCl \rightarrow Cl_2(g) + HNO_3 \tag{4.7}$$

where (g) represents a volatile species that desorbs from the cloud particle. When sunlight returns in Spring, Cl_2 and HOCl are broken down into Cl and ClO and ozone destruction can begin as per Equation (4.4). Although some of the HCl involved in this process comes from volcanic emissions, it is feared that most of the chlorine causing this damage originates from CFCs. Since CFCs have an atmospheric lifetime of ~ 100 years, their influence could continue well into the next century, even if all releases were to be stopped now.

It is now planned to phase out CFCs and replace them where absolutely necessary by halocarbon compounds containing hydrogen and fluorine. The hydrogen renders the molecule susceptible to attack by tropospheric OH, reducing its lifetime — the amount that does reach the stratosphere is much less damaging as fluorine does not have the ozone destroying properties of Chlorine. The reason for this is that fluorine is so reactive it combines directly with water vapour to form hydrofluoric acid:

$$F + H_2O \rightarrow HF + OH \tag{4.8}$$

HF is resistant to photolysis and so the fluorine is bound until it diffuses out of the stratosphere.

Thus, significant change in the chemical composition of a planetary atmosphere is already an undoubted capability of human civilization. Since many of the trace gases released by farming and industry are climatically significant in parts per billion or million, "'global warming" is also being spoken about as an anthropogenic process.

4.1.3. Alteration of the Earth's Surface Temperature

Geological evidence suggests that the mean global surface temperature of the Earth (T_{surf}) has remained within a habitable range over the last 3.8 billion years. During the Phanerozoic Eon (since ~ 590 million years ago), T_{surf} has fluctuated between 'hothouse' periods such as the mid Cretaceous (~ 100 million years B.P.) and the depths of an ice age (as recent as 15,000 years B.P.) by perhaps only +10°C to -5°C about the present value of 15°C [15]. These changes would have been wrought primarily by changes in the atmospheric greenhouse effect (ΔT_{green}) and the planetary albedo (see Equation 3.4). For instance, it is thought that the Cretaceous Earth had a more substantial ocean cover and ice free poles (lower albedo) and a pCO_2 6 - 10 times greater than now (higher ΔT_{green}). Earth in a typical ice age would have had more land surface and ice cover (higher albedo) and a pCO_2 ~ 80 ppm lower than pre-industrial levels (lower ΔT_{green}). Various causes have been proposed for these long-term disturbances in the Earth's habitable steady state, such as shifts in the configuration of the continents, the formation of new mountain ranges, regular cycles of the planet's obliquity and orbital eccentricity and changes in the pattern of carbon sequestration by the biosphere.

A parameter often used in discussions of climate change is *radiative forcing* — an imposed perturbation of the planetary radiation balance that affects temperature. The strongest anthropogenic forcing appears to be due to greenhouse gas emissions and the generation of tropospheric aerosols.

Water vapour is the strongest greenhouse gas in the Earth's atmosphere, but since it is in a temperature-related equilibrium with a large surface reservoir, its main influence in climate change is as a positive feedback ($f > 1$; Equation 3.5) on the radiative forcing produced by other agents. The water vapour greenhouse is therefore determined internally within the climate system and is not directly affected by man.

The characteristics of other greenhouse gases, of varying importance, are shown in Table 4.4, including their average residence time in the atmosphere between source and sink, their infrared absorption band centres and an estimate of their greenhouse effect, calculated on a molecule for molecule basis relative to CO_2. Some gases are particularly good absorbers because of the strength and distribution of their bands within the infrared spectrum. The way naturally occurring greenhouse gases work to block the planet's outgoing infrared radiation is illustrated in Fig. 4.3. It shows that water vapour and CO_2 absorb infrared effectively at longer wavelengths than 15μm and shorter than 7μm, but between these there exists a 'window' in the spectrum, interrupted prominently by the absorption of ozone at 9.6 μm, through which heat can leak into space. Anthropogenic emissions of CO_2, CH_4 and N_2O, strengthen the absorption bands of naturally occurring gases; however, emission of the entirely artificial CFCs has the potential to cause by far the most substantial forcing per unit concentration. It can be seen in Table 4.4 that CFCs have strong absorption bands in the window region which are unsaturated due to the low abundance of these compounds. Thus any addition to their concentration causes a large radiative forcing with a greenhouse effect > 10,000 times that of CO_2 [18]. Moreover, since these chemicals are so unreactive and are not destroyed until they reach the stratosphere (or the ionosphere, in the case of the even more stable perfluorocarbons), their lifetimes are very long, from decades to centuries.

TABLE 4.4 PROPERTIES OF TRACE GREENHOUSE GASES

Chemical Group	Chemical Formula	Dominant Source	Dominant Sink	Estimated Average Residence Time (years)	Infrared Absorption Band Centres (μm)	Radiative forcing per molecule relative to CO_2
Carbon dioxide	CO_2	N,A	O	50-200	15.0	1
Hydro-carbons	CH_4	N,A	T(OH)	10	6.51, 7.65	21
Nitrogen Compounds	N_2O	N,A	S(UV)	150	4.5, 7.78, 17.0	206
	NH_3	N,A	T	0.01	10.53	
Perfluoro-carbons	CF_4 (F14)	A	I	50000	7.78, 7.93, 15.8	
	C_2F_6 (F116)	A	I	10000	8.00, 8.96, 14.00	
	SF_6	A	I	3200	~ 10.5	~ 37000
Chlorofluoro-carbons	$CFCl_3$ (F11)	A	S(UV)	65	9.22, 11.82	12400
	CF_2Cl_2 (F12)	A	S(UV)	130	8.68, 9.13, 10.93	15800
	CF_3Cl (F13)	A	S(UV),I	400	8.26, 9.07, 12.77	
	CHF_2Cl (F22)	A	T(OH)	15.8	7.63, 9.00, 10.93	10700
	$CFCl_2CF_2Cl$ (F113)	A	S(UV)	90		15800
	CF_2ClCF_2Cl (F114)	A	S(UV)	200		18300
	CF_3CF_2Cl (F115)	A	S(UV)	400		14500
Chloro-carbons	CH_3Cl	N(O)	T(OH)	1.5	7.14, 9.85, 13.66	
	CH_2Cl_2	A	T(OH)	0.6	7.89, 11.14, 13.19, 13.45	
	$CHCl_3$	A	T(OH)	0.7	8.19, 12.92	
	CCl_4	A	S(UV)	50	12.99	5720
	CH_3CCl_3	A	T(OH)	7	7.22, 9.26, 13.79	2730
Others	CF_3Br	A	S(UV)	110	8.27, 9.22	10000
	O_3	N	S(UV)	0.1-0.3	9.6	
	SO_2	N,A	T(OH)	0.001	7.35, 8.69	

N = natural; A = anthropogenic; O = ocean; T = troposphere; S = stratosphere; I = ionosphere; OH = hydroxyl radical; UV = ultraviolet light. Compiled from data in Refs 16,18-20.

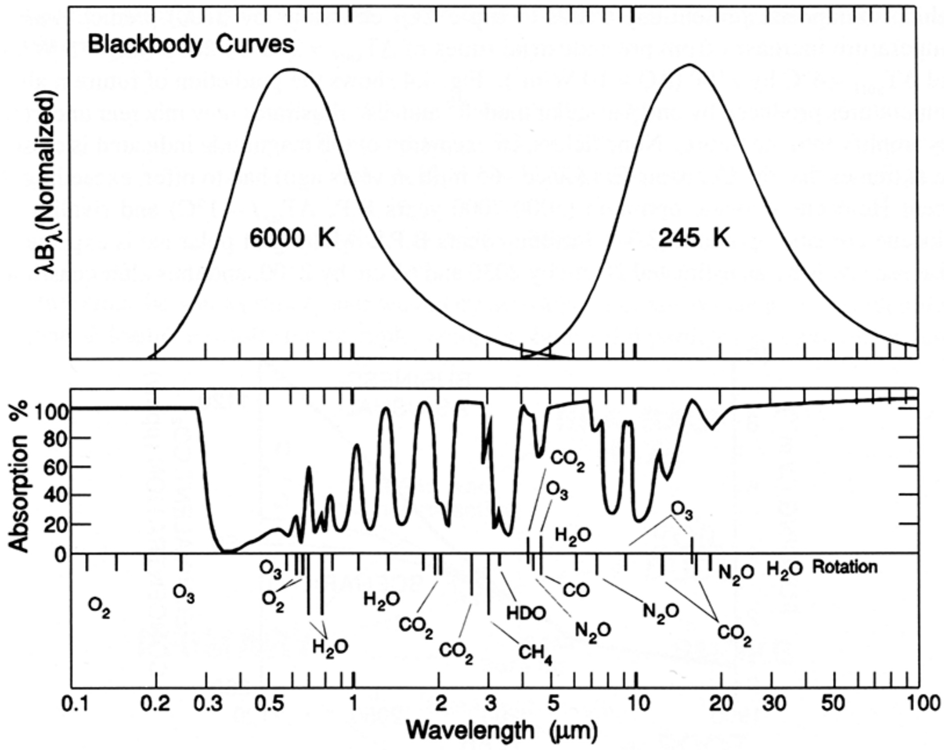

Figure 4.3 *Spectral distribution for emission from the Sun (6000K) and the Earth (245K) showing absorption of a beam of radiation reaching the ground. Absorption bands for various gases are labelled. The infrared window is clearly visible between wavelengths of 7-15μm. (Reproduced with permission from Ref. [17].)*

As well as direct radiative forcing altering T_{surf}, processes within the climate system, such as the relationship of water vapour, snow and ice cover with temperature, also influence the new radiative balance. Following a small radiative forcing of ΔQ W/m^2 being absorbed *at the surface*, the surface temperature will change by [16]:

$$\Delta T = \Delta Q / \lambda \qquad (4.9)$$

where λ is known as the climate sensitivity parameter. Various climate models have estimated differing values of λ, but in the simplest case where the Earth radiates at T_{eff} as a black body (see Equation 2.15), $\lambda = 4\sigma T_{eff}^3 \approx 3.7$ W/m^2/K. Since an often quoted estimate of the radiative forcing produced by a doubling of CO_2 is $\Delta Q \approx 4$ W/m^2, the increase in surface temperature due to greenhouse heating alone would be $\Delta T = 4 / 3.7 \approx 1.1$°C. However, as per Equation (3.5), we would expect forcing from one cause to be augmented by a feedback factor f. For a doubled CO_2 therefore, the final equilibrium global mean surface temperature increment would be:

$$\Delta T_{surf} \approx 1.1f \qquad (4.10)$$

Climate models have determined a range of estimates for the global warming resulting from a doubling of CO_2 (known as the *climate sensitivity*) and most are between $\Delta T_{surf} \approx 1.5$ - 4.5°C. Thus, according to these numbers, small climate forcings by greenhouse gases may be amplified by feedbacks in the system by a factor of $f \approx 1.4 - 4.1$. The attainment of new equilibrium surface temperatures would take many years due to the immense thermal capacity of the oceans. In climate models that assume the present day case of an increase in radiative forcing which is approximately linear, the actual or *realised* temperature change is about 50% of the final equilibrium change, in the case of a climate sensitivity of 4.5°C, and 80% of equilibrium when the sensitivity is 1.5°C. Once the forcing reaches a steady state, temperature continues to approach the equilibrium value on some timescale of many decades [21].

It is now strongly suspected that anthropogenic emissions of trace greenhouse gases have already caused a mean global temperature increase of $\Delta T_{surf} \approx 0.5 - 1$°C since pre-industrial times. This may not seem much, but five of the warmest years on record have been in the 1980's. About three quarters of the anthropogenic contribution to ΔT_{green} is estimated to be due to CO_2 (55%), CH_4 (15%) and N_2O (6%), because of the sheer quantity of these gases added to the atmosphere (see Table 4.2). CFCs account for a quarter of the contribution, even though their total concentration (mostly CFC-11 and 12) is not much more than 1 ppb [10]. Many climatologists expect this warming trend to accelerate to a rate of increase of ~ 0.3°C/decade in the next century. Climate models when applied to 'business as usual' scenarios (which extrapolate present day trends to triple CO_2 emissions by 2100) predict *realised* temperature increases from pre-industrial times of $\Delta T_{surf} \approx$ 2°C by 2030 ($\Delta Q \approx 5$ W/m^2) and $\Delta T_{surf} \approx 4$°C by 2100 ($\Delta Q \approx 10$ W/m^2). Fig. 4.4 shows the prediction of future realised temperatures produced by one particular model [10] and also illustrates well how inherent uncertainties amplify into the future. Nonetheless, an excursion of the magnitude indicated is close to the extremes that the Cenozoic Era (since ~ 65 million years ago) had to offer, exceeding the recent Holocene climatic optimum (5 000 - 7 000 years B.P., $\Delta T_{surf} \approx 1$°C) and rivalling the Pliocene climatic optimum (3.3-4.3 million years B.P.). Melting of polar ice is expected to substantially raise sea levels, by an estimated 20 cm by 2030 and 65cm by 2100, and thus to alter coastlines.

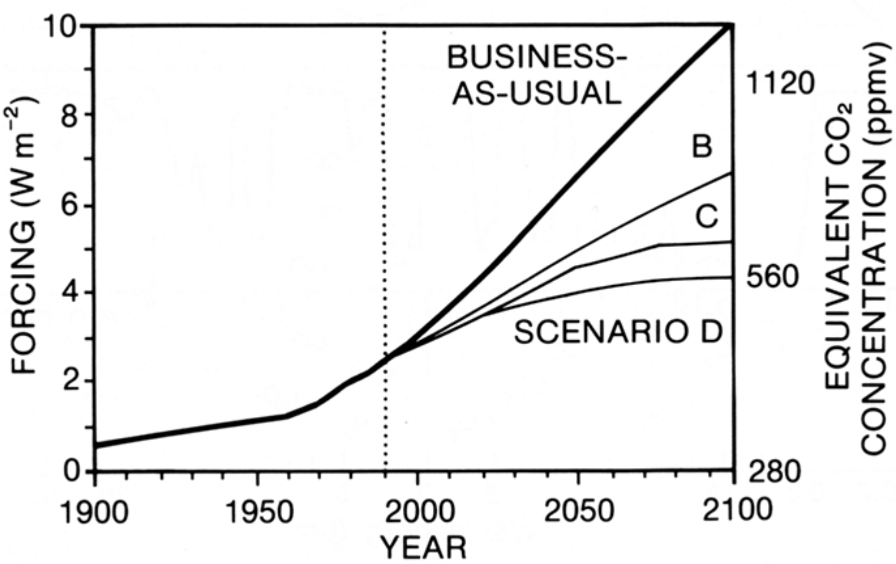

Figure 4.4 *Simulation of the realized increase of global temperature from 1850 to 1990 due to observed increases in greenhouse gases, and predictions of the rise between 1990 and 2100 in a "business as usual" emission scenario. (Reproduced with permission from Ref. [10].)*

Planetary Engineering on the Earth

Civilization also has the ability to generate a *cooling* influence on climate. A *negative* climatic forcing can be caused by aerosol particles which backscatter and absorb sunlight. Aerosols are much more difficult to model than greenhouse gases as they are so variable in particle size, physical properties, chemical composition and spatial and temporal distribution. Tropospheric aerosols are transient and, since they exhibit great spatial variability, tend to affect local or regional energy balances. Stratospheric aerosols, on the other hand, are longer lasting and more homogeneous in both composition and distribution and tend to influence the whole globe. Particles in the size range 0.1 - 1 μm have the strongest climatic forcing since they have low sink rates and the largest total scattering cross section per unit mass. They are nonetheless scavenged by clouds and precipitation, but not as fast as larger particles of > 1 μm.

Various aerosol types and formation mechanisms are set out in Fig. 4.5, The two main categories are *primary aerosols* — particles injected directly into the atmosphere from the surface and *secondary aerosols* — formed in the atmosphere from precursors by chemical and microphysical processes [13]. The most important secondary aerosol consists of droplets of sulphate compounds, principally sulphuric acid. Its precursor is sulphur dioxide, sometimes itself generated from other sulphur gases:

$$\begin{aligned} &SO_2 + OH + M \rightarrow HSO_3 + M \\ &HSO_3 + O_2 \rightarrow SO_3 + HO_2 \\ &SO_3 + H_2O \rightarrow H_2SO_4 \\ &H_2SO_4 \xrightarrow{H_2O} \text{Sulphate aerosol} \end{aligned} \tag{4.11}$$

The difference between primary and secondary aerosols is not always clear-cut. Both industrial and volcanic aerosols, for example, comprise of both solid particles and gaseous precursors. Solids often predominate at first, but later the aerosol properties become dominated by more long-lived secondary products such as sulphuric acid.

Sea salt and soil dust are too ephemeral to cause any major degree of climatic influence. Biological production of dimethyl sulphide (DMS) by phytoplankton is thought to be significant in determining the albedo of clouds over the oceans and has even been linked to a speculative Gaian mechanism for stabilising climate [22]. However, the most climatically significant natural aerosol is stratospheric sulphuric acid produced by the plumes from volcanic eruptions. Events such as El Chichon and Mt Pinatubo (see Plate 4.3), which occur at intervals of 1 - 30 years inject ~ 5 - 10 million tonnes of S into the stratosphere and are capable of inducing a temporary ~ 1 year interruption of global warming trends [23]. Larger volcanoes, such as Tambora, which caused the 'year without a summer' in 1815 inject ~ 100 million tonnes of sulphur into the stratosphere, but only occur at intervals of ~ 100 - 300 years [13].

The strongest climate forcing due to anthropogenic aerosols are those released into the troposphere by industry or biomass burning. These tend to be concentrated in the Northern Hemisphere, particularly downwind of conurbations. Again, the most significant of the many types of aerosol produced is secondary sulphate generated from the SO_2 pollution of fossil fuel power stations and metal smelting. These affect the radiation balance in two ways: the aerosols scatter radiation directly and they increase the reflective properties of clouds by increasing the density of cloud condensation nuclei. Because of the greater difficulty of modelling aerosols, their potential impact on climate has become appreciated more recently than for greenhouse gases. It has now been estimated that the *negative* radiative forcing due to anthropogenic aerosols may be as much as minus 1 - 2 W/m^2 — *comparable with the positive forcing produced to date by anthropogenic greenhouse gases* [24]. It is indeed ironic, and possibly fortunate, that inadvertent man-made influences on climate have been offsetting each other, to the extent that more rapid changes have been mitigated. Whilst more of the feared global warming results from civilization's consumption of fossil fuels, the reflective aerosols produced as a by-product may have bought us extra time to appreciate and understand the full extent of our actions.

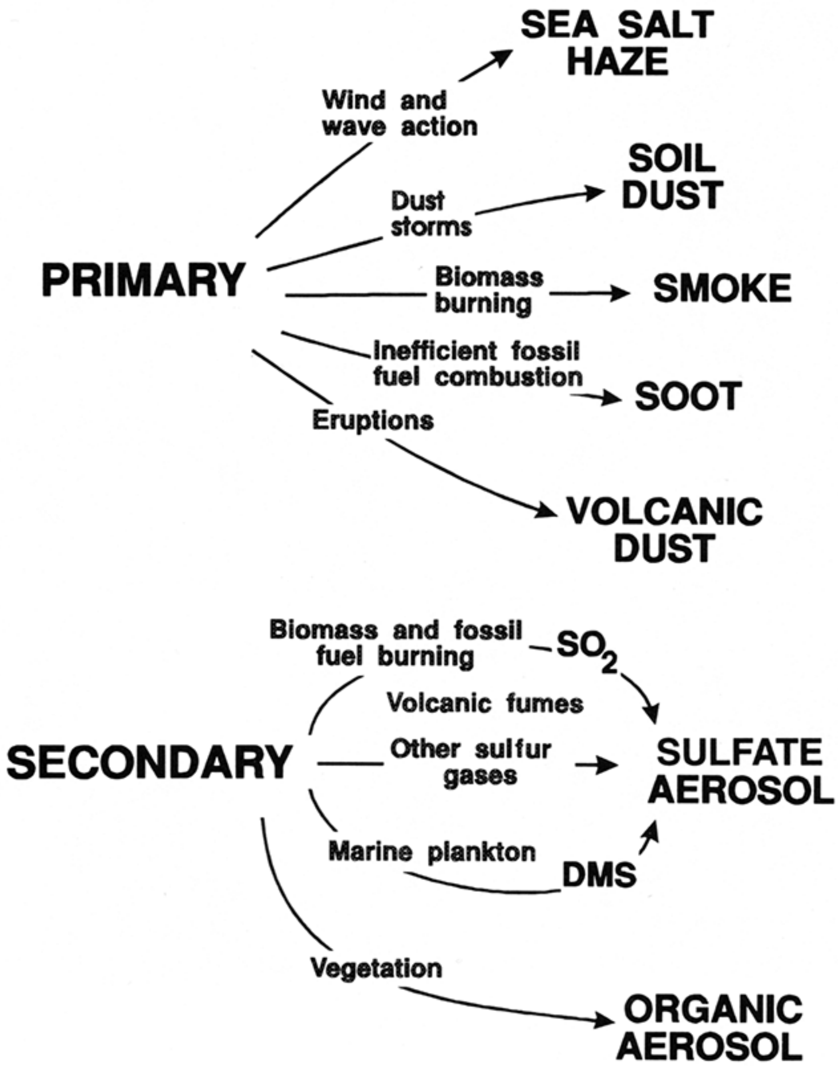

Figure 4.5 *Atmospheric aerosols and mechanisms of formation classified according to primary or secondary generation.*

Table 4.2 shows that annual industrial sulphur emissions already exceed those of the natural background by a factor of ~ 1.5 and are substantially in excess of El Chichon-type eruptions. Even the short-term climatic effects of a Tambora are minor compared with the capacity of those tools of late 20th century civilization devoted to the art of mass (and self-) destruction. Calculations of the effects of dust and soot injected into the stratosphere as a by-product of a nuclear war suggest that the interruption of sunlight could plunge the continental interiors below freezing for several months, temperatures as low as -40°C being possible [8]. A man-made catastrophe such as this would rival in its environmental effects the impact of a significant sized asteroid.

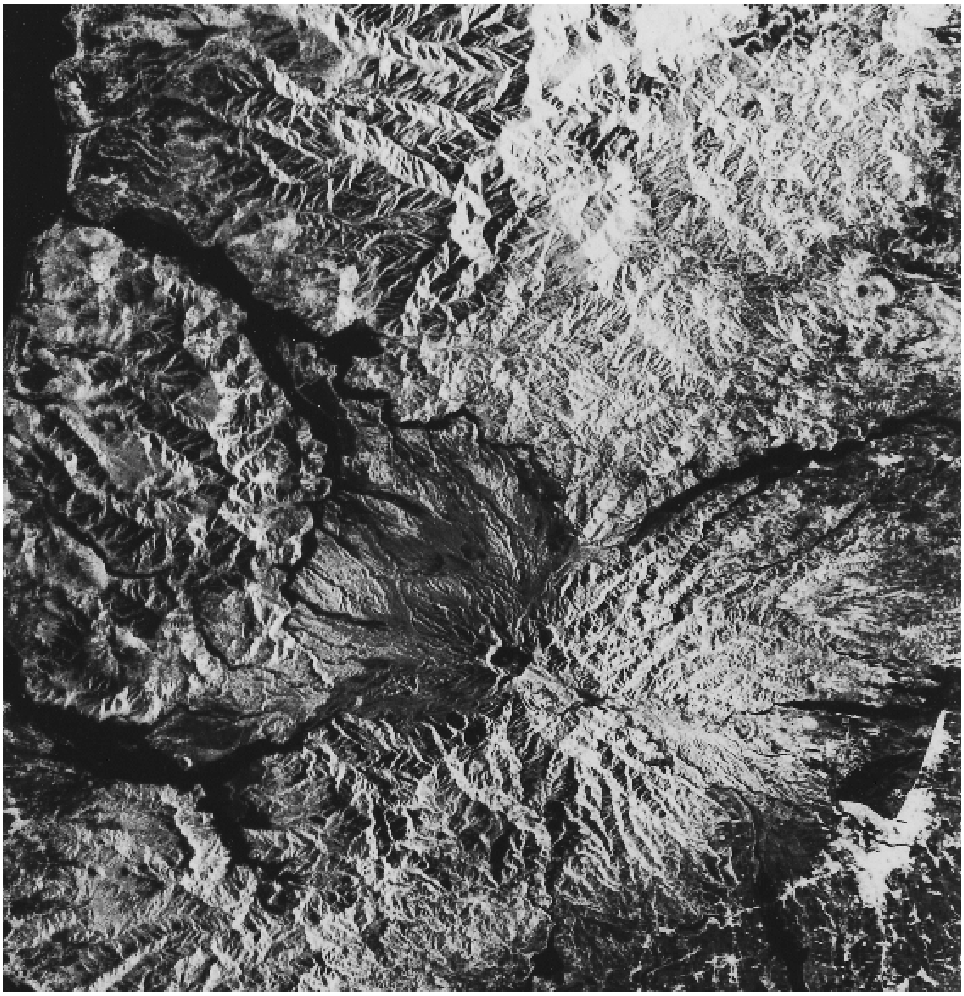

Plate 4.3 *The eruption of Mt Pinatubo in the Philippines, June 15th 1991. Reflective sulphate aerosols injected into the Stratosphere as a result of this event are thought to have caused two consecutive cool Summers in 1992 and 1993. As described in Section 4.2.5, prospective geoengineers already have the technology to artificially contaminate the stratosphere with submicrometre dust and aerosols, thereby emulating this process. (Source: Science Photo Library.)*

4.1.4 Use of Energy

The above examples of the world-altering capacity of global civilization may be impressive, but in energy terms they are quite minor compared to what is potentially achievable.

The total world primary power production is ~ 10 TW, which is about 10% of the power used by the biosphere for carbon fixation and about a quarter of the planet's total geothermal heat flow. A further ~ 20 TW can be said to be in the control of mankind, representing our manipulation of a large fraction of continental NPP [4]. A nuclear war would be equivalent to a short-lived, suicidal, spasm of ~ 1000 TW (see Section 2.5.2 and Table 2.9). The Earth's total insolation however (the solar radiation impinging on the top of the atmosphere) is ~ 175000 TW and the power reaching the Earth's surface is about 60% of this. The power potentially available to a purely planet-based civilization is thus considerably in excess of current usage. The power available to a space based civilization would be vastly greater: solar power stations having the advantages of continual daylight, a vacuum, unlimited room and the possibility of being sited much closer to the Sun [25].

However, it is important to bear in mind that about 75% of world primary energy production comes from the combustion of fossil fuels. Indeed, the rapid development of industrial civilization has been almost entirely a fossil fuel-powered phenomenon, made possible because the procedure of exploiting coal, oil and natural gas reserves *provides* much more energy than it *consumes* (it has a high *net energy ratio*). This was especially true of the more rich and accessible fossil fuel deposits, such as the Texas oil fields, which provided net energy at a ratio of ~ 50:1. Fossil fuels and the associated oxidant O_2 however represent a store of potential energy accumulated by the biosphere over hundreds of millions of years. They are finite and will not occur at all on other planets where there has never been life. Moreover, as has been described in the previous two Sections, unrestrained fossil fuel use is now causing concern about forcing unwelcome changes in the environment.

Thus, if industrial civilization is to persist on Earth, let alone establish itself permanently in space, reliance on fossil fuels must be reduced, and eventually abandoned, in favour of renewable resources. The essentials of this transition are shown in Fig. 4.6 and are essentially identical for a) terrestrial civilization in the 21st century and b) the creation of an independent space-based civilization [26]. The big question is: *given our temporary wealth of fossil fuels, can we switch to renewables in a way that maintains, or increases, the quantity of net energy fed into the world economy?* In the case of space, we must ask: *can a limited investment of terrestrial resources in space settlement provide the basis for self-sustaining growth?* Or in other words: *can net energy be provided from space resources whilst the Earth is still supplying energy subsidy?* If the answer to all these questions is *yes*, then the noosphere, space colonization and ultimately, terraforming, are all possible. This 'yes assumption' is the most fundamental one implicit in all terraforming scenarios.

Prospects for future renewable energy supply on Earth have become more favourable due to impressive technical gains made in the last decade. A recent detailed report published under the auspices of the United Nations Conference on Energy and Development (UNCED) summed up its major findings as: *"Given adequate support, renewable energy technologies can meet much of the growing demand at prices lower than those usually forecast for conventional energy. By the middle of the 21st century, renewable sources of energy could account for three fifths of the world's electricity market and two fifths of the market for fuels used directly."* [27]

Consistent with this scenario is an eight-fold increase in world economic activity by 2050 and a reduction of CO_2 emissions to ~ 75% of that in 1985. The use of fossil fuels, especially coal and oil, is not eliminated but is substantially reduced in relative importance. Renewable resources taking their place are hydropower, intermittent renewables (wind and direct solar), and biomass. All of these would be available on a terraformed planet, whereas the economy of an extra-planetary civilization would be based primarily on the 3.9×10^{14} TW of direct solar output. The one hoped-for future power source about which one can make no conclusions either way is controlled nuclear fusion. Current work on turning fusion (which works excellently as an explosive) into a commercial energy source has yet to demonstrate "breakeven", let alone to prove that it can generate net energy after accounting for the subsidies inherent in infrastructure and fuel acquisition and processing. However, if fusion power becomes viable, then it will open up the darker, outer Solar System for settlement, where fusion fuel (isotopes such as deuterium and helium-3) exists in abundance.

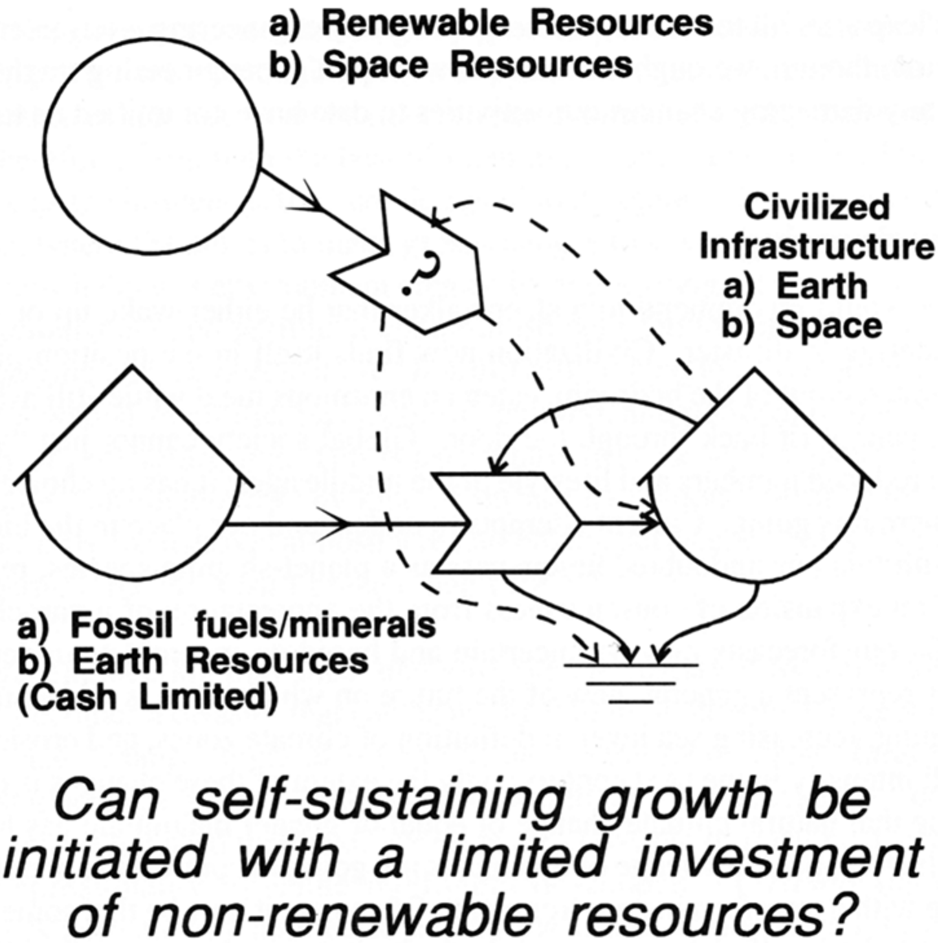

Figure 4.6 *The question of a continuing supply of net energy is fundamental for the survival of technological civilization on Earth and its establishment in space. a) Can terrestrial civilization successfully switch from fossil fuels to renewable energy in the next century? b) Can a space-based civilization rapidly cut its umbilical cord to Earth and grow on extraterrestrial resources? (Adapted from Ref. [26].)*

Thus, whilst many of the details are uncertain, it is clear that human activities are the most potent force remodelling the Earth's crust and the most powerful perturbing influences on the climate and chemical composition of the atmosphere. All of this is achieved with a power 0.02% of the planet's total insolation, possibly a trivial quantity compared to what a future civilization might be able to muster. The fact that these activities occur in a piecemeal fashion, mostly as part of the routine maintenance of competing nations has tended to obscure the planet-shaping power of civilization as a whole. *The fact is that humanity is subjecting the Earth to an unplanned and haphazard experiment in planetary engineering* [28]. We already possess many of the planetary engineering tools listed in Table 3.6. Thus, it is not such a speculative leap after all to consider *directed* planetary engineering — terraforming — on other planets [1]. First of all however, we ought to consider what part geoengineering might play on Earth, to mitigate any damaging changes our activities to date have committed us to in the future.

4.2 Geoengineering

Most people would recommend to a sleepwalker that he either wake up, or go back to bed before blundering to disaster. Civilization now finds itself in the position of a sleepwalker who has wandered out of the bedroom, eaten an enormous meal whilst still asleep and is now so obese he cannot fit back through the door. Global society cannot just "switch off" and return to the reduced numbers and lifestyle of the middle ages; it has no choice but to wake up and look where it is going. Current attempts to understand our place in the biosphere, and to reconcile with this our undoubted uniqueness as a planet-shaping species, represent the beginnings of an expansion of consciousness from the appreciation of a parochial, to a global order. Whilst our forecasts may be uncertain and based on incomplete understanding, they nevertheless represent a general view of the future on which there is widespread consensus: global warming, increasing sea level, redefinition of climate zones, and erosion of the ozone layer will all intensify in the next century — only the extent of these changes is in doubt [10]. It is certainly true that natural climate change of equal or greater magnitude has happened many times in prehistory, but knowledge of this fact is not going to comfort the people who actually have to cope with a transforming environment. Of course, it may be that some of the changes may turn out to be beneficial, such as a warmer Siberia for instance; however, the general feeling is that civilization would do better living with the Earth it knows, rather than in some uncertain hothouse future.

The question therefore is, now that we are beginning to look ahead, how can conscious action counteract our unconscious influences on climate change? The obvious answer is to conserve, use and re-use our resources more efficiently — the goal being as high a level of economic activity as possible that is commensurate with a *sustainable* existence within the biosphere. Technological civilization can persist without having to carry on "business as usual," with its increasing dangers, right through the next century. Predictions of the global warming arising in scenarios where greenhouse gas emissions are reduced, through improved fuel-use efficiency and a partial switch to renewable energy, suggest that we might contain ΔT_{surf} to about half the value expected under "business as usual." This must be the best way forward, but is not the subject of this book. If sustainability and climatic stability cannot be attained fast enough, then we may have to consider deploying engineered countermeasures by adding *intention* and *design* to planet-altering capacities we already possess.

First of all, it should be emphasized that geoengineering faces many practical difficulties that are greater even than those of terraforming. This may seem counter-intuitive when simply comparing the magnitude of the two tasks, until one reflects on all the possible implications and dangers of attempting to tamper with a immensely complex biosphere on an inhabited planet. Climatic zones, ecosystems, nation states and people are all in place and, since environmental quality is so sensitive to its governing parameters, geoengineering must act to maintain the universal status quo ante, rather than maintaining it in one place and altering it elsewhere. Predicting *all* the effects and ramifications of an engineered perturbation of the biosphere is unlikely to be possible. Therefore, even with the best of intentions, geoengineering will pose risks potentially as large as the influences they are designed to mitigate. These problems are less so for terraforming, where the aim is to make gross changes to a *non-living* planet and to introduce life into a new habitable environment created by engineering. It is thus a *creative*, rather than a *conservationist*, act and permits a compromise between the uncertainties inherent in planetary engineering and the needs of life. It is difficult to imagine terraforming being faced with quite such a web of scientific, legal, ethical, cultural and political obstacles that would stand in the way of geoengineering. This is particularly the case with a planet such as Venus, a literal "hell-hole," unsuitable for any kind of surface habitation. Terraforming this world would only pose risks for its toxic atmosphere and baking surface, whereas for the Earth our adage should perhaps be, "If it isn't broken, don't fix it."

Nevertheless, geoengineering may most likely become necessary if looming anthropogenic climate change becomes a disaster that can only be avoided in time by a temporary technical fix. Natural climate change might also be mitigated in the more distant future, such as to prevent the next glaciation which, if unrestrained, would bury the wreckage of Northern civilization under several hundred metres of ice. It is also possible to imagine a situation in the remote future (presumably by some intelligent descendant of *Homo sapiens*) where geoengineering is permanently applied to extend the life of a biosphere no longer able to conduct satisfactory homoeostasis due to a hotter, more evolved Sun.

Proposals for 21st century geoengineering techniques have been published, in varying detail, since the mid 1970's and are set out in Table 4.5. As with terraforming, this sub-discipline of planetary engineering has had a significant upsurge of interest in the last few years — an important recent event being a session entitled “Global Environmental Engineering” that was held at the American Geophysical Union in 1991, at which seven papers by leading climate specialists were presented. James Oberg, whose interests have veered from terraforming towards geoengineering in recent years, followed this by organising another of his colloquia at Houston, this one at the 23rd Lunar and Planetary Conference in 1992 under the banner, “Geoengineering for Biosphere Repair.”

Whilst most of the field's published papers exhibit highly creative thinking and a belief that engineered mitigation of climate change is technically and economically feasible, all emphasize the foolhardiness of proceeding with such measures based on present understanding. Realistically, implementation of any geoengineering technique will require the successful negotiation of a sequence of stages — something similar to the following:

1. Acquisition of more and better data.
2. Further and more detailed theoretical modelling.
3. Small-scale mitigation experiments.
4. Broad agreement on technical feasibility, strategy and outcome.
5. Addressing issues such as law, politics, environmental ethics, finance etc.
6. Development of full-scale infrastructure.
7. Implementation.

Following this, progress would have to be continually monitored, assessed and adjusted or switched off if necessary. Various techniques that might be developed and deployed in this way are covered below in a similar order to their appearance in Table 4.5.

4.2.1. Reforestation

A number of mitigation strategies have been suggested to counter the increasing build-up of CO_2 in the atmosphere — the anthropogenic greenhouse gas that is causing most concern.

The most straightforward way to go about this would be to induce the land biota to absorb more CO_2. This could be done by growing new forests, effectively turning effluent from fossil fuel and biomass burning into tree trunks. If this biomass is stored, or used to replace fossil fuel in power stations, then the net addition of CO_2 into the atmosphere could be prevented. (This is because carbon is not being released from long-term

TABLE 4.5 GEOENGINEERING PROPOSALS

Application	Technique	Tools
Intrinsic geoengineering		
Reduction of greenhouse effect → mitigation of global warming.	Increase sequestration of CO_2 in land biomass.	Managed plantations of trees and swamp plants.
	Increase sequestration of CO_2 in oceanic biomass.	Fe^{2+} fertilizer, ocean going ships.
	Inject CO_2 from power stations into exhausted oil wells and deep oceans.	Compressors, pipelines etc.
	Accelerate decomposition of tropospheric CFCs.	Powerful laser arrays, mirrors.
Enhancement of albedo → mitigation of global warming.	Emplace stratospheric aerosol/dust layer.	Dust, sulphur/SO_2, naval guns, rockets, aircraft.
	Increase tropospheric cloud cover with manufactured cloud condensation nuclei.	Sulphur, incinerators, ocean going ships.
Reduction of ozone depletion → repair of polar ozone holes.	Inject ozone layer with chlorine scavenging chemicals.	Alkanes, rockets, aircraft.
Extrinsic geoengineering		
Reduction of insolation → mitigation of global warming.	Interruption of sunlight above the top of the atmosphere.	Space screens, station-keeping mechanisms and ancillary infrastructure, space dust.
Augmentation of insolation → nighttime illumination, search and rescue, increase productivity of crops and solar power.	Capture and re-direct sunlight onto dark hemisphere.	Space mirrors, station-keeping mechanisms and ancillary infrastructure.
Protection from asteroid or comet impact → mitigation of global catastrophe.	Alter trajectory of threatening body.	Nuclear explosives, mass drivers, delivery systems.

storage underground.) Reforestation as a geoengineering technique has been suggested by different authors for over a decade [29-32] and the problem is similar in scope to the task of providing for the world's energy needs by switching from consuming fossil fuels to biomass [33]. Rather than following any individual approach here, we highlight the scale of the problem and some of its principal concerns with some simple calculations.

The parameter with which to start is the *net primary productivity* of vegetation (NPP) which equals the amount of organic matter fixed by photosynthesis minus the amount consumed by plant respiration. In other words, it represents the rate of synthesis of biomass that can go into fresh plant growth or consumption by heterotrophs. The maximum theoretical efficiency of NPP (the conversion of leaf-incident light energy into the chemical energy of glucose) under field conditions is $\varepsilon \approx 5\%$ for C4 plants and $\varepsilon \approx 3\%$ for C3 plants. NPP is often expressed in dry tonnes/hectare/year and can be calculated so [30]:

$$NPP = \frac{\varepsilon \times S_{daily} \times f_{warm} \times f_{peak} \times 365 \times 100^2}{E_{biomass}} \tag{4.12}$$

where S_{daily} is the annually averaged total daily insolation (J/m^2/day); f_{warm} is the fraction of the year warm enough for productive photosynthesis (growing season); f_{peak} is the average insolation factor in the growing season and $E_{biomass}$ is the energy content of biomass (~ 16 GJ/ dry tonne). For the tropics, we estimate $S_{daily} \approx$ 21 MJ/m^2/day, $f_{warm} = 1$ and $f_{peak} = 1$; for the temperate regions, $S_{daily} \approx$ 13 MJ/m^2/day, $f_{warm} \approx 5/12$ and $f_{peak} \approx$ 1.5. Equation 4.12 therefore becomes:

$$\begin{aligned} NPP_{tropics} &\approx 4790\varepsilon \text{ t/ha/yr} \\ NPP_{temperate} &\approx 1850\varepsilon \text{ t/ha/yr} \end{aligned} \tag{4.13}$$

Referring back to Table 2.10, it can be seen that efficiencies of naturally occurring ecosystems and agriculture never approach theoretical maxima and usually lie between $\varepsilon \approx 0.1$ - 1%. Reasons for this include lack of a full canopy, diseases and limited supplies of nutrients and water.

The amount of biomass comprising long-lived growth however is less than NPP as it must take into account the consumption of plant matter by the biotic community. The quantity of ultimate interest to geoengineers is therefore the *net community production*, where NCP = NPP minus heterotrophic respiration. In a young, growing forest, where community photosynthesis (P) > respiration (R), NCP > 0. But for a mature forest approaching ecological climax, $R \rightarrow P$ and $NCP \rightarrow 0$. Thus a typical hectare of tropical rain forest may produce ~ 20 tonnes of biomass per year but *all of it* is consumed and recycled — there is no net accumulation of carbon.

It is clear therefore that we must plant new forests to mop up atmospheric CO_2 and are faced with a choice of either natural forests, or managed tree plantations, the energetics of which are illustrated in Fig. 4.7. Natural forests have the advantages of being autonomous, fostering a high biodiversity and having superior aesthetic qualities, but their NCPs would be modest and would tend to zero in ~ 40 - 100 years as they approached ecological climax (see Plate 4.4). In contrast, the managed plantation is growing trees as an agricultural crop, often as a monoculture and with a much reduced population of consumers; NCP is therefore greater, but at the cost of having to supply an extrinsic energy subsidy in form of human work, involving cropping, pest control, irrigation and applications of fertilizer. The plantation could theoretically be kept productive indefinitely, so long as crops are regularly coppiced, or rotated, to keep stands in an immature state, and other subsidies also continue.

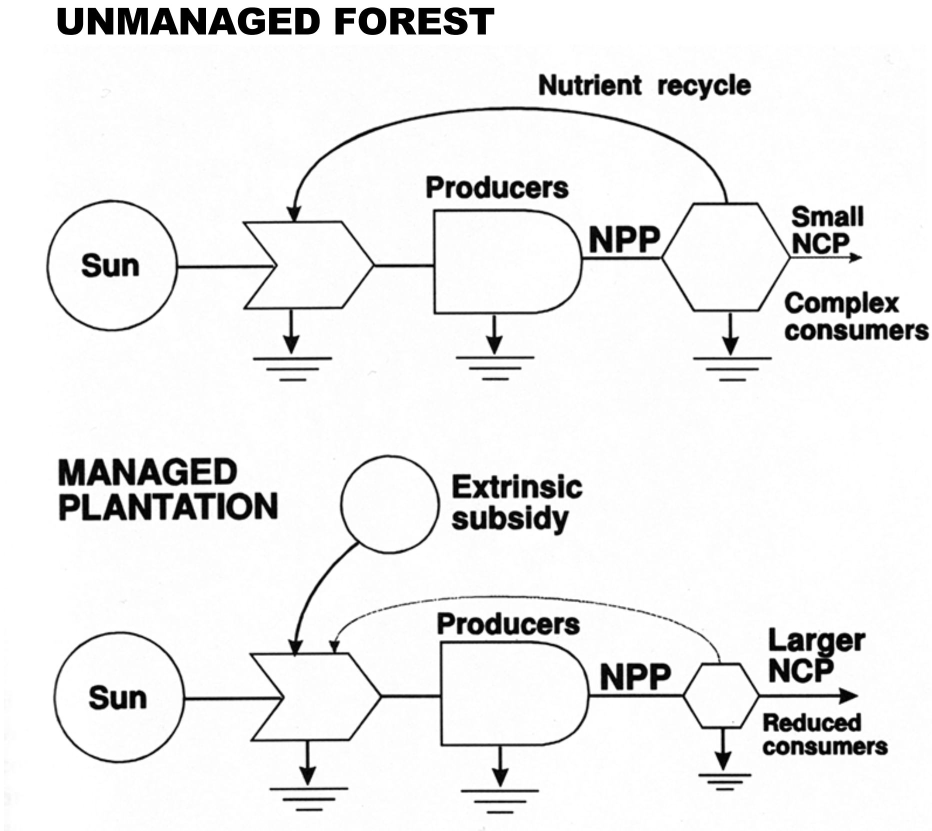

Figure 4.7 *Managed plantations achieve a higher net community production than would be found in a natural ecosystem in part because the population of consumers is significantly reduced. However, this can be sustained only by providing extrinsic energy subsidies such as irrigation, fertilization, and human work. This is both to optimize growing conditions and to substitute for natural energy flows that have been excluded.*

The references cited quote numerous estimates of the amount of dry biomass accumulated by growing forests or tree plantations and could be reviewed at length. However, for our purposes, it suffices merely to determine "ball-park" figures for NCP which would be generally acceptable [33]. Fully stocked, natural forests usually accumulate ≤ 5 t/ha/yr, whereas experimental poplar and willow plantations in the EC aim to generate 10 - 12 t/ha/yr. As one would expect, the tropics can support much more rapid growth, eucalyptus plantations in Brazil routinely producing 10 - 20, and in favourable areas, as much as 40 t/ha/yr. Sugar cane, a highly productive C4 plant, achieved a world-wide yield in 1987 of 36 t/ha/yr, the country with the most efficient yield being Zambia which produced 770,000 tonnes of above-ground dry biomass on just 10,000 hectares. Unprecedented yields of trees are being achieved in experiments with small, intensively managed, plots: in the US Pacific Northwest, genetically improved hybrid poplars have gained 43 t/ha/yr and in Brazil stands of *Eucalyptus grandis* have grown by 65 t/ha/yr. Larger-scale plantations however, especially when sited on less than ideal land, usually exhibit yields less than half these field records. In their section on supply prospects for biomass energy, the UNCED report stated [33], *"It is reasonable to expect yields* [of energy plantations] *averaged over hundreds of millions of hectares would range from 15 to 20 tonnes per hectare* *per year during the first quarter of the 21st century and 20 to 30 tonnes per hectare per year in the second quarter of the next century."*

Plate 4.4 *Primary production in this South London wood can be dated very accurately. Fifty years ago this scene would have shown cratered piles of masonry and few signs of life — all that was left of a row of Victorian houses demolished by the Luftwaffe. Ecological succession in the interim and modest management has created a stand of vegetation so dense that a main road 40 yards away is invisible and almost inaudible. (Photo by Martyn Fogg.)*

Annual anthropogenic emissions of carbon dioxide total to ~ 26,000 million tonnes and its accumulation in the atmosphere is occurring at about half this rate (where the other half is disappearing to is not yet clear, but it may be dissolving in the oceans). Thus, we presently face a task of disposing of ~ 13,000 Mt CO_2/yr ≈ 3500 million tonnes of carbon. As fossil fuel emissions increase, this annual increment will grow further. To estimate the mitigating potential of reforestation, we examine three cases chosen from the discussion above: by converting dry biomass to fixed carbon (a factor of 0.4), we obtain NCP values of growing natural forests of 2 t C/ha/yr; managed plantations of 6 t C/ha/yr and "high-tech" plantations of 10 t C/ha/yr. The reforested area required in km^2 to counteract the entire CO_2 build-up is therefore simply:

$$a_r = \frac{3.5 \times 10^9}{100 \times \text{NCP}} \tag{4.14}$$

Results of the calculation in each of the three cases are shown in Table 4.6, along with the ratio of a_r to total land area, to the area of a large country (the USA) and a small country (the UK).

TABLE 4.6 REFORESTATION REQUIRED TO MITIGATE CO_2 BUILDUP

	NCP (tonnes-C/ha/yr)	Reforested area (10^6 km^2)	a_r/a_{land}	a_r/a_{USA}	a_r/a_{UK}
Natural forests	2	17.5	0.12	1.9	73
Managed plantations	6	5.8	0.04	0.62	24
High-tech plantations	10	3.5	0.02	0.37	15

It is evident that the areas required to tackle the entire problem with reforestation alone are very large. This is especially true in the case of unmanaged forests which would need to cover ~ 12% of the land surface — an area almost double that of the USA and over seventy times that of Britain! Moreover, as the forests approach maturity in 40 - 100 years, their NCPs would tend to zero and a new forest of similar size (or greater if fossil fuel emissions have increased) would need to be planted; this is unless trees from the mature forest are cropped, rotated and their biomass is used as a substitute for fossil fuel. Managed plantations fare better in that they only require ~ 2 - 4% of total land area (about half the area of the USA), which might be found by an equitable sharing of the responsibility for reforestation amongst as many nations as possible. However, silviculture on such a huge scale has never been done before and the magnitude of the subsidies required is unknown. Storage of the large quantities of biomass produced could pose difficulties. Again, the obvious solution seems to be to develop biomass as a major source of primary energy, possibly by using integrated gasifier/gas turbine technology, originally designed for the efficient combustion of coal [34].

Reforestation certainly seems to have many attractive aspects as a geoengineering option for the 21st century. Not only would it provide a renewable alternative to fossil fuel, but we might also expect improved air and water quality, increased abundance of wildlife and greater recreational opportunities. However, one can also foresee several obvious difficulties with the idea. Massive reforestation will doubtless compete with other uses for land, especially with the needs of food production. New forests may therefore be constrained to land of marginal quality and might therefore suffer from resource limitations and an increased need for subsidy. There will have to be a long-term commitment to maintenance and the increased biodiversity, mentioned above as a benefit, may not arise if broad expanses of monocultures are opted for. Worst of all, there is bound to be international bickering over which nations should bear the brunt of the programme. Should the area each nation is required to plant be proportional to the amount of suitable vacant land available, or to its consumption of fossil fuels? Should some nations pay for others to plant the forests they cannot?

There are thus many questions to be solved before reforestation can evolve from a purely local activity to a true geoengineering technique. We need to know more about forest ecology and biology — what are the optimum species mixes of trees to plant, on what type of land and where. We must accumulate more experience of silviculture — how to maximise and sustain yields of forest products, whilst minimizing human input. And we must also develop a better understanding of the economics of large-scale reforestation and the investment and returns likely over ~ 100 year timescales.

Thus, there seem to be no fundamental scientific obstacles in the way of the reforestation option. However, it certainly goes against the current trend in developing countries where net *de*forestation is happening at an alarming rate. These countries, such as Brazil and Indonesia, happen to be some of the optimum regions for growing forests, but presently to opposite is happening. The natural climax area of moist tropic forest is ~ 16 million km^2 — the area of that left in place is ~ 9 million km^2 [4]. A glance back at Table 4.6 shows that reforesting the difference between these two figures could fulfil the demands of the whole programme, but this will not be practical. Geoengineering with trees is such a land-hungry technique that it may not be realistic as a sole solution to the anthropogenic build-up of CO_2. Nevertheless, it is almost bound to be a factor in any strategy integrating several techniques, possibly starting modestly and growing if benefits are proven. This is recognised in a recent publication, "Policy Implications of Greenhouse Warming" [32] (PIGW) produced by the Committee on Science Engineering and Public Policy (under the aegis of the US National Academy of Sciences, National Academy of Engineering and Institute of Medicine) which recommends that we, *"Explore a moderate domestic reforestation programme and support international reforestation efforts."* Their Mitigation Panel estimated that an initial target to reforest 28.7 Mha of *"economically marginal or environmentally sensitive pasturelands or croplands and non-federal forestlands"* could sequester 240 Mt CO_2 equivalent per year (about 10% of the US emissions) at a cost of \$3 - \$10 per tonne.

Trees are not the only land-based option for drawing down large amounts of CO_2. Marsh plants have also been nominated [29], since some species such as water hyacinths demonstrate phenomenal growth (~ 150 dry tonnes of biomass/hectare/year). However, the total area of marshland will be much less than that available for forestation and marsh-plant biomass will pose greater problems for long-term sequestration or conversion into useful products. Other ideas have included shallow ponds of algae aerated by the flue gases from power stations and large plantations of halophyte vegetation, irrigated with the salty water found naturally in some desert areas. However, in whatever form it takes, the exploitation of photosynthesis is a practise intimately associated with civilization. Using plants as planetary engineering tools therefore makes sense not just for Earth, but on other planets too.

4.2.2 Stimulation of Biomass Production in the Ocean

With a mass ~ 270 times that of the atmosphere, the oceans are of immense importance to the Earth's climate and biogeochemical cycles. Thus, when evaluating geoengineering options, it certainly makes sense to consider how the properties of the oceans and its ecosystems can be put to good use. The total NPP of the oceans is only about half that of the land, even though they are over 3.5 times the area. In principle therefore, there may be some scope for drawing down additional CO_2 into the oceans by stimulating fresh NPP; if some fraction of this biomass can escape consumption and realisation by transportation to depth, and then some mitigation of anthropogenic CO_2 build-up will be achievable.

A possible method of doing this has been proposed by the late John Martin and colleagues of the Moss Landing Marine Laboratories in California [35,36]. They have pointed out that primary productivity over vast areas of the Southern Ocean appears not to be limited by supplies of major nutrients (such as nitrate and phosphate), which are abundant, but by a deficiency if iron. Small quantities of iron are essential for cell metabolism (such as in the manufacture of cytochrome enzymes) and in iron-rich coastal waters (where they measured Fe at a concentration of 7.4 nmol/l) they found NPP to be ~ 30 times higher than in the normal iron-poor areas (Fe at 0.16 nmol/l) where ~ 90% of the stock of major nutrients remains unused. The supply problem arises because the high reactivity of iron in aqueous solution results in it being rapidly scavenged by particulate material. Moreover, its occurrence in surface waters seems not to come from up welling from depth, but from airborne dust blown off the continents or released from melting ice. The remoteness of the Southern Ocean from land therefore results in its waters being particularly deficient in iron (see Plate 4.5).

This sensitivity of NPP over huge areas to parts per billion of one particular element has naturally led Martin *et al* to speculate that at other times the productivity of the Southern Ocean could have been considerably enhanced, with important consequences for the Earth's climate. In their words [35]: *"Judging by the unused excess of major plant nutrients, this lack of essential Fe seems to be severely limiting the power of the 'biological pump' and thus contributing to the raised atmospheric concentrations typical of previous and present interglacial periods... In contrast, greatly enhanced Fe input from atmospheric dust may have stimulated phytoplankton growth and increased the power and efficiency of the biological pump, thus contributing to the drawing down of* CO_2 *during glacial maxima."*

Should this hypothesis be true, then the process described with its, *"... very large return of C for a small investment in Fe..,"* [36] has obvious relevance to the contemporary situation. Martin *et al* estimated that, if stimulated by the fertilization of ~ 0.1 - 0.5 Mt Fe/yr, the up welling of major nutrients in the area of the Antarctic Ocean could support an additional ~ 1800 Mt C/yr of NPP. The naturally pertaining condition and how it is susceptible to influence by geoengineering is illustrated in Fig. 4.8. It also shows a potential difficulty with the scheme in that a net draw down of CO_2, in excess of that embodied within a larger standing crop, would have to be accompanied by the exportation of dead biomass into temporary storage in deeper waters. Thus an important constraint on the rate at which CO_2 is taken up by the oceans is the rate at which vertical mixing of oceanic water can overturn the CO_2 excess from the fertilized region into the abyss.

There have been two important modelling studies of the dynamical aspects of the iron fertilization scenario, which come to slightly differing conclusions. The first, by T.-H Peng of the Oak Ridge National Laboratory in Tennessee and W.H. Broeker of Columbia University [37], concluded that the process would have very little effect. Assuming 100 years of totally successful fertilization (all the applied iron is utilized by phytoplankton), they calculated the CO_2 content of the atmosphere would be only 10 ± 5% less than it would have been in the absence of fertilization.

Plate 4.5 *Photo taken of the Earth's Southern Oceans by Apollo 17, showing the Antarctic ice cap Southern Africa and Madagascar. It is the iron-poor waters of these regions that would require fertilization in the scenario of Martin et al. in order to stimulate phytoplankton productivity and to draw down atmospheric CO_2. (Photo courtesy of NASA.)*

The second study, by F. Joos and U. Siegenthaler of the University of Bern and S.L. Sarmiento from Princeton [38], is a little more sanguine. This is mainly because they assumed a larger oceanic area subject to fertilization (16% of the total oceanic area) and also took into account the non-linear relationship between pCO_2 in the atmosphere and the amount of dissolved CO_2 in surface waters. Again, to gauge an upper limit to the effect, they assumed perfectly effective fertilization, but in the context of three different scenarios: 1) where pCO_2 is set at pre-industrial levels and there are no anthropogenic emissions; 2) a controlled emissions scenario where CO_2 additions to the present 355 ppm in the atmosphere are restricted to 1990 levels; and 3) 'business as usual', where anthropogenic emissions continue to grow, reaching 22,400 Mt C/yr by 2100. In each of these cases, the model was run with and without Fe fertilization. The results of the simulations for the years 2040 and 2090 are plotted in Fig. 4.9. Carbon dioxide draw down rates of ~ 2000 Mt C/yr were achieved in fertilized cases which reduced the atmospheric concentration of CO_2 in the emission scenarios by 50 - 58 ppm after 50 years and 90 - 107 ppm after 100 years over the levels predicted for the controls. Fertilization was found to gain in effectiveness with higher pCO_2 since this increased the quantity dissolved in surface waters and hence available for photosynthesis. The strategy therefore was predicted to bring about a significant CO_2 reduction, although of a magnitude far too small to mitigate the entire problem. In fact, if one looks at the data for 2090, CO_2 has risen to 665 ppm in the case of 'business as usual' and fertilization; in contrast, restricted emissions and no fertilization results in 506 ppm. The authors thus summed up their findings by stating: *"The most important conclusion we draw from our calculations is that, although the effect of iron fertilization is large enough to justify further study, the effect of a significant change in the emissions of CO_2 is even larger."* In a separate piece [39], Sarmiento reinforced this view when he wrote, *"We cannot afford to have a quick fix iron fertilization strategy, with all its attendant problems, draw attention away from the far more effective and reliable strategy of emission control through such measures as fuel efficiency and biomass fuel substitution."*

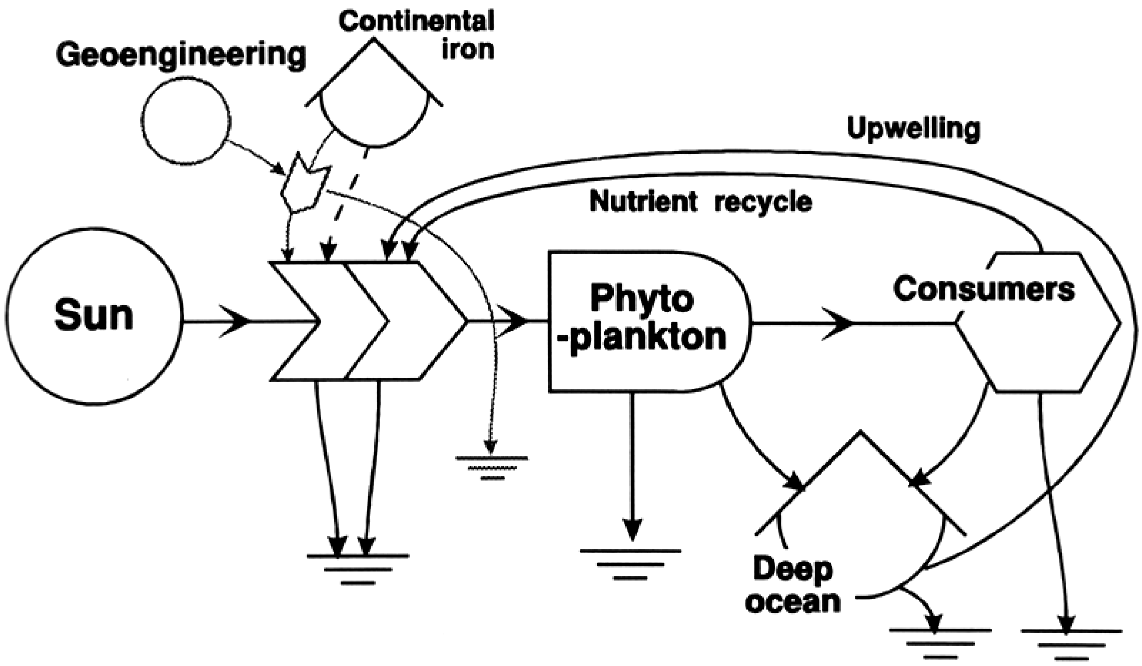

Figure 4.8 *Energy/matter flow in the Martin et al. Iron Fertilization Model* [35,36]. *Growth of phytoplankton in the southern ocean requires both major nutrients (supplied by up welling) and Fe^{2+} supplied as airborne dust from land). Geoengineering stimulates better growth by supplying extra iron where it is the limiting factor, but CO_2 drawdown depends on the rate of transport of carbon into the deep ocean.*

So, iron fertilization of the Southern Ocean still has to be proven as a viable geoengineering technique. It remains highly speculative and its likely effectiveness is unclear. Many crucial aspects of the process still need to be understood, such as what effect the stimulation of huge phytoplankton blooms would have on oceanic ecosystems and whether or not there are other micronutrients apart from iron that must be taken into account. (Recently it has been suggested that phytoplankton productivity might also be limited by the availability of inorganic zinc in seawater. Zinc is required as a constituent of the enzyme carbonic anhydrase, involved in the uptake of bicarbonate anions, and can be substituted for by cobalt or cadmium [40].) Another difficulty that the present studies agree upon is that fertilization must be an ongoing process — once it stops the additional CO_2 sequestered in the oceans will return to the atmosphere in a similar period of time that it took to store it there in the first place. Despite these misgivings however, it is certainly possible to imagine this prospective geoengineering technique being suitable for evaluation by quite large-scale experiments at sea that are unlikely to intrude upon or pose any direct danger to civilization.

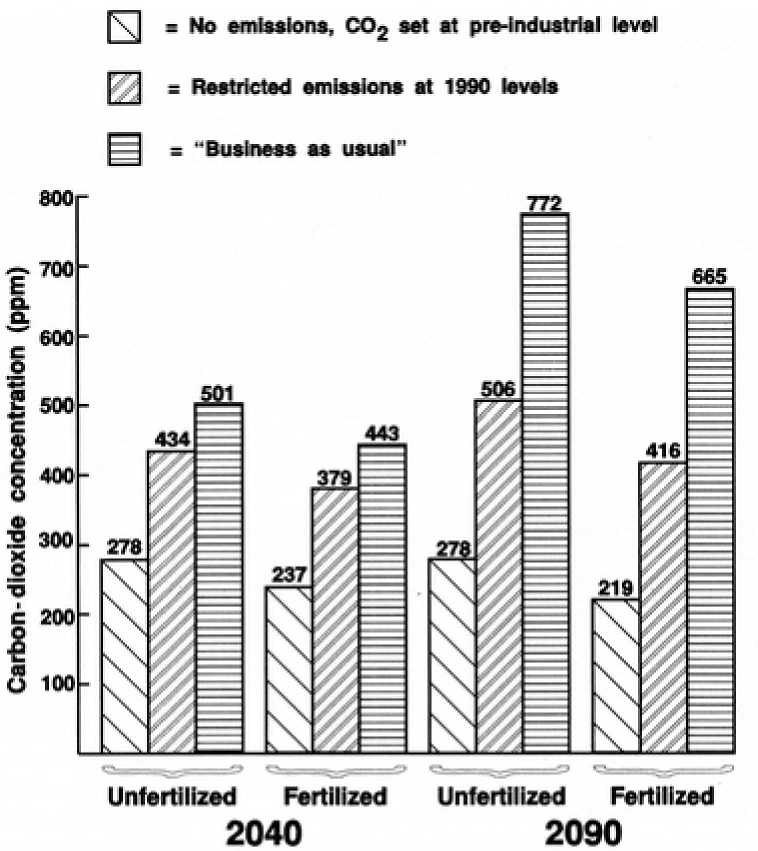

Figure 4.9 *Results of the iron fertilization calculations of Joos et al. showing atmospheric CO_2 concentrations in 2040 and 2090, in both fertilized and unfertilised cases, for a "control" and two different emission scenarios. (Histogram constructed from tabulated data in Ref. [38].)*

The results of the first such iron-enrichment experiment have recently been published [41-43]. The authors were a team of American and British oceanographers, and whilst they took pains to deny any association of their research with climate manipulation, it was of obvious and direct relevance. In mid-October 1993 the research ship *RV Columbus Iselin* fertilized 64 km^2 of the equatorial Pacific Ocean in the vicinity of the Galapagos Islands with 15,600 l of a solution containing 8100 mol of Fe^{2+} and 0.35 mol of an inert marker (SF_6). This was dispensed at 12 l/s into the ship's propeller wash as it steamed in a criss-cross pattern across the target area at a speed of 9 km/hr. The effect was to increase the concentration of iron in surface waters from 0.06 nmol/l to 3.8 nmol/l. For the next ten days the enriched zone was tracked and measurements were taken of a variety of parameters such as nutrient and chlorophyll concentrations.

A biological response was detected within 24 hours. Primary productivity increased by a factor of three, autotrophic biomass doubled and heterotrophic biomass increased by 50%. Thus proof has finally been obtained that phytoplankton growth, in a natural setting, *is* physiologically limited by a dearth of iron. However, although some response to fertilization was noted, it was transient and production was not stimulated to the extent that major nutrients became depleted (as is observed in bottled experiments). As stated in one of the reports [42]: *"We conclude that an artificial fertilization of this region of ocean by addition of inorganic iron salt does not result in the realization of more than a small fraction (3-12%) of the potential for draw down of surface water (and thus, eventually, atmospheric)* CO_2*."*

The reason for this less than complete response is not yet known. It may be that heterotrophs simply responded to the three-fold increase in their food supply and consumed it three times faster, hence returning organic carbon back to CO_2 at a more rapid rate; or the 'one-off' nature of the experiment may have been the cause — iron was found to be rapidly lost from the system, a difficulty not found in bottled simulations. The results of the *Columbus Iselin* experiment, whilst suggestive that iron fertilization may only be a marginally effective geoengineering technique, may therefore not necessarily apply in the case of more continual enrichments in the Southern Ocean. But to really know, larger-scale and prolonged experiments in the right setting are needed.

On the assumption that the technique actually works as conceived by Martin *et al*, the Mitigation Panel of the PIGW study [32] has estimated the resource and hardware requirements of its implementation. To mitigate 1800 - 3000 Mt C/yr with applications of ~ 0.5 Mt FeCl and $FeSO_4$ would require a fleet of 20 ships, each of 10,000 tonne capacity, steaming a grand total of a million miles each year and being replenished every two months. This is not a large fleet in comparison to some navies and commercial maritime companies. The calculated cost of this endeavour is \$1 - \$15 per sequestered tonne of CO_2.

4.2.3 Direct Sequestration of Carbon Dioxide

Burning fossil fuels basically involves withdrawing carbon from storage within long-term biogeochemical cycles (from the lithosphere) and dumping it in the arena of the short-term cycles (the atmosphere and hydrosphere). The two techniques discussed above have adopted the method of trying to assimilate this extra carbon in short-term cycles via biochemical conversion. An alternative approach is to simply treat anthropogenic CO_2 as waste and to find some reservoir big enough to store it in.

The oceans contain ~ 3.5×10^7 Mt of dissolved carbon, some 10,000 times the annual amount needing to be dealt with by geoengineers. The waters of the Earth are therefore so capacious and so well buffered by their inherent carbonate chemistry, that they could theoretically store a substantial fraction of civilization's CO_2 emissions without becoming significantly more acidic. However, the problem with the solution of CO_2 into the oceans over the timescale of global warming is that it is too slow. Carbon in fossil fuels has to pass through a chain of dilutions and interfaces before the CO_2 produced by combustion ends up in the deep ocean (see Fig. 4.10). A rate that particularly limits the speed at which uptake can occur is the gradual mixing of surface waters with those at depth.

A geoengineering technique for overcoming this problem was originally suggested by Cesare Marchetti of the International Institute for Applied System Analysis in Austria [44]. He proposed bypassing the natural processes of dilution and mixing by injecting liquid carbon dioxide directly into descending ocean currents. Once isolated by the high density and sluggish circulation regime of the deep ocean waters, it would be prevented from returning to the atmosphere for as long as ~ 1000 years.

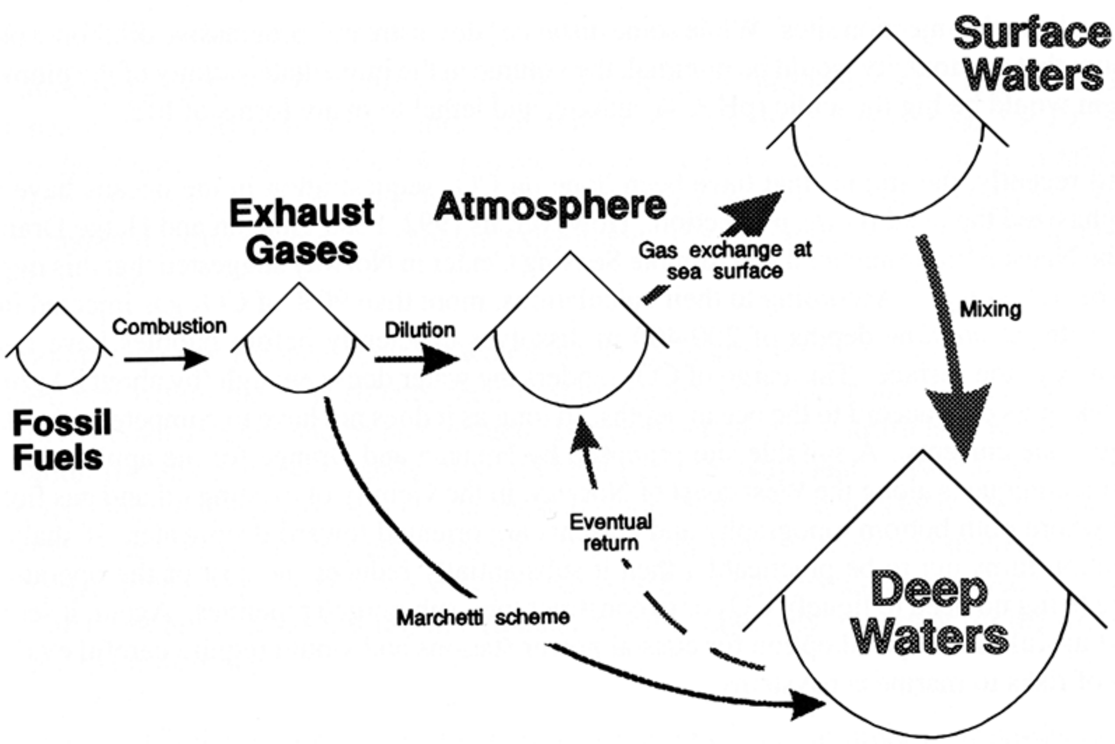

Figure 4.10 *The process of progressive dilution, from carbon in fossil fuels to dissolved CO_2 in the deep ocean. Marchetti proposed shortcutting this slow process and injecting power station effluent directly into the deep ocean.*

The scheme as envisioned by Marchetti would involve first stripping carbon dioxide from combustion gases in fossil fuel power stations. The next step would be to liquefy it at room temperature by compression to 60 - 70 atm in which state it would flow readily like water. It would then be pumped in overland pipelines, similar to those designed to handle natural gas, to disposal sites. One such location Marchetti nominated as ideal, is the bottom of the Straight of Gibraltar. Here, there emerges an outflow of dense water from the Mediterranean which sinks down the continental rise to an equilibrium buoyancy level of ~ 1500 m, whereupon it fans out to cover most of the Atlantic. The flow rate of this current is ~ 10^8 Mt/year, involving a mass of water of about 10,000 times that of the CO_2 requiring disposal. Thus, once the exhaust plume had mixed thoroughly with surrounding waters, its properties would not be greatly altered. An alternative way to sequester carbon dioxide in the deep ocean, if the advantage of a strong descending current is not available, would be to construct a longer pipe right down to a depth of ~ 3000 m. At these pressures, liquid CO_2 is significantly denser than water and would sink of its own accord to the ocean floor where it might collect and pool in a fashion similar to the hot brine 'lakes' at the bottom of the Red Sea. Possibly, solid CO_2 hydrates might form and settle as a layer of underwater 'snow'. Clearly, further modelling and experimentation is required before we develop a more detailed picture of the fate of carbon dioxide in this incompletely understood environment.

Although direct carbon dioxide sequestration into the oceans overcomes many of the uncertainties inherent in the iron fertilization scenario (with its dependence on natural mixing timescales), it still has a number of difficulties. For a start, it is only intended to deal with the ~ 50% of anthropogenic CO_2 released by power stations, leaving the balance of the emissions to continue as before. It actually *enhances* the total production of CO_2 since the scrubbing and storage of flue gases would consume about a fifth of a power station's output, entailing the consumption of 20% *more* fuel to maintain its power rating. Significant additional obstacles are the logistics of a large-scale operation to pipe emissions from numerous inland sites, the cost of constructing and maintaining pipelines, and the expense of laying their termini far out to sea, under depths of hundreds to thousands of metres of water. Estimated costs of such a program [45] come to ~ \$10 - \$70 per sequestered tonne of CO_2, although there are possibilities of reducing this by designing a pipeline network to be shared by a number of power stations, or by limiting the strategy to those situated in coastal areas. Another obvious, but unquantified, problem would be the impact of CO_2-rich plumes of water, emanating from the injection sites, on marine life. Whilst some distance "downstream," progressive dilution would ensure that any toxicity would be minimal, the volume in the immediate vicinity of the plume's origin would be highly acidic (pH < 4), anoxic, and thus lethal to many forms of life.

Until recently, the studies that have been done on CO_2 sequestration in the oceans have all emphasized the need for *deep* injection. However, in 1992, Peter Huagan and Helge Drange of the Nansen Environmental and Remote Sensing Centre in Norway suggested that this might not be necessary [46]. According to their calculations, more than 90% of CO_2 gas injected into seawater at *shallow* depths of 200 - 400 m dissolves efficiently before bubbles have risen half the way to the surface. This cargo of CO_2 renders the water dense enough (by about 8 kg/m^3) to sink of its own accord to the ocean depths, so long as it does not have to compete with other large-scale currents. A suitable site proposed by Huagan and Drange for the application of their technique is along the West coast of Norway, in the vicinity of existing oil and gas fields and where both bottom topography and currents are orientated toward deep water. If shallow injection turns out to be practicable, then it substantially reduces the cost of the operation, there being no need to liquefy CO_2 or to construct long submerged pipelines. Again, however it seems most useful as a disposal option for coastal power stations and would require careful evaluation of risks to marine ecosystems.

Carbon dioxide sequestration in the oceans is therefore almost certainly feasible and capable of "sweeping large quantities under the carpet" for some considerable time. Other direct sequestration techniques have been studied, such as injecting CO_2 into exhausted oil wells, or into offshore saline aquifers [45]. There has even been a somewhat bizarre suggestion of storing it in frozen form on the land surface as huge insulated blocks of dry ice. The dangers of these surface or subterranean methods should be assessed very carefully as a sudden release of carbon dioxide gas into the environment could suffocate local inhabitants over a large area. Direct sequestration therefore is really suited best to buy time for better methods to come on-line, such as those that integrate emissions with biochemistry. In fact the process boils down to a more wasteful and expensive way of burning fossil fuels — with short-term benefits, but long-term disadvantages a prudent geoengineering strategy would do well to avoid. However, as a way of disposing of limited quantities of CO_2 in favourable circumstances, it might still turn out to be the method of choice.

4.2.4 Mitigation of the Environmental Impact of Chlorofluorocarbons

Other climate forcing gases must be dealt with by geoengineering techniques other from those described above. This is particularly the case with CFCs which, as we have seen, have both a strong greenhouse effect and, once they reach the stratosphere, an indirect influence on ozone depletion.

4.2.4.1 Direct Removal

To directly purge CFCs from the atmosphere would be an enormous task. Thomas Stix of Princeton University gave some impression of the scale by writing, *"To process $5x10^{15}$ tons of sea level air in 10 years would, for example, require the air to flow continuously at 80 km/hr through an intake port measuring 500 square km in cross section."* Undaunted by this however, and in the true spirit of the thought experiment, Stix then continued to work out how it might be done [47].

He pointed out that physical removal would not be necessary, for if CFC molecules could be dissociated within the troposphere, their fission fragments (being polar molecules) should dissolve in rain droplets and be precipitated. He ruled out the use of artificially produced UV radiation for this purpose because it would be much too inefficient. Instead, he proposed *infrared multiphoton dissociation* as the most ideal method. This works by intense excitation of a molecule's vibrational modes, absorption of 20 - 30 photons in succession shattering chemical bonds. In the case of CFCs, wavelengths between 8.5 - 12 μm would be required (see Table 4.4), precise tuning to the absorption frequencies being especially important for the first few vibrational transitions.

Stix therefore envisaged the use of powerful batteries of infrared lasers to process tropospheric air. Ideally, multiple frequency beams should be used so as to permit the simultaneous destruction of several different CFC compounds. He investigated a number of energy wastage processes that would reduce the beam intensity. Atmospheric absorption of IR radiation poses a potential difficulty as it is very wavelength-sensitive and depends on the atmospheric content of water vapour, aerosols, as well as temperature and altitude. However, computer simulations of a 50 km-long horizontal beam at a height of 4.2 km showed that at certain specific wavelengths coinciding with CFC absorption peaks > 90% transmission efficiency was possible. More substantial energy losses could be caused by dexcitation of CFC molecules by collisions with air molecules. Stix estimated that this could be overcome by tripling the power of the beam to deliver 375 MW/cm^2 in a pulse duration of 16 ns (6 J/cm^2).

The most important limitation on Stix's scheme, which was most influential on its final manifestation, is a phenomenon called rotational Raman scattering. This refers to the inelastic scattering of photons by nitrogen molecules, changing their rotational state and thereby depleting or incrementing the photon energy. With very intense beams of primary radiation, *stimulated* Raman scattering can occur with substantial amplification of the effect. Since the gain is proportional to beam intensity × beam length × frequency × gas density, and since all these parameters except for length are fixed (we have already determined beam intensity), it turns out that beam lengths are restricted to 5 km or less to avoid significant frequency-space diffusion of laser power. Stix proposed overcoming this difficulty by bouncing the laser light off mirrors designed to reflect the primary frequency, but to absorb the scattered frequencies.

This fundamental necessity to limit uninterrupted beams to 5 km in length, led to his final concept for a tropospheric CFC purging system as illustrated in Fig. 4.11. Stix envisaged it being constructed on mountainsides at high altitudes (> 4 km) so as to reduce the amount of absorption by atmospheric water vapour. As an illustrative example, he discussed an arrangement of mirrors and lasers 5 km apart and 1 km high. The laser beams would be 2m x 2m square and so it would take 500 such beams, arranged horizontally, across the 5 km gap, travelling a total of 2500 km, to fill its cross section. However, he felt that any particular laser should be able to work efficiently over 150 km, its beam therefore traversing the gap 30 times by being reflected to and fro by mirrors. Thus, the number of lasers required are 2500/150 ≈ 17, along with 483 mirrors.

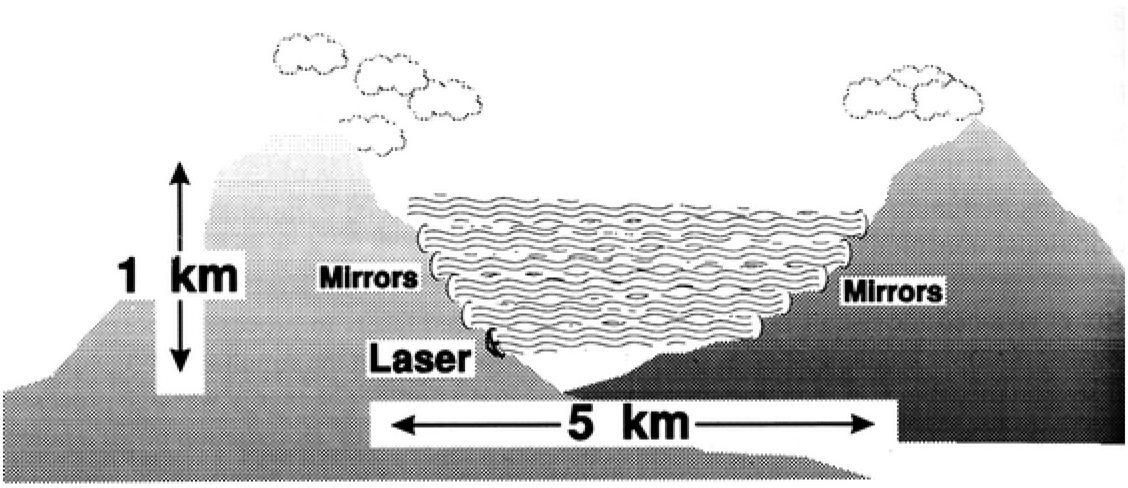

Figure 4.11 *Stix's thought experiment for purging the atmosphere of CFCs – a 5 km by 1 km laser curtain. 150 such installations would need to be operated for ten years. The illustration is greatly simplified, showing only one laser/mirror system. (Adapted from Ref. [47].)*

This arrangement would create an 'energy curtain' of 5 km^2 though which winds would transport air at (an assumed) mean wind speed of 80 km/hr. A fresh column of air would therefore pass through the curtain every 0.09 seconds, requiring the lasers to operate at 11 pulses per second. Assuming free electron lasers are used with an efficiency of 0.3, the total power of the installation would be: 375 MW/cm^2 × 1.6x10^{-8} s × 200^2 × 11 × 1/0.3 × 17 ≈ 150 MW. Since the air at such altitudes is only about two thirds as dense as sea level air, 150 such installations would be required to process the Earth's entire troposphere in 10 years, dissociating a total of 25 kg CFCs per second and 800,000 tonnes per year. The electrical power demand would be ~ 0.02 TW, about 2% of the world's present consumption of electricity.

Not surprisingly, Stix admitted to the speculative and marginally practical nature of his scheme but felt that its various obstacles might be overcome by technological advances, *"... the scenario offered here would be enormously extravagant both to install and operate. Furthermore, considerations that go beyond this crude scoping out of the problem may well add to difficulty and expense. On the other hand, a factor of 5 or 10 improvement in the above estimate of overall efficiency would bring the concept of processing the atmosphere to the point where its cost, while very large indeed, might well be matched by its global benefit."*

This author is inclined to be a little more cautious. Additional problems that spring to mind include multiple recycling of gases; fouling of the mirrors; and the effect on wildlife, especially birds, that stray into a photon beam with an average energy density 482 times that of top-of-atmosphere sunlight.

4.2.4.2 Removal of Active Chlorine

Since CFCs are so difficult to remove from the atmosphere as intact molecules, immobilization of their highly reactive breakdown products is another option. Such a strategy would have no effect on the greenhouse warming due to CFCs but could help repair the damage being done to the ozone layer by active chlorine. In Section 4.1.2, it was shown how chlorine released from the ultraviolet photodissociation of CFCs can catalyse ozone destruction — a phenomenon that is particularly acute in austral Spring due to the manufacture of labile chlorine compounds within polar stratospheric clouds during the Winter darkness [14]. The several weeks in Spring when chlorine is being activated would therefore be the best time for geoengineers to intervene to mitigate ozone loss.

A possible method of achieving this has been investigated by Ralph Cicerone and Scott Elliott of the University of California at Irvine and Richard Turco of the University of California at Los Angeles [48]. Their concept involves the injection of alkane gases into the ozone layer which would scavenge active chlorine when it occurs at its most destructive concentration. The two chemicals included in their modelling were ethane (C_2H_6) and propane (C_3H_8), which react with chlorine in the following manner:

$$\begin{aligned} C_2H_6 + Cl &\rightarrow C_2H_5 + HCl \\ C_3H_8 + Cl &\rightarrow C_3H_7 + HCl \qquad (4.15), \end{aligned}$$

to give hydrogen chloride, a compound that does not attack ozone.

Cicerone *et al* tested the efficacy of this strategy by running a detailed model of Antarctic ozone chemistry with two different sets of input parameters, scenario 'H' and scenario 'B', which bracket our understanding of the behaviour of the ozone layer. They reasoned that since, during the time of peak ozone destruction, the concentration of Cl can be as high as ~ 2 ppb, injections of ethane or propane to a similar, or higher, concentration would be needed. They thus simulated the effect of each chemical separately at concentrations of both 1.8 and 3.6 ppb.

The amounts of ozone remaining in their fully developed ozone holes are shown in Fig. 4.12 and it is clear that a mixed response to alkane injections is predicted. Scenario 'H', which tends to maximise the production of active chlorine, develops a very deep ozone hole which is substantially reduced by ethane and propane at both concentrations — the latter having the most beneficial effect of the two. However, scenario 'B' produced a residue of nitrogen oxides left over from Winter processing that went into forming $ClONO_2$. This then reacted with the HCl produced by the alkanes to give Cl_2 (see Equation 4.7), increasing the number of chlorine atoms present in labile compounds. So, in this case, 1.8 ppb of ethane or propane produce a *deeper* ozone hole. However, 3.6 ppb of both compounds provide enough scavenging power to reduce ozone destruction, propane being again the most effective. Thus the model seems to be suggesting that, to be on the safe side, alkane injections of double the concentration of active chlorine would be needed. The model was also used to study future scenarios where the concentration of active chlorine in the ozone layer is ~ 30% higher than now. Here the authors tested the effects of injections of 2.64 and 5.28 ppb of alkanes and came to qualitatively similar conclusions as with the present day case: where there were substantial quantities of nitrogen oxides left over from chemical reactions in the dark, the larger of the two injections was required for a mitigation of ozone depletion.

Cicerone *et al.* took care to emphasize that their model was sensitive to many assumptions and uncertainties. Details of chemical reactions, both in the gas phase and on aerosol droplets, need to be better understood along with the processes that create the Antarctic vortex and control the mixing of stratospheric air. They estimated that an ozone hole repair project would need about 50,000 tonnes of alkanes to be distributed uniformly throughout a 2×10^7 km^2 region between altitudes of 15 - 20 km. This would have to be done in the first few weeks of early Spring and would thus require a substantial fleet of large aeroplanes. Although the number of craft would be well within the capacity of an international effort, a particular difficulty might be to ensure even distribution of their cargo, as natural mixing processes over the timescale concerned are too slow. If hydrocarbons are to be added before sunrise, additional loss processes might come into play and larger quantities will be needed.

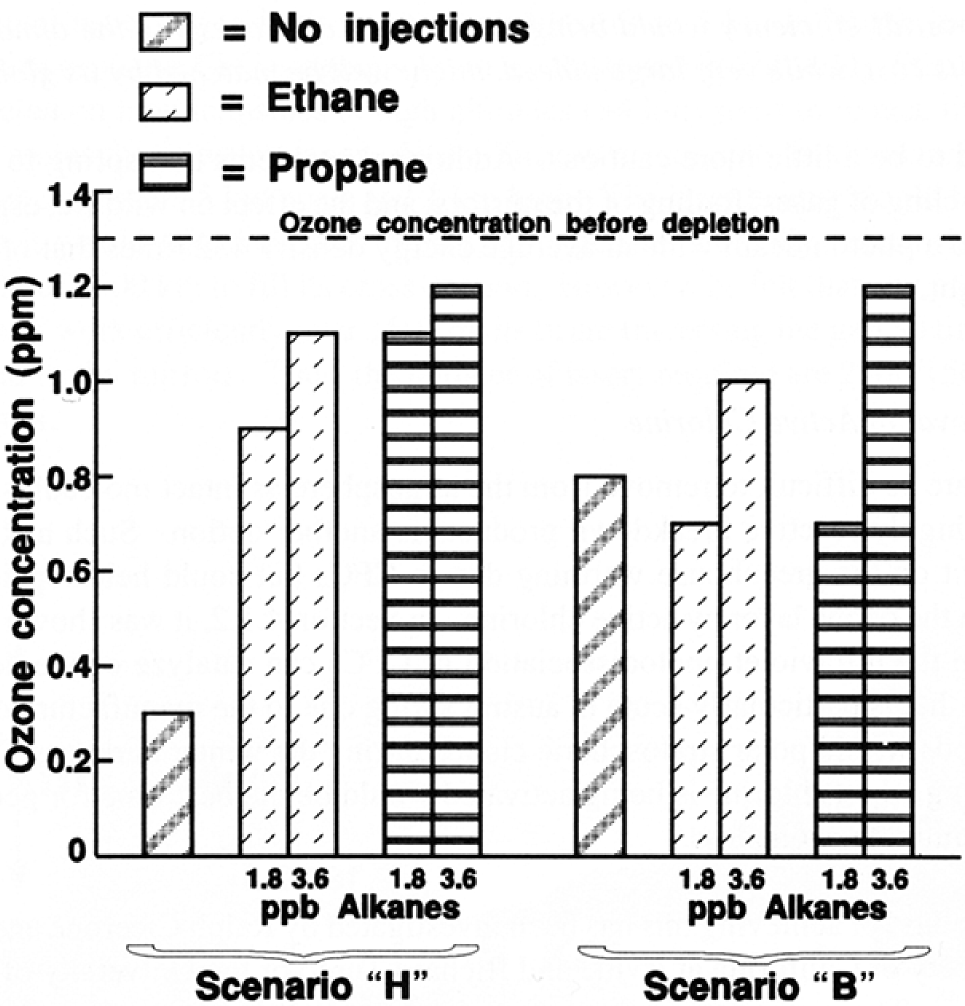

***Figure** 4.12 Ozone concentrations in fully developed ozone holes, according to the model of Cicerone et al. Scenario "H" and scenario "B" represent different initial conditions. The results of a control run are shown along with the effects of injections of 1.8 or 3.6 ppm ethane or propane. (Histogram bars are estimated to the nearest 0.1 ppb from figures in Ref. [48].)*

The mixed results of this study seemed to engender mixed feelings in its authors, which came out in their summation: *"Although these initial calculations are encouraging, it is not clear whether such an intervention will be feasible... Experiments can be imagined with vertically thin atmospheric layers wherein the injected hydrocarbons would be consumed and the present concept could be tested. Before any actual injection experiment is undertaken there are many scientific, technical, legal and ethical questions to be faced, not the least of which is the issue of unintended side effects."*

A completely different concept for removing active chlorine as been suggested by A.Y. Wong *et al.* of the University of California at Los Angeles [49]. They have noted that negative chlorine ions are 'inert' with respect to ozone chemistry and do not participate in catalytic destruction at all. In experiments in large chambers designed to simulate ozone destruction by chlorine atoms released from photo dissociated $CFCl_3$, they demonstrated that injections of negative charges from a plasma source brought about a recovery in ozone concentration. The process appears to involve the initial formation of oxygen ions, followed by charge transfer to the more electronegative chlorine by collisions. As Cl is converted into Cl^-, the breakdown of ozone is greatly reduced and the chlorine ions can be collected by positively charged surfaces.

Wong *et al.* compared their concept in a positive light with that of chemical methods of purging chlorine: *"This charge-induced method is very different from a proposed mitigation method using chemicals. Charges can be retrieved and will not introduce long-lasting problems such as greenhouse warming."*

One is left wondering however over the practicality of enlarging such a concept from the laboratory bench to the necessary scale. At least one can say in favour of the chemical method of Cicerone *et al.* that large-scale implementation is easy to conceive of. Nevertheless, Wong and co-workers are apparently going ahead with some of the scientific and engineering studies needed to prove their idea as a viable proposition.

4.2.5 Alteration of the Abundance of Aerosols and Cloud Condensation Nuclei

An alternative to manipulating the radiative forcing produced by greenhouse gases is to alter the input of solar radiation. However, in the case of the near-future Earth, such an approach, although potentially very powerful, does not address the root cause of global warming. Thus, demands on geoengineering techniques of this type will grow at a faster rate than those which act to reduce the build-up of greenhouse gases. An *intrinsic* method of controlling the insolation absorbed by the surface is to change a planet's albedo, and hence the fraction of sunlight it reflects directly back into space.

A practical way of doing this might be to increase the concentration of atmospheric aerosols which can both act to backscatter solar radiation and contribute to cloud formation. As was discussed in Section 4.1.3, it is thought that the present anthropogenic production of sulphate aerosols may already be responsible for a forcing of $\Delta Q \approx -1$ W/m^2 [24]. The intention of geoengineers therefore could be to consciously enhance this effect. A typical calculation assumes a need for a 1% reduction of incoming sunlight which would cause a global radiative forcing of $\Delta Q \approx -2.4$ W/m^2; this would give rise to a direct cooling of $\Delta T \approx -1^oC$ and, after feedbacks, an equilibrium temperature drop of $\Delta T_{surf} \approx -2^oC$.

Although most of the anthropogenic negative radiative forcing is due to tropospheric aerosols, there are some advantages in placing reflective particles at higher altitudes. Stratospheric aerosols are not scavenged by clouds and are therefore longer lasting (1 - 3 years) and achieve a more uniform distribution across the globe. A number of studies have been done of the feasibility of creating and maintaining an artificial layer of submicrometer particles at heights of > 12 km — similar in nature to those formed by the intermittent injection of material into the stratosphere by volcanic eruptions. Estimates of the annual mass requirements of such a layer usually range between ~ 1 - 10 million tonnes of particulates (sulphuric acid aerosols being at the lower, and dust at the higher end of this range). The Soviet climatologist M.I. Budyko was the first to propose stratospheric sulphate aerosol distribution as a geoengineering technique and had in mind delivering the needed material with high-flying aeroplanes [50]. To save weight, he suggested that their cargo should be sulphur (32% the weight of sulphuric acid), which could be burned and expelled into the environment as SO_2. This would then be converted into sulphuric acid by the chemical reaction scheme shown in Equations (4.11). An alternative would be to take aloft carbonyl sulphide (64% the weight of H_2SO_4), the most common natural precursor of stratospheric sulphate. It undergoes photodissociation and conversion to SO_2 by the following scheme:

$$\begin{aligned} COS + h\nu &\rightarrow S + CO \\ S + O_2 &\rightarrow SO + O \\ SO + O_2 &\rightarrow SO_2 + O \end{aligned} \tag{4.16}$$

A feeling for the minimum scale of Budyko's strategy can be obtained by assuming an annual requirement to transport 320,000 - 640,000 tonnes of aerosol precursor and cargo planes available with a carrying capacity of 100 tonnes (such as the US C5-B). This would therefore entail 9 - 18 flights per day and a fleet of perhaps double the number of aircraft. Perhaps surprisingly therefore, the task seems to be well within current ability, although one must bear in mind that operations have to continue indefinitely and the above estimate could easily be an order of magnitude too low.

The Mitigation Panel of the PIGW report [32] concentrated instead on evaluating the use of submicrometre dust. They assumed that a stratospheric dust loading of 10 million tonnes would be adequate to counteract the warming equivalent of an additional 1000 billion tonnes of carbon present in the atmosphere as CO_2. Their scenarios therefore are equivalent to what is required to mitigate a doubling of CO_2 sometime next century. One of the delivery systems they appraised was the use of 16" naval guns which can loft 1 tonne payloads to a height of 20 km (see Plate 4.6). Assuming a dust lifetime of 2 years, we would therefore require 5 million shots per year — or about one every 6 seconds. The estimate of the annual cost of this method came to ~ \$0.03 to mitigate the warming of each tonne of CO_2. This may seem rather high as it implies a cost per shot of ~ \$6,000. However, it is possible that the amount of dust required might be ten times the above estimate increasing the expense still further; alternatively, using dust which is optimised for scattering (such as the 0.5 μm by 0.1 μm needles advocated by PIGW) could reduce both the mass to be lifted and expense by a factor of ~ 100.

The Panel also reconsidered a previous proposal [51] to distribute soot into the upper troposphere and lower stratosphere by re-tuning the engines of commercial aircraft to burn their fuel under richer than normal conditions during the high altitude part of their flight. Based on an estimate of the 1981 consumption of jet fuel (140 million tonnes) it appears that airliners might be able to distribute ~ 1.4 million tonnes of particulates per year, at altitudes of > 9 km, if just 1% of their exhaust is emitted as soot. Whilst this is a substantial mass, it is ~ 7 times less than that needed for the full mitigation scenario. Moreover, soot — especially in the troposphere — has a shorter lifetime than stratospheric dust (about 2 - 3 months), reducing the effective shielding by a further factor of 4. Aircraft exhausts therefore cannot counteract the full forcing of a CO_2 doubling, but could perhaps mitigate the effect of several year's worth of CO_2 emissions at a cost of ~ \$0.003 per tonne of CO_2 per year.

One of the most effective ways to use aerosols in the troposphere is to exploit their properties as cloud condensation nuclei (CCN). PIGW based its assessment of the possibilities of cloud stimulation on a previous estimate that a CO_2 doubling could be offset by a 4% increase in cloud cover over the oceans. Taking into account the rate at which CCN are depleted from clouds, the Mitigation Panel estimated that their aim could be achieved by increasing the supply of CCN by 30%. This would involve producing and discharging into the ocean winds ~ 31,000 tonnes of SO_2 per day, about equivalent to the output of 365 coal-burning power plants. Whilst this quantity may sound alarming, it is only equivalent to an additional 6% of present anthropogenic sulphur emissions and about 25% of the airborne sulphate produced by marine algae. The Mitigation Panel envisaged such a project could be tackled by 200 ships, of capacity 10,000 tonnes, streaming the sub-tropical Pacific and Atlantic oceans and burning sulphur into winds directed away from land. The cost of this enterprise was estimated at ~ $2 billion per year — amounting to $100 billion for a forty year duration.

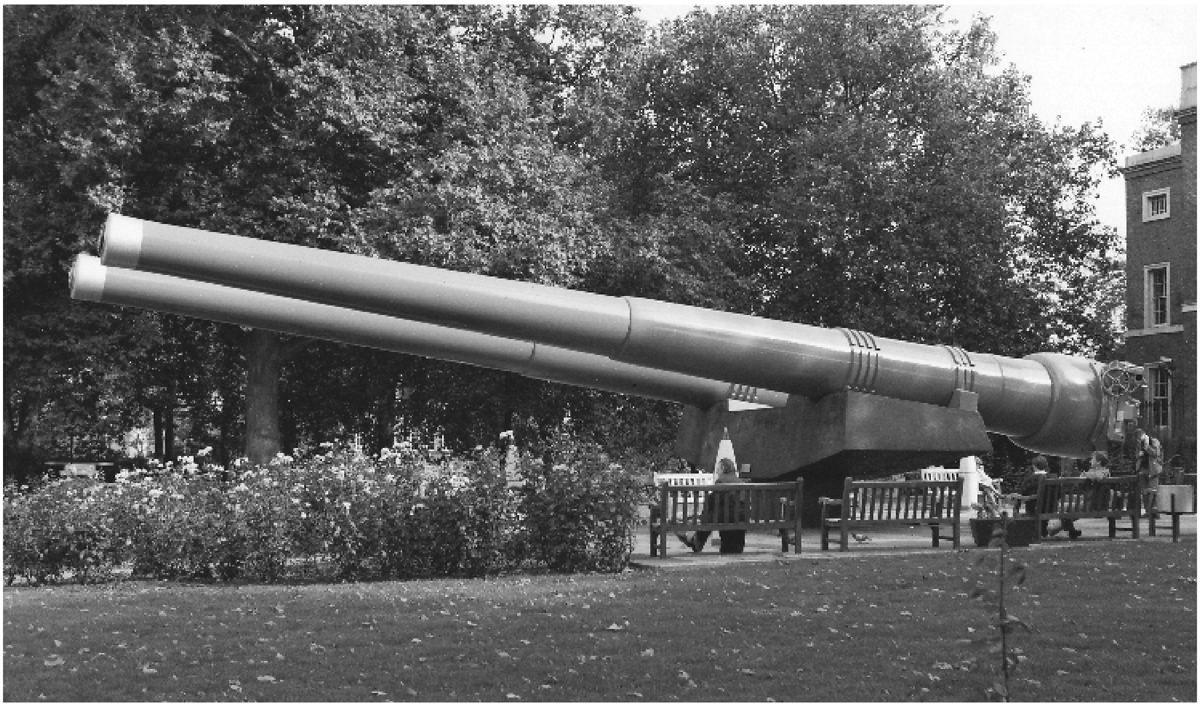

Plate 4.6 *The technology embodied in these 15-inch naval guns dates back to 1912. They are similar to the cannon required in the PIGW scenario that are powerful enough to lob ~ 1 tonne dust-laden shells into the Stratosphere. (Photo by Martyn Fogg.)*

As with all speculative applications of geoengineering, albedo enhancement contains many uncertainties. Estimates of the quantity of particulates required to mitigate any particular radiative forcing are very crude and probably not known to within an order of magnitude. Side effects would need to be properly assessed and weighed against the hoped-for benefits; these include heating of the stratosphere, stimulation of further aerosol-related chemistry and an increase in acidic fallout at the surface. Other consequences are more difficult to predict and might only become manifest after feeding through the climate system in some unexpected way. Since albedo enhancement only tackles the symptoms of global warming rather than the cause, it is best suited as a temporary measure to be brought into play if strategies for reducing net emissions of greenhouse gases are taking too long. Nevertheless, it is a measure that could be quite easily investigated by a series of experiments of increasing scale. It emulates natural processes and requires an ability at which we are already highly skilled — discharging pollutants into the atmosphere. Thus, of all the geoengineering techniques that would be applicable on a large scale, it seems to be one of the most feasible and inexpensive.

4.2.6. Redirection of Radiation in Space

Another way to manipulate the Earth's surface insolation is to place our reflective layer above the atmosphere — *in space*. This takes us therefore to *extrinsic* techniques of planetary engineering that are fundamentally reliant on space technology. Any realistic large-scale extraterrestrial project will have to exploit local resources and is therefore based on assumptions of the technical and economic feasibility of space manufacturing (see Fig. 4.6). Unless all work is to be done by autonomous or remotely controlled machines, the habitation of space by project personnel, and possibly their families, also enters the picture. Extrinsic geoengineering techniques therefore are inevitably more futuristic, rarely requiring new science, but usually advances in the engineering of spacecraft, habitats, support machinery etc. This does not render them any less possible, only more distant in their implementation.

4.2.6.1 Shadowing the Earth

Space-based devices that absorb or reflect sunlight could be used as geoengineering tools for a number of applications. Most recently however, they have most often been discussed in the context of bringing about a negative radiative forcing to combat global warming [52-56]. The Earth's surface therefore would be shadowed from some fraction of solar radiation sufficient to offset the positive forcing of greenhouse gas emissions and, in this sense, the technique works in the same way as the dust/aerosol layers discussed in the previous section. Assuming, for simplicity, that the Sun is a point source of light at infinity, the size of the shading area required to screen out 1% of the Earth's insolation is 1% of the planet's projected area, i.e. $a_s = 0.01\pi r_\oplus^2 \approx 1.28\text{x}10^{12}$ m (where $r_\oplus$ is the radius of the Earth). This figure is actually a minimum as the size gradually increases with distance from the planet and not all the shading area may be correctly aligned between the Earth and Sun at any one time — reducing its *shadowing efficiency* to $e_s < 1$ and therefore requiring an increase in area of $1/e_s$ [53]. If constructed as a single object, even this minimum area is equivalent to an enormous parasol about 1280 km across, roughly the area of a country the size of Peru. Yet the scale of the project is not as daunting as this analogy suggests. Sunlight can be interrupted by very thin layers of opaque matter and lightweight, flimsy, structures that would collapse on Earth could hold their shape perfectly well in the airless, free-fall, conditions of space. Ultra-thin films made from common materials are therefore the key to fabricating devices with large areas and relatively little mass. Examples of thin films that everybody is familiar with include aluminium cooking foil (13 - 25 μm thick) and plastic wrapping (13 μm thick). Material designed for solar sail spacecraft has to be much thinner than this to maximise the acceleration the sail is capable of: one design for such a material is therefore only 2μm thick, consisting of aluminium-coated polymer [57]. We may therefore be able to provide films for space reflectors with areal densities of $\rho_a < 5$ g/m^2 and a total mass, for the area given above, of ~ 6 million tonnes. Handling this amount of processed material is already well within the capabilities of civilization and it is interesting to note that it is of the same order as estimates for the mass of stratospheric dust required in the albedo enhancement scenario. The disadvantage with the dust is that it must be continually replenished every year, whereas if one's reflective surface is a fabricated, semi-permanent, structure in space, then it might require renewal on a much longer timescale. Of course, structural support for space reflector material will add to its overall areal density and mass, but this might be offset by more high-tech thinner material, possibly perforated at a sub micron scale so that it will still interrupt visible light.

Four categories of orbit can be envisaged for space parasols and are listed, along with their relative merits, in Table 4.7. Use of the first two, low Earth orbit (LEO) and geostationary orbit (GEO), are hampered by many severe difficulties that will probably rule them out as viable choices for the purpose in question [53,54]. The principal problem is that since parasols would be circling the Earth, they would only be positioned between the Earth and Sun during a small part of their orbit. Their shadowing efficiency would therefore be low, particularly in the case of GEO where $e_s \approx 1.5\times10^{-3}$, requiring the shading area (a_s) to be multiplied by ~ 670. This is obviously not the way to proceed as it greatly increases the resources, industry and expense involved in cutting down the insolation by the desired fraction. Other objections include the overcrowding of orbits already used by regular satellites; the intrusive visibility inherent in the screen being so close overhead; the reflection of unwanted sunlight onto the planet's night hemisphere; and the complexity of maintaining such extended objects correctly orientated when subject to planetary tidal forces, gas drag, and light pressure. Close orbits do have one dubious advantage and that is, if we are faced with a climatic emergency, and there has been no development of extraterrestrial resources, then LEO could be filled with fleets of parasols launched from the surface of the Earth. However, it is difficult to imagine such a panic measure being practical; it would require a huge increase in launch capability (> 1 million 50 tonne launch increments) and would thus significantly contribute to environmental stress in its own right.

TABLE 4.7 COMPARISON OF POTENTIAL SPACE PARASOL ORBITS

Site	Distance	Efficiency	Advantages	Disadvantages
Low Earth Orbit (LEO)	~ 1000 km	~ 0.1	Proximity	Traffic jams Environmental impact High visibility Shadows Control complexity Launch pollution Environmental impact Night illumination Gas drag
Geostationary Orbit (GEO)	36,000 km	$1.5x10^{-3}$	Construction from lunar or asteroidal material?	Traffic jams Environmental impact Visibility Orbital instability Launch pollution?
L1 Libration Point	0.01 AU	1	Permanence Quasi-stability Ease of control Little visibility Few traffic jams Construction from lunar or asteroidal material?	Remoteness of site Lunar perturbations Launch pollution?
Levitated Orbit	~ 0.1 AU	1	Permanence? Ease of control? Little visibility No traffic jams Construction from lunar or asteroidal material?	Remoteness of site Long communications delay Launch pollution?

Since it takes 22 times less energy to launch a payload off the Moon than Earth, and there is no atmosphere to worry about, it makes sense to obtain and process the raw materials for the parasol from the Moon, or convenient near-Earth asteroids. The manufacture of large quantities of thin film in space should not present an overwhelming obstacle, especially if it can be made from commonly occurring substances. (Scenarios of space manufacturing in the context of the construction of space habitats envisage the fabrication of much more complex items.) Sub-sections of parasol might then be conveniently and cheaply launched into their shadowing orbit where they might deploy automatically, or be assembled into larger structures.

A much better choice of shadowing orbit would be available if we could permanently interpose a parasol (or fleet of parasols) between the Earth and the Sun. This would ideally involve a stable orbit that co-revolves with the Earth such that, to an observer on the ground, the parasols would stay fixed relative to the Sun (except for an oscillation across the solar disc in response to a parallax effect caused by the planet's rotation). However, for a parasol to possess the same angular velocity as the Earth, at a smaller orbital radius where the Sun's gravity is stronger, an additional outwards force is necessary. It so happens that one of the Sun-Earth libration points (where centrifugal force and the forces of solar and terrestrial gravity balance) is situated inward from the Earth on the Earth-Sun line. This point is called L1 and is shown along with the other libration points L2 - L5 in Fig. 4.13. An object placed at L1 will co-revolve with the Earth about the Sun because of the additional outward force provided by the Earth's gravity.

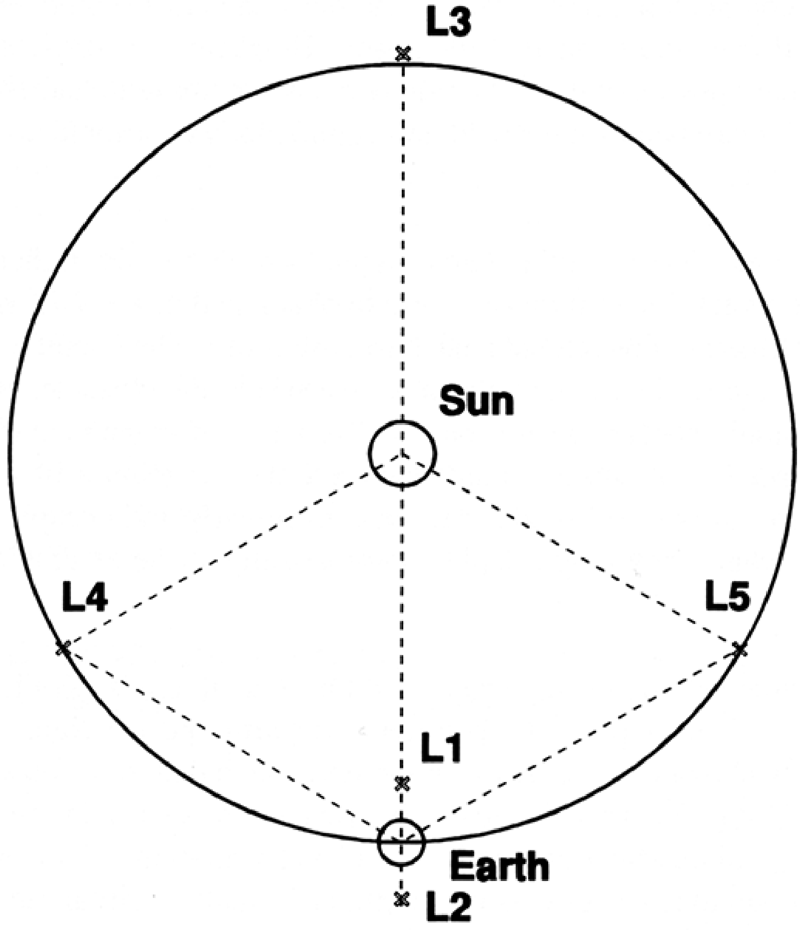

Figure 4.13 *The five Earth-Sun libration points. Masses placed at L1, L2, or L3 are positionally unstable along the Earth-Sun line, but are fully stable at L4 and L5. L1 is a suitable location for a co-revolving space parasol. (Schematic is geometrically correct but not to scale.)*

The situation is in fact more complex than this because L1 is only a semi-stable region, resisting perturbation perpendicular to the Earth-Sun line only. Additionally, a wide, thin object such as a solar sail will also be subject to an extra outwards pressure due to sunlight, displacing its equilibrium inwards of L1. For a planar, totally reflective sail, the equilibrium point is determined from the following balance of forces:

$$GM_{\odot}m_s/R_{\odot,s}^{\ 2} - Gm_{\oplus}m_s/R_{\oplus,s}^{\ 2} - m_s\omega_{\oplus}^{\ 2}\, R_{\odot,s} - 2a_sS_{\oplus}\, R_{\oplus}^{\ 2}/cR_{\odot,s}^{\ 2} = 0 \qquad (4.17)$$

where the first two terms are the gravitational force from the Sun and Earth respectively, the third is the centrifugal force on the sail and the fourth is the photon pressure. Individual quantities are as follows: G is the gravitational constant (6.672×10^{-11} Nm^2/kg^2); $M_{\odot}$ is the solar mass (1.99×10^{30} kg); m_s is the mass of the sail; $R_{\odot,s}$ is the distance of the sail from the Sun; $m_{\oplus}$ is the mass of the Earth (6×10^{24} kg); $R_{\oplus,s}$ is the distance of the sail from the Earth; $\omega_{\oplus}$ is the angular velocity of both the sail and the Earth (since they co-revolve); a_s is the area of the sail; $S_{\oplus}$ is the Earth's insolation (1370 W/m^2); $R_{\oplus}$ is the Earth's orbital radius (1.496×10^{11} m $\equiv$ 1 AU) and c is the speed of light (3×10^8 m/s). When the photon pressure is zero, we obtain for the L1 point $R_{\oplus,s} \approx$ 1.5 million km $\approx$ 0.01 AU (about four times the distance to the Moon.

Since the photon pressure on a solar sail is proportional to its area and not its mass, the acceleration is inversely proportional to its areal density r_a. Thus, the thinner and less massive the solar sail, the further it is displaced from the L1 point, stability being achieved for $R_{\oplus,s} \approx$ 0.02 AU and 0.05 AU for $\rho_a \approx 29$ g/m^2 and 11 g/m^2 respectively. Thus, the more one lessens the mass of the parasol by using sails of higher performance, the less one is able to exploit the semi-stable properties of the L1 region. The ideal parasol for the L1 point is therefore not a solar sail at all but a thin disc that would be minimally reflective on its Sun-facing side and with a high infrared emissivity on its Earth-facing side. The photon thrust from radiated infrared energy could therefore be used to offset the thrust from absorption.

A particularly elegant solution to this problem was proposed by James Early of the Lawrence Livermore National Laboratory [55]. He suggested fabricating a 2000 km diameter parasol (his aim being to cut out 2% of sunlight) made from 10 μm-thick glass which would be scored with a pattern of parallel grooves on one side. It would thus act as a prism, deflecting sunlight through just half a degree, sufficient to miss the Earth. Because the structure is *transparent*, it is subject to a very low photon pressure, with a calculated equilibrium point of $R_{\oplus,s} \approx$ 1.58 million km, very close to L1. Another advantage of glass as the main parasol material is that the raw materials from which to make it are readily available in lunar soils, although the feasibility of producing good quality, ultra-thin glass sheets on the Moon remains to be demonstrated.

Most space reflector systems one can conceive of are going to need some kind of active positional control. The first reason for this is that the L1 point is only semi-stable and a station-keeping mechanism will be required to prevent displacement along the Earth-Sun line. Even so, thrust requirements are very low and could be easily done by making a small fraction of the parasol's area adjustable, so that it can function as an attitude control device, minutely varying the applied photon pressure [55]. It would be a task that would be much less tricky than the fly by wire systems of modern fighter aircraft and could therefore be handled autonomously by a simple on board computer. The second reason for active positional control is that the structures being proposed can be unstable due to their sheer size. Early's parasol, for instance, is a single object that is balanced only where it intersects the Earth-Sun line; all other parts would experience a small radial acceleration towards the centre that would be balanced by rotating the structure about the Earth-Sun line at a rate of 2 cycles/year. A slightly faster rotation would give it an outwards radial stress that would maintain it as a flat disk. However, in Early's words [55], this situation itself creates another difficulty, *"The disk* *rotation will unfortunately act as a gyroscope which keeps the disk orientated with its axis pointed in one direction. Since the disk axis must always point toward the Sun, a torque must be applied to the disk by a control system to cause the disk to precess at one cycle per year. It is not clear if this control system is simpler than using solar sails at the perimeter of the disk to supply a radial tension to balance the radial gravitational acceleration."*

So, it may be that adjustable solar sails may be the most economical method of both positional and structural control. This returns one therefore to considering the entire parasol as a solar sail and looking for orbits other than L1 which might be suitable. Michael Mautner of the University of Canterbury in New Zealand has investigated the space parasol idea and the more general concept of space-based control of climate in some depth [54,56]. His results are based on the assumption that we will have a need to screen out 3% of sunlight, which being equivalent to $\Delta Q \approx 7$ W/m^2 applies to worst-case emission scenarios toward the end of the next century. Along with Kelly Parks of the American Rocket Company, California [56], he pointed out that beyond $R_{\oplus,s} = 0.05$ AU , the Earth's gravitational influence becomes negligible (term 2 in Equation 4.17) but that high performance solar sails can still co-revolve with the Earth because photon pressure alone is enough to balance gravity allowing them to travel in non-Keplerian "levitated" orbits (see Fig. 4.14). In this case, the distance from the Earth to the levitated orbit simplifies to:

$$R_{\oplus,s} \approx R_{\oplus} - R_{\oplus}(1 - 1.5/\rho_a)^{1/3} \qquad (4.18)$$

Thus, for parasol areal densities of $\rho_a \approx 5.5$ g/m^2 and 3.1 g/m^2 we obtain levitated shadowing orbits of $R_{\oplus,s} \approx$ 0.1 AU and 0.2 AU respectively. There would be no point in using orbits any closer to the Sun than this due to the interference of the planet Venus. Active control of the screen would be required and caused Mautner and Parks to reject the notion of it being stable as a single object. Instead they envisaged a fleet of ~ 38,000 100 km^2 parasols, stabilized and maintained in position with an estimated adjustable sail area of just 812 m^2.

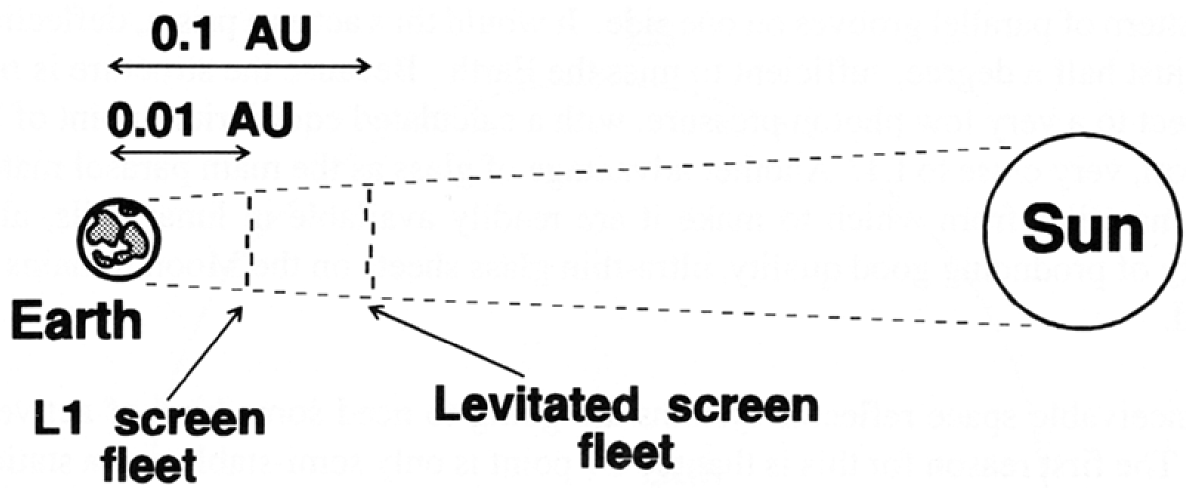

Figure 4.14 *Parasols that co-revolve with the Earth. Location at either the L1 point or in some levitated orbit (depending on acceleration by photon pressure) would be suitable. (Not to scale; adapted from Ref. [56].)*

Planetary Engineering on the Earth

A space-based solution to the symptoms of the Earth's unwanted radiative forcing in the next century is therefore scientifically feasible and merely requires us *to develop and become experienced at space-based engineering*. Influencing the Earth's climate from L1 or levitated orbits has some obvious advantages over measures that are implemented within our planet's biosphere. The technique would be non-invasive, non-polluting (if most industrial activities are confined to space) and manipulation of insolation can be very precise. Screen fleets can be manoeuvred in and out of position comparatively rapidly; negative forcing therefore being adjustable and predictable over shorter timescales than intrinsic geoengineering techniques, the effects of which have to work their way through various physical and biogeochemical processes.

Not surprisingly, estimates for the cost of a space parasol project are very crude and vary widely. Mautner [54] quotes a range of \$0.1- \$1 trillion, less than the \$1 - \$10 trillion he estimates from real estate damage due to global warming by the end of the next century. Early's estimate [55] is \$1 - \$10 trillion and the PIGW report (which considers only the unattractive case of LEO parasols) came to \$5.5 - \$55 trillion [32]. The economics of extrinsic geoengineering are therefore critically dependent on screen lifetime. If we assume that the scenarios referred to above can mitigate the warming equivalent of 4000 billion tonnes of CO_2 and screen components, or individual mini-parasols have a 10 - 40 year lifetime, yearly costs range from \$0.0006 - \$1.4 per tonne of CO_2. Whilst the space programme's track record of underestimating costs would probably drive the real expense into the higher end of this bracket, a collateral benefit of such a project could be that its necessary extraterrestrial operations could lay the foundations for the permanent habitation of space.

4.2.6.2 Supplying Extra Sunlight

In view of the fact that > 99.9% of the energy flowing through the biosphere comes from sunlight (see Table 2.9), one would expect there to be a multitude of potential applications arising from the use of space reflectors as *mirrors* to *increase* the Earth's insolation. Orbiting mirrors have been studied by various engineers as far back as the German space pioneer Hermann Oberth in 1928. However, because we currently have no need for a *substantial* increase in the solar input (indeed as we have seen, the opposite may be the case), most proposed applications of reflected illumination are usually small in geographical scale and thus cannot be truly defined as geoengineering. Some of these local augmentations though might have predictable consequent global effects and it is certainly possible to imagine a more ambitious use of orbiting mirrors on a worldwide scale for the purposes of preventing a future ice age. In addition, as well as stimulating the same sort of space industrialization mentioned above for parasol deployment, enlarged versions of mirror systems for geoengineering applications are likely to be useful terraforming tools. It is therefore appropriate to briefly cover options for enhancing Earth's supply of sunlight.

The most prominent researcher to have investigated what he called “Space Light Technology” was the German-born American space engineer, Krafft Ehrike [59,60]. The results of his ten years' consideration of the problem were published at the end of the seventies in an enormous review paper [59] — containing a detailed study of the possible uses of space light; the design of the mirrors; an evaluation of the choice of orbits in which to situate them; their patterns of lighting in target areas; methods of deployment and an assessment of their economics. Although mirrors can be designed to provide almost any chosen illumination, Ehrike's overall concept divides naturally into two basic categories of system — the *lunetta*, which provides lighting comparable, or in excess of, a bright moonlit night and the *soletta*, which can deliver artificial daylight. Details of these systems are shown in Table 4.8 and includes Ehrike's breakdown of the soletta into four functional sub-categories.

TABLE 4.8 EHRIKE'S SPACE LIGHT UTILITY SPECTRUM

System	Generic Function	Equivalent Illumination	Orbit	Reflector Unit Area / km^2	Total Reflecting Area / km^2	Specific Applications	Purpose / Product
Lunetta	Area lighting	10 – 150 full moons	Highly Inclined LEO	0.01 - 0.1	15 - 30	Added Agricultural Labour Hours, Urban Illumination, Disaster Area lighting	Crop loss Prevention, Equipment Utilization, Multicropping, Public safety, Brownout/ Blackout Backup, New urban developments
Agrisoletta	Weather modification Processing heat	0.2 - 0.6 suns	Highly Inclined LEO	5 - 10	2500 - 7500	Local Weather stabilization Precipitation management Desalination Crop drying	Food Production, Hydro-power Assurance, Wind power, Fresh water, Crop loss Reduction, Fuel conservation
Powersoletta	Power generation	1 sun	Sun Synchronous LEO	5 - 12	10000 - 14000	Photovoltaic conversion Chemical energy Thermal energy	Electricity, Solar hydrogen Heating cooling
Biosoletta	Bio-production enhancement	0.3 - 0.6 suns 1 sun	Highly Inclined LEO GEO	5 - 10 70 - 100	2500 - 7500 100000	Food production Biomass production Land plants Kelp	Land crops, Sea food, Chemical energy
Metsoletta	Climate management	~ 1 sun	GEO	70 - 100	60000	Manipulation of lows and highs	Prevent Excessively long wet, dry or cold periods

Space light technology is predicted to be extremely versatile, being able to perform tasks for which there are no technological alternatives. Even the most ambitious systems are more than an order of magnitude smaller than the size of the parasol system considered above to combat greenhouse warming and so their augmentation of the solar constant is slight. Nevertheless, even though solar input is being increased by a small fraction, it is possible to pick out applications from Table 4.8 which might be helpful to 21st century geoengineers. The *powersoletta*, which could serve to increase the intensity and duration of sunlight available to surface solar power stations would permit a reduction in fossil fuel consumption. Of course, it would be directly incrementing the planet's energy budget, but would not be producing a greenhouse gas as an end-product that can give rise to long-term heating. Similarly, the *biosoletta*, which is intended to be used to boost plant growth (especially when targeted on regions where light is a major factor limiting NPP) could produce a net cooling, since the negative radiative forcing of less CO_2, integrated over its atmospheric residence time, might be greater than the instantaneous positive forcing of the space light. If it is possible to optimize the global biota for production by broadly “improving” the weather and climate by *agrisoletta* and *metsoletta* respectively (an uncertain prospect), then this might magnify the capacity of ecosystems to safely incorporate and process man's fossil fuel effluents. Thus, counter to intuition, there may be realistic scenarios where carefully controlled incrementation of solar radiation may also be a technique of use to geoengineers concerned with a warming Earth.

Many of the principles of design, construction and stabilization of space mirrors are the same as for parasols — the fundamental difference is that one is manipulating *light* and the other *shadow*. Since Ehrike was considering solettas for LEO and GEO only, he found that it was best to break down the needed surface area into co-orbiting clusters of mirrors. Smaller solettas in such orbits are easier to stabilize and manoeuvre and Table 4.8 shows that his designs usually involved each of his systems consisting of several hundred mirrors, usually with ~ 10 per cluster.

A small experimental mirror, similar to what Ehrike called a *proto-lunetta*, was actually tested by the Russians on February 4th 1993 (a date that may prove of historical significance as being the first use of a system with potential for scaling up into a true extrinsic planetary engineering tool). The potential relevance of space light to the Russians is obvious, much of their land being at high Northern latitudes and being subject to extended Winter darkness. It is therefore not surprising that many of the potential applications listed in Table 4.8, especially options to illuminate cities, construction sites and disaster areas, have led them to take a more advanced and practical interest in the concept. Reports occasionally appear in the Western media of their *Noviy Svet* (New Light) program which plans a set of about a hundred 200 m wide reflectors orbiting at altitudes of 1550 - 5530 km and fulfilling a lunetta-type function. The mirror that was flown in 1993 was a one tenth scale test bed for *Noviy Svet* and was called *Znamia* (Banner), being a 20 m disk of 5 μm aluminized plastic consisting of eight segments folded on an umbrella-like frame. It was stowed in a rotatable drum on the nose of an unmanned *Progress* space freighter which, after docking in the normal way with *Mir* and being unloaded of provisions, withdrew a few hundred metres so that Mir's crew could observe the deployment. This was done by rotating the drum with an electric motor and thus using centrifugal force to both unfurl *Znamia* and maintain its shape. A five hour-long experiment then proceeded in which the angle of the *Progress* was controlled to point the mirror towards the night hemisphere of the Earth. Mir's crew could quite clearly observe a small patch of reflected light passing over the dark surface below and observers in Canada, France and other parts of Europe reported seeing a brief flash from the sky as the mirror's beam swept overhead [61]. From the point of view of the *Znamia* project team, the experiment was a great success, although much work remains to be done before a bigger system becomes practical. For instance, the total mass of Znamia's reflecting film was just 4 kg, as opposed to the 40 kg for its framework; it will be essential therefore to reduce the mass of structural support. However, this does not appear to be a major conceptual problem as substantial overall areal density savings are expected to occur simply on redesigning and scaling the system up to larger size.

The first practical step to demonstrating the feasibility of space light technology has therefore already been taken successfully. There appear no fundamental limitations to constructing mirror systems on the scale envisaged by Ehrike — or larger. The manipulation of solar flux required to combat the onset of the next ice age (which is almost certain to happen eventually and which would be disastrous for civilization) will be of a similar order to that involved in offsetting global warming in the next century, the difference being that geoengineers will be needing to use solettas as opposed to parasols. To cope with a demand for space light of > 1% $S_{\oplus}$, the capacity of Ehrike's largest systems would have to be increased at least ten-fold. In this case, there are other soletta designs that might serve the purpose of a general and uniform increase in the Earth's insolation better than simple mirror clusters in Keplerian orbit. Mirrors behind the Earth, orbiting the L2 point to stay out of its shadow, are a possibility as well as much more advanced multi-component designs levitated and stabilized by retro-reflection or by balancing photon pressure against the Earth's gravity. The most extraordinary of these soletta designs however are usually applied to terraforming concepts and are thus covered later in this book.

As with all geoengineering techniques, a proper evaluation of the ecological impact of space light would have to be undertaken. However, since few of the applications in Table 4.8 require the removal of darkness over wide areas of land, serious risks to the function of the biosphere seem unlikely. The summarize therefore, the exploitation of space light, which is by far the most abundant energy flow in the Solar System, holds great promise for a multitude of applications. Space reflectors, used to either increase or decrease a planet's insolation, will be particularly important planetary engineering tools — applicable in varying forms to the terraforming of a wide range of planets. This is because of their potential precision, efficiency, and high net energy ratio. Mautner's estimate of the latter [56] suggests that, even after just a few years of operation, space reflectors located a similar distance as the Earth from the Sun might typically have handled > 10^6 times more energy than that needed for their construction and emplacement. Thus, consideration of extrinsic geoengineering techniques and the establishment of their theoretical feasibility, greatly supports arguments for the realism of terraforming.

4.2.7 Perturbation of Earth-Crossing Asteroids and Comets

At first sight, the idea of altering the orbits of other Solar System bodies may seem to have little to do with geoengineering — that is unless they happen to be on collision course with the Earth. Since there is no functional distinction between preventing gradual and expected environmental change (such as in those measures discussed above) and the more haphazard damage of a cosmic impact, the protection of the Earth from collisions with asteroids (see Plate 4.7) and comets clearly comes within the remit of extrinsic geoengineering. The difference lies in which of the Earth's energy flows is subject to manipulation: the mitigation of global warming involves tweaking the huge and steady fluxes of visible and infrared radiation; whereas the prevention of an asteroid strike involves controlling the Earth's kinetic energy input from space, which can vary over small timescales from near zero to many times the solar input. It is in this sense that the cosmic impact danger is random: with present day detection methods, a potential impactor may only be recognized a few years in advance — or worse, when collision is only days away. An avoidance strategy therefore must be capable of a rapid, flexible and effective response.

4.2.7.1 The Nature and Scale of the Risk

Earth-crossing asteroids and comets are now thought to pose a not-insignificant threat to civilization. This is because, even though their chances of hitting the Earth are very low, a modest-sized impact could slaughter so many people at once that the chance of dying in one such rare event of mass mortality is said to be similar to the individual probability of being killed in an aeroplane accident [62]. This is not so much due to the mass of the impacting objects (we noted in Section 4.1.1 that humanity already moves up to a ~ 10 km cube of rock each year — the mass of a medium size asteroid), but their velocity of impact. This will be a minimum of 11 km/s (the Earth's escape velocity) and will more likely approach 30 km/s (the Earth's orbital velocity); a comet in a retrograde orbit colliding head on could strike at an enormous 70 km/s.

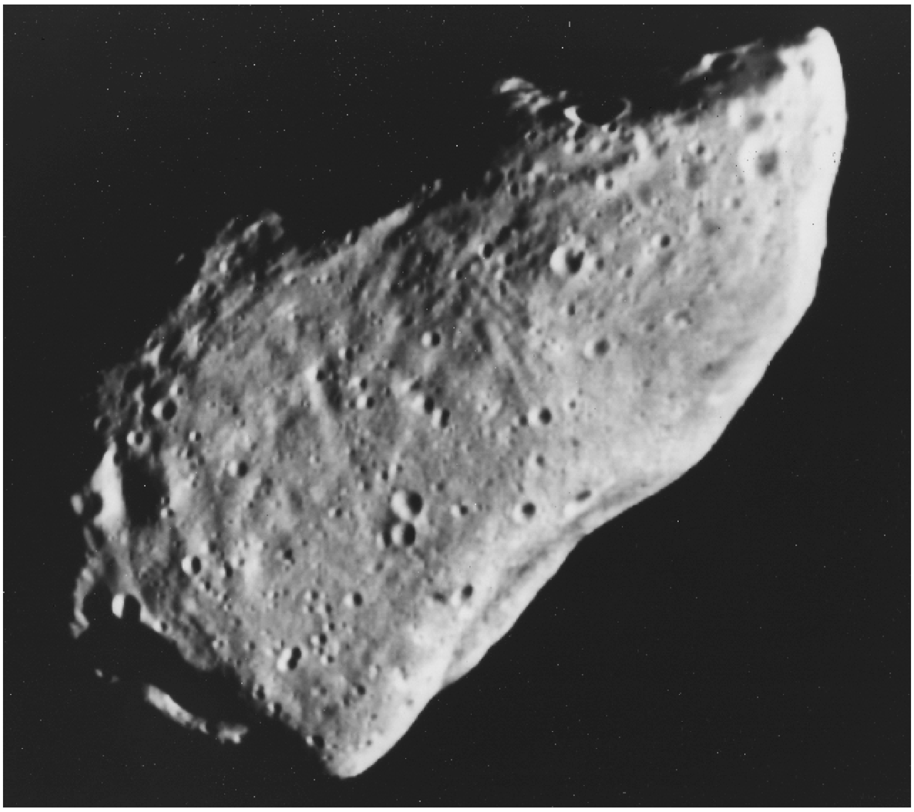

Plate 4.7 *The Asteroid 951 Gaspra, as imaged by the Jupiter-bound space probe Galileo. Gaspra is a highly irregular body with principal diameters of 18.2, 10.5 and 8.9 km (mean diameter ~12.2 km) and is similar in size to the proposed K-T impactor. There is presently no risk that Gaspra will collide with the Earth as it is a resident of the main Asteroid belt, being encountered by Galileo at a distance of 2.2 AU from the Sun. There exists, however, a substantial population of such objects that do cross Earth's orbit and which are of potential danger. (Photo courtesy of NASA.)*

Taking a typical impact velocity of v_i = 30 km/s and an impactor density of 2000 kg/m^3, the kinetic energy of a projectile expressed in megatons of TNT-equivalent (1 Mt $\approx$ 4.2x10^{15} J) is approximately:

$$E_i \approx 10^5 \, (d_i \, / \, \mathrm{km})^3 \;\; \mathrm{Mt} \qquad (4.19)$$

where d_i is the diameter of the object (assumed to be spherical) in km. (The result of Equation 4.19 scales with velocity by a factor $(v_i \, / \, 30 \text{ km/s})^2$.) This simple expression makes obvious the large energies released by even minor impacts. A 100 m asteroid embodies ~ 100 Mt of kinetic energy, roughly double that of the largest exploded hydrogen bomb and would therefore cause massive loss of life if striking in a populated area. The collision of a 1 km asteroid releases ten times the energy of the world's arsenal of nuclear weapons and is considered to be at the threshold where impacts pose a danger to the global environment, not just by heat and blast but through more long-lived processes, such as dust injection into the stratosphere etc.

Examples of the terrain created by impact processes are very common and can be seen all over the Solar System, although most impact scars date back to the final stages of planetary accretion. This accretion however has not entirely ceased and there remains plenty of asteroidal and cometary debris in space on orbits that intersect with those of the planets. The most recent example of a damaging strike on the Earth was only as far back as the 30th June 1908 over Tunguska, Siberia, where a small incoming asteroid is thought to have broken up at ~ 8 km altitude, creating an airburst explosion of 30 - 40 Mt and flattening trees in the forest below to a distance of 80 km. Fortunately, the area was largely uninhabited. About 40,000 years ago the Barringer crater (see Plate 4.1) was formed by a 5 - 15 Mt explosion, probably caused by a small impactor just a few tens of metres across and made of iron — the reason why it survived passage through the atmosphere to reach the surface. It is now seeming ever more likely [63] that sixty five million years ago (still quite “recent” in terms of geological time) the infamous Cretaceous-Tertiary (K-T) extinction (the most famous casualties of which were the dinosaurs) was caused by the collision with a ~ 10 km asteroid, releasing an awesome ~ 10^8 Mt in just a few seconds (≈ 10^4 world nuclear arsenals or ≈ one month of the Earth's total insolation). A large ~ 200 km diameter crater of the right date and which matches the size predicted for an event of this magnitude has now been found at Chicxulub of the northeast coast of Yucatan [64]. The damage wrought by such a blow would have been appalling, combining virtually every disaster a student of apocalypse can imagine — searing heat; pulverizing blast; titanic earthquakes; huge tidal waves; acid rain; extensive wildfires; months of cold under darkened, dust-laden skies, followed by a heat wave when the atmosphere cleared. Any semblance of the human order of things would be destroyed by a catastrophe of this magnitude and whether enough people would survive to be able to reconstruct civilization close to its present aspect is uncertain.

Solid material is falling through the Earth's atmosphere all the time, but the frequency of globally-damaging impacts ($d_i \geq 1$ km) can only be estimated within wide bounds as new “Near-Earth Objects” (NEOs) are being continually discovered (see Plate 4.8). It is thought that there exists a population of > 1000 NEOs of $d_i \geq$ 1 km with a collision rate with the Earth of about 4 every million years [60]. Because of their greater rarity, objects of > 2.5 km diameter only strike about once every ten million years and the impact of 10 km, K-T-type projectiles are fortunately as rare as one every 100 million years. If this was the only impact flux there was to worry about, then perhaps civilization, with its characteristic timescale of ~ 1000 years, could probably afford to take its chances and concentrate on more predictable problems. However, Barringer and Tunguska-type impacts occur much more frequently: this is because the size distribution of asteroids and comets favours larger numbers of smaller bodies — objects which are harder to detect and yet are still capable of causing considerable regional damage. This size distribution, expressed cumulatively, is of the form:

$$n(\geq d_i) \propto d_i^{-\gamma} \tag{4.20}$$

where $n(\geq d_i)$ is the number of objects equal to or larger than d_i and γ lies between 1 and 2 (and is thought to be closer to 2). Thus, for each order of magnitude reduction in size class, we find objects are 10 - 100 times as numerous. It is this appreciation of size distribution that allows us to estimate the frequency of impact explosions in the megaton to gigaton range [66], such as shown in Fig. 4.15. Impacts of the energy of Barringer are expected every few hundred years and a Tunguska every millennium. Such an event air bursting over the remote oceans or polar regions may attract little notice — not so however over most of the temperate and tropical land surfaces. Mortality rates could therefore range from zero to > 1 million. Engineering these inevitable events out of the human future is therefore desirable.

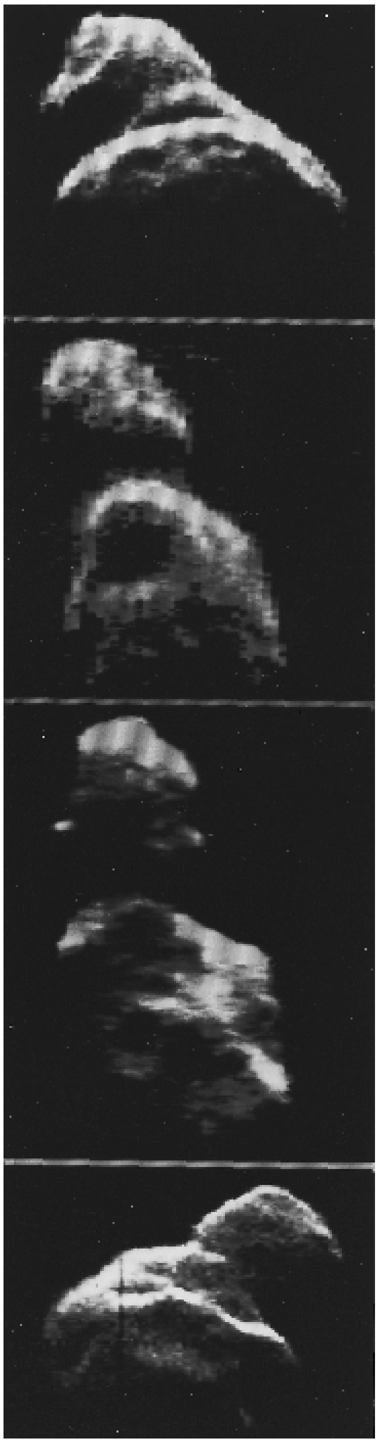

Plate 4.8 *Radar images made of the asteroid 4179 Toutatis made during a recent ~4 million km close encounter with the Earth in late 1992. The images reveal two irregularly shaped cratered objects, ~4 km and ~2 km in average diameter, in contact with each other. Toutatis is one of the family of Near-Earth Objects (NEOs) that pose the greatest danger to Earth. (Photo courtesy of NASA.)*

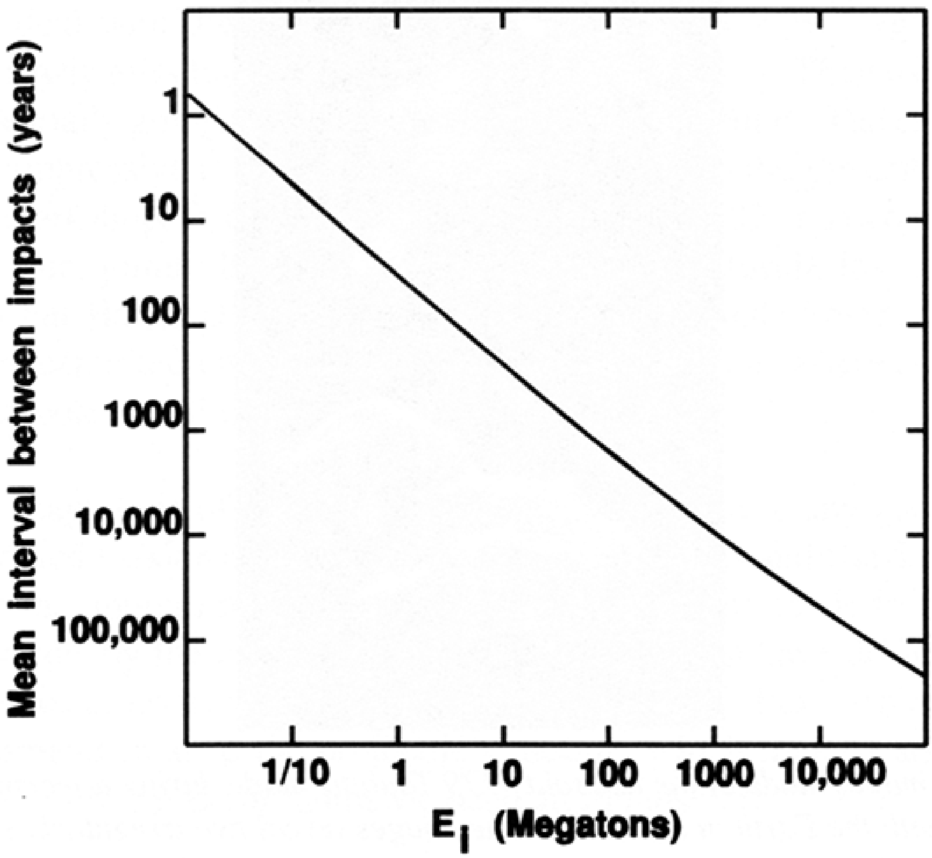

Figure 4.15 *An estimate of the frequency of small cosmic impacts on the Earth, expressed in megatons of kinetic energy. (Adapted from data by E. Shoemaker and reproduced with permission from Ref. [66].)*

4.2.7.2 Methods of Deflecting Near-Earth Objects

Incoming projectiles of the type discussed must be dealt with above the atmosphere and as far away as possible. At the very least therefore, a strategy for preventing dangerous impacts will require spacecraft capable of rendezvousing with threatening NEOs and deflecting them in some way by incrementing their velocity (v_i) with an impulse (Δv_i) sufficient to cause them to miss the Earth.

Two kinds of prevention scenario can be envisaged, and here we use the terminology of Johndale Solem of the Los Alamos National Laboratory [67]. They are:

1. *Remote Interdiction* — where collision is predicted several orbital periods (years) away.
2. *Terminal Interception* — where collision is imminent, the projectile is < 1 AU (days) away and closing.

A number of studies, at varying levels of formality, have been done of technological solutions to the impact threat. As with many other aspects of geoengineering, interest has grown recently along with increased knowledge and understanding. The first such exercise was Project Icarus, an interdisciplinary student project in systems engineering held in the Spring term in 1967 at MIT. The student group was given a task of designing a terminal interception-type mission to deal with the asteroid Icarus (a ~ 1.3 km, 4×10^{12} kg object) which was scheduled to narrowly miss Earth in June 1968 by ~ 6 million km. They were asked to assume that Icarus was actually going to hit and their job was to prevent it. The student's final report was sufficiently impressive to be published and is cited up to the present day [68]. Since then, NASA has held workshops to discuss the issue in 1981 and 1992 and two notable papers have been published: one, jointly by Thomas Ahrens of the California Institute of Technology, Pasadena, and Alan Harris at JPL [62] and the other by Johndale Solem [67]. As with project Icarus, Solem concentrated on evaluating terminal interception, whereas Ahrens and Harris have looked at remote interdiction.

To ascertain the magnitude of the deflection velocity required in any given case, we following below an abbreviated version of the reasoning given by Ahrens and Harris [62]. With either of the above scenarios, the impulse must be sufficient to perturb a projectile from an impact trajectory. In other words, by the time it reaches the Earth, it must have drifted from its original course by a distance at least as large as the Earth's radius $r_\oplus$. For terminal interception it is best to thrust perpendicular to the projectile's motion, which imparts an eccentricity to its orbit. To perturb it by one Earth radius we need an impulse of:

$$\Delta v_i \approx v_i r_\oplus / R_i \tag{4.21}$$

where R_i is its semi-major axis. Taking the values of the right hand side of the equation to equal those of Earth (a reasonable approximation for a NEO — 30 km/s, 6378 km and 1 AU respectively) we find that $\Delta v_i \approx 1.3$ m/s. To perturb a body in a short time compared with the orbital period (< 1 radian of orbital motion, i.e. < 58 days), a linear estimate for the perturbation velocity suffices and we get the simple expression:

$$\Delta v_i \approx r_\oplus / t \approx \frac{75 \text{ m/s}}{t \text{ (days)}} \tag{4.22}$$

where t is the time to impact. Thus, closer to the Earth than 1 AU, the required perpendicular velocity impulse is inversely proportional to distance. Taking v_i as the approach velocity and making it equal 30 km/s as before, interception at 1 AU requires $\Delta v_i \approx 1.3$ m/s; at 0.1 AU, $\Delta v_i \approx 13$ m/s and at 0.01 AU, $\Delta v_i \approx 130$ m/s. If we leave interception until the projectile is passing the Moon (384,000 km away), then we need a huge $\Delta v_i \approx 506$ m/s.

Ahrens and Harris pointed out that if an impact can be predicted several orbital periods ahead, then a better option is to thrust parallel to the orbital motion to cause a change in semi-major axis and period. The long-term drift that this would cause results in a perturbation, for a given Δv_i, roughly three times that of the above case. So, for a 1 $r_\oplus$ deflection in a remote interdiction scenario, we need:

$$\Delta v_i \approx r_\oplus / 3t \approx \frac{0.07 \text{ m/s}}{t \text{ (years)}} \tag{4.23}$$

Thus, if collisions can be predicted ten years ahead, perturbations of $\Delta v_i < 1$ cm/s will suffice. These equations therefore illustrate a basic distinction between terminal interception and remote interdiction scenarios — a two or more order of magnitude difference in Δv_i, the first being measured most conveniently in units of metres per second and the latter in centimetres per second.

Three methods have been proposed for providing this deflection impulse:

1. Direct Impact — the transfer of momentum to a projectile by the collision of inert rocket vehicles. This has been found to only be of use in deflecting very small < 100 m objects. Any larger than this, and the momentum of the projectile is simply too great to be significantly changed by rockets of feasible mass.
2. Propulsion Systems — reaction engines placed on the projectile such as mass drivers which can mine and eject material. Such systems could certainly steer asteroids gradually around the Solar System and have been proposed in the context of bring such objects to within a convenient distance from Earth for mineral extraction.
3. Nuclear Explosives — these offer a solution that is much more practical and efficient than direct impact, primarily because their energy density is ~ 10^4 times as great as the kinetic energy density of the projectile. We briefly discuss this nuclear option first.

The work of those working on terminal interception assumes the optimum use of a nuclear explosive being to detonate it on the surface of the projectile. This would excavate a crater, ejecting material into space and, to conserve momentum, the projectile would receive an impulse in the opposite direction. Calculations of the effectiveness of this mechanism led to the final scheme adopted by the Project Icarus team [68] being sequential launches of six Saturn V rockets, each equipped with a 100 Mt warhead and intercepting Icarus at distances between 0.2 - 0.01 AU.

Solem's study of terminal interception is more wide ranging and is not geared to providing any specific proposals [67]. He summed up his approach by writing, *"Because different assailants could possess a wide range of densities and material properties, the principal value of this work is to show the relationships among the various parameters."* Nonetheless one can glean from Solem's graphs that interception of 100 m - 1 km projectiles at ranges of 0.001 - 0.1 AU will require warheads of megaton to gigaton yield. A particular problem he identified at interception distances of < 0.03 AU is that the Δv_i requirement for deflection becomes large enough that the required surface-detonated nuclear explosion runs the risk of fragmenting the body altogether. The damage sustained by the Earth by a buckshot of large fragments might possibly be worse than a single impact, which at least concentrates all the incoming kinetic energy in one place. Another difficulty is that a surface burst will be making a crater small in dimension to that of the projectile and, if it is not of spherical shape and the explosion is out of line with the centre of mass and the desired Δv_i vector, some of the momentum imparted will be wasted in altering the projectile's spin-angular, rather than linear, momentum.

An alternative way of using nuclear explosives that could lessen these problems was suggested by Ahrens and Harris [62]; namely, the standoff detonation illustrated in Fig. 4.16. Here, the warhead is detonated a distance of ($\sqrt{2}$ - 1) of the projectile's radius above its surface where it can irradiate an optimum 30% of its total area (assuming spherical shape). The explosive is designed specifically to maximise its production of neutrons which are absorbed by the top 20 cm of the projectile's crust which heats, expands and spalls away. As is shown, a Δv_i is imparted in the opposite direction to the motion of the ejecta. There appears to be a disagreement between papers as to the thrust per explosive yield offered by this strategy; Solem claiming that it would be 35 times less efficient than surface explosions and Ahrens and Harris maintaining that both methods are roughly comparable. However, both concur that this more distributed application of force, even with non-spherical objects, results in a lesser chance of fragmentation and a reduced addition of angular momentum. It would therefore be the method of choice for remote interdiction; Ahrens and Harris calculating the impulse imparted per kiloton yield to objects of density 2000 kg/m^3 and made from “soft rock” to be:

$$\Delta v_i \approx 11\times10^{-3}\,(\mathrm{km}/d_i)^3\ \mathrm{cm/s/kt} \qquad (4.24)$$

Thus, deflection of asteroids of d_i of 100 m, 1 km, and 10 km respectively by the Δv_i = 1 cm/s needed for remote interdiction require standoff detonations of 0.1 kt, 0.1 Mt and 0.1 Gt respectively. As we would expect, these energies are ~ 3 orders of magnitude less than those involved in terminal interception and led Ahrens and Harris to conclude, *"... the development of the charges required to deflect large Earth-crossing objects seems to be feasible technologically."*

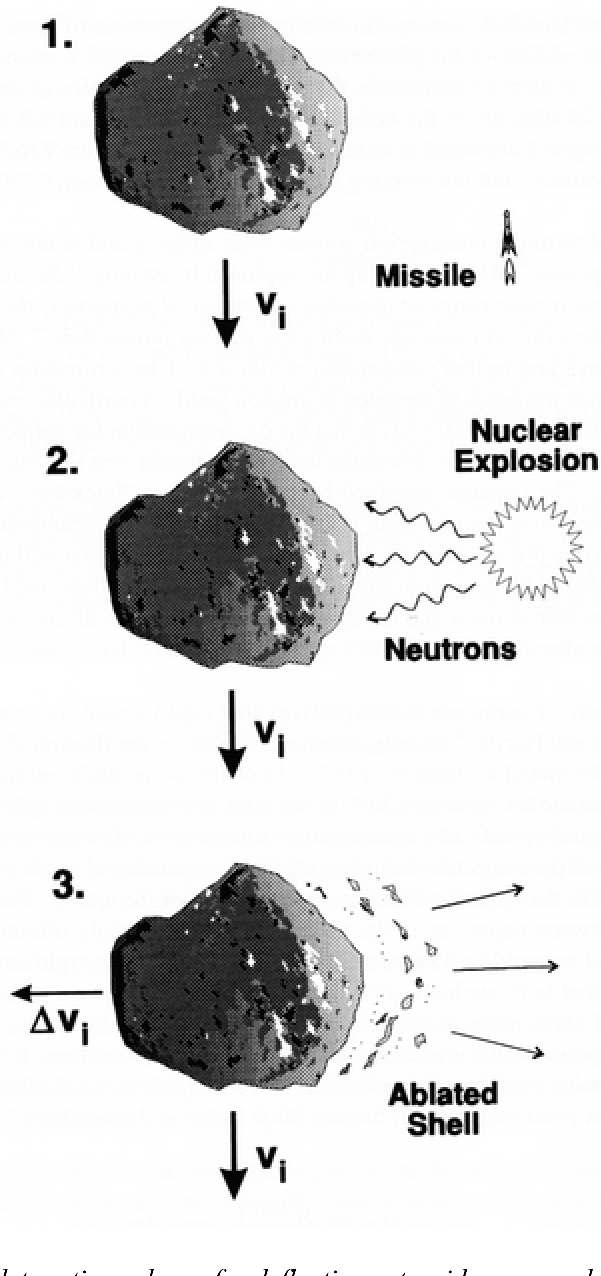

Figure 4.16 *The standoff nuclear detonation scheme for deflecting asteroids proposed by Ahrens and* Harris [62] . *Intense neutron irradiation of the side facing the explosion spalls off the top ~20 cm of surface material , imparting a thrust.*

Not all studies however favour the use of nuclear explosives to deflect oncoming impactors. H.J. Melosh of the Lunar and Planetary Laboratory of the University of Arizona and L.V. Nemchinov of the Institute for Dynamics of Geospheres of the Russian Academy of Sciences have returned to the idea of an asteroid propulsion system [69]. The trouble with previous ideas along these lines is that they involved siting complex machinery, such as mass driver thrusters, on the threatening asteroid many years in advance, and operating such machinery continuously for some time (see Plate 4.11). The concept of Melosh and Nemchinov, that ofusing solar sails to generate thrust, would still only be of use for remote interdiction, but otherwise disposes of many of the mechanical complexities. However it is important to note that they do not propose to use the thrust of solar sails directly, as this would be much too inefficient. They envisage using the energy in sunlight, but not the momentum.

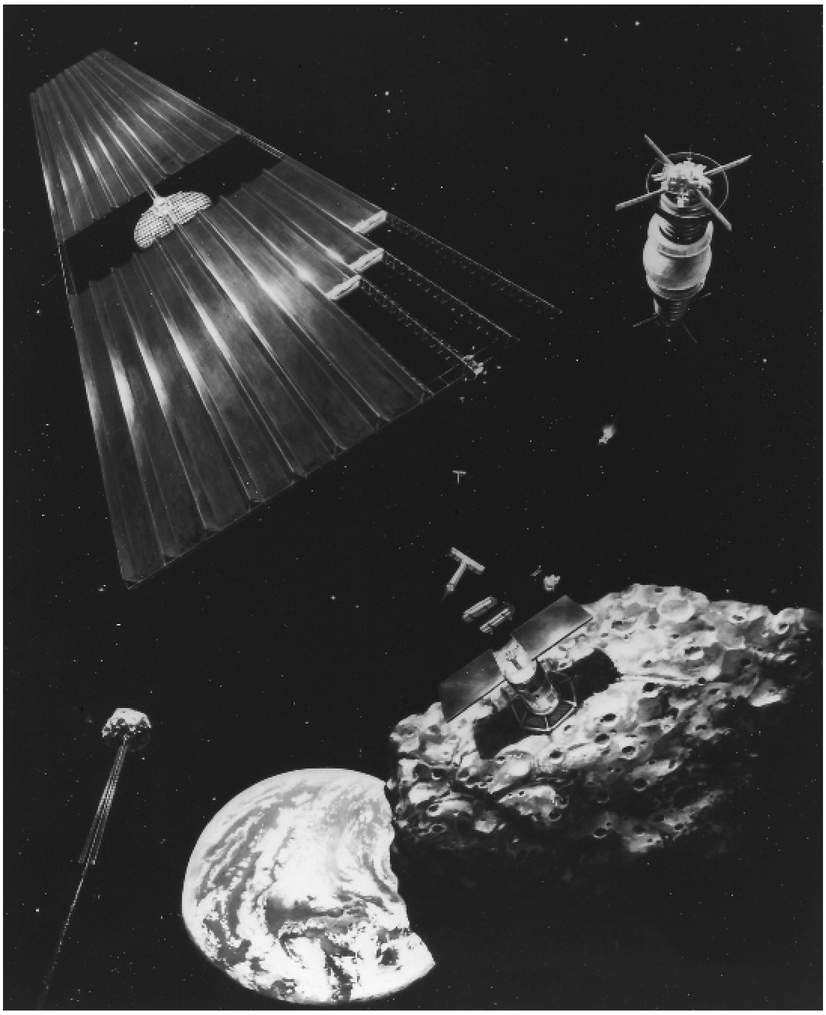

Plate 4.11 *Mass drivers could be used to propel small asteroids, as illustrated by this painting inspired by design work done at the NASA-Ames Research Center in 1977. Here we see two ~ 100 m scale chunks of rock parked in Earth orbit for the purpose of providing raw materials for the construction of a Solar Power Satellite and a Bernal Sphere space settlement. If asteroids can be steered, then those on collision course with the Earth might be deflected away. The trouble with the mass driver method is it requires the prediction of a collision and the installation and continuous operation of complex equipment many years in advance. (Artist: Denise Watt; photo courtesy of NASA.)*

Melosh and Nemchinov propose arranging solar sails in the vicinity of a potential impactor in order to focus sunlight into an intense spot on the object's surface where the energy density is sufficient to cause rapid vaporization. The blow off of ablated material would naturally impart an opposite thrust to the asteroid, turning it into a crude, solar-powered, rocket and emulating the known effect of sunlight in generating the gas jets that perturb cometary orbits (see Fig. 4.17). Assuming the process is 50% efficient (the gas jet would be nothing like a well collimated exhaust) they calculated that the thrust on a silicate object would be ~ 3.3×10^{-5} N/W of collected energy, or 0.03 N/m^2 of ablation mirror at a distance from the Sun of 1 AU (a factor of ~ 3000 better that that for a pure solar sail system). They claimed further that deflecting icy objects, because of their more volatile composition, *"... would have a factor of four further advantage."*

In the case of mitigating a collision with the Earth by continuous thrusting over timescales of years, their modelling predicted that the diameter of ablation mirror, D_c / km would have to be:

$$D_c \approx 0.16\, d_i(\text{km})^{3/2} / t(\text{years}) \tag{4.25}$$

where, as before, d_i is the diameter of the impactor (of asteroidal composition) and t the time to impact. Thus, a 0.5 km diameter ablation mirror operating for 1 year could safely divert a 2.2 km object; operating for a decade, it could protect the Earth from collision with a 10 km object.

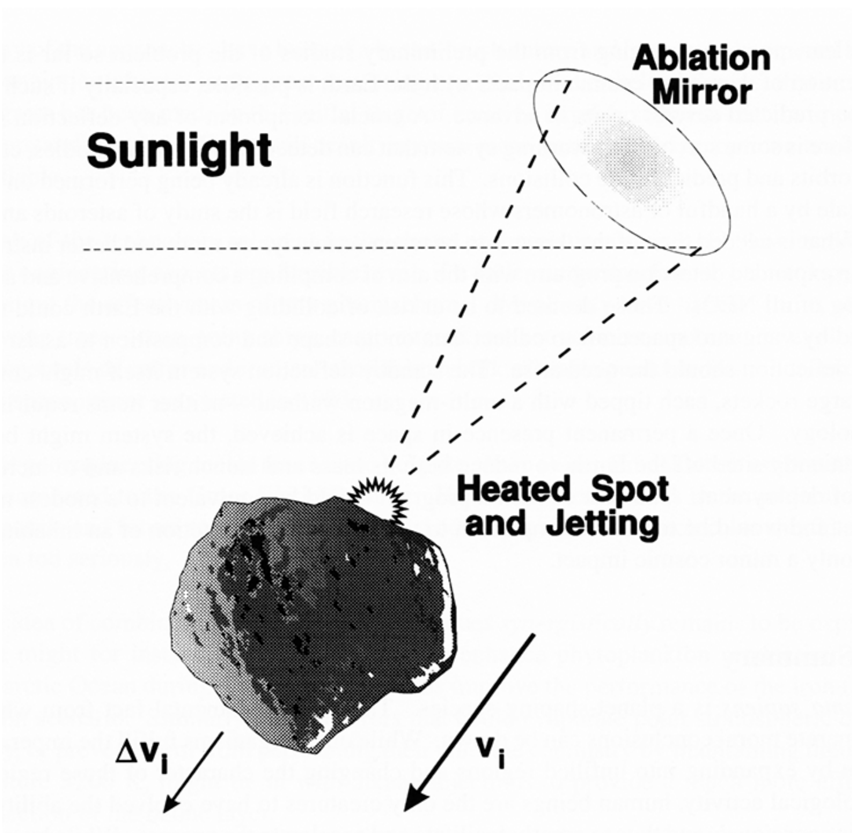

Figure 4.17 *The solar-powered rocket scheme for deflecting asteroids proposed by Melosh and Nemchinov[69]. Focused sunlight creates a jet of vaporized surface material, imparting a thrust.*

In a comparison, Melosh and Nemchinov claimed superior performance for such a solar powered rocket system over proposals for deflection by standoff nuclear explosives. However, their assumed efficiency of 50% in producing jetting by the evaporation of rock on an exposed open surface is almost certainly much too high [70]. In support of their proposal they made the valid points that the ablation mirror would weigh much less that a nuclear warhead (about one ton for 2-µm-thick aluminized Mylar) and could be stowed and launched in the space shuttle cargo bay. Such a system would have the ability to fly to its destination in the manner of a true solar sail and might be reusable. Furthermore, it would have a minimal risk of disrupting its target and could not easily be misused as a weapon. Nevertheless the nature of providing a constant impulse, rather than a sudden one, still entails some kind of continuous station-keeping mechanism, even with a system as simple as a solar sail. The question of the degradation of the mirror's surface by ablated gas and dust during the years it has to operate also must be addressed. Thus, the engineering options for impactor deflection in the context of remote interdiction scenarios are open to debate. Long advance times might favour a propulsion system approach, but nuclear explosives still seem the tools of choice where collision is imminent.

The clear message emerging from the preliminary studies of the problem performed so far is that the prevention of damaging cosmic impacts with the Earth is possible — most especially if such threats can be predicted several orbits in advance. A crucial component of any deflection scheme therefore is some sort of early warning system that can detect Earth-crossing bodies, calculate their orbits and predict future collisions. This function is already being performed on a modest scale by a handful of astronomers whose research field is the study of asteroids and comets. What is needed then, if the threat is to be taken seriously, are more and better instruments and an expanded detection programme, with the aim of compiling a comprehensive and accurate catalogue of all near-Earth objects. Those deemed to be at risk of colliding with the Earth could then be visited by vanguard spacecraft to collect data on its shape and composition to assist in efficient deflection, should the need arise. The standby deflection system itself might consist of ~ 10 large rockets, each tipped with a multi-megaton warhead — neither items requiring new technology. Once a permanent presence in space is achieved, the system might be more conveniently sited off the Earth, to reduce both its mass and launch risks and to increase its ease of deployment. The cost of such a program therefore would be equivalent to a modest military budget and would be trivial in comparison to the cost of reconstruction of an inhabited area after only a minor cosmic impact.

4.3 Summary

- *Homo sapiens* is a planet-shaping species. This is a fundamental fact from which no concrete moral conclusions can be drawn. Whilst other organisms fulfil the imperative of life by expanding into unfilled regions and changing the character of those regions via biological activity, human beings are the only creatures to have evolved the ability to do this *consciously* and thus to greatly facilitate and accelerate the process. Whilst humanity's impact on the global environment has been unintentional, civilization has now reached the stage where it can contemplate conscious engineering on a worldwide scale.
- Energy and mass flows now being handled by civilization, as part if its "metabolism," now rival many natural ones. Mankind is believed to be perhaps the dominant influence in shaping the Earth's surface, in determining the trace gas composition of the atmosphere and in bringing about global warming.
- Planetary-scale engineering on the Earth may become a necessity if adverse environmental change threatens to cause widespread harm. As a method of mitigating anthropogenic change however, it is no long-term substitute to the practise of sustainable planetary management.

- It is also possible to foresee geoengineering being used to offset severe climate fluctuations of a natural origin, such as ice ages. In the distant future geoengineering has the potential to extend the lifetime of the biosphere by protecting the Earth from a hotter Sun.
- A wide range of geoengineering concepts have been studied, including techniques for manipulating sunlight, the greenhouse effect, biogeochemical cycles and the impact flux. Many of the approaches have been of a broad-brush nature and have been hampered by the uncertainties inherent in the processes being modelled. Nevertheless, the fact that so much progress has been made in this initial stage of creative enquiry, suggests that an improved understanding of the Earth will result in even more geoengineering options becoming available.
- Much of the technology inherent in the above proposals is surprisingly 'low-tech'. All their engineering aspects are feasible, even if a fuller understanding of planetology later rules out the effectiveness of any given scheme. We already have hybrid strains of fast-growing trees, ocean-going ships, cargo aircraft, rocket vehicles and nuclear explosives. Compounds of sulphur and iron are available in bulk as waste products from industry. The first space mirror was tested in 1993.
- Most geoengineering measures seem to be quite cheap to implement when estimated costs are compared to the Gross World Product. However, uncertainties in the realism of the proposals and future scientific and technical advances, mean that such costs should not be taken too seriously.
- The idea of combining geoengineering techniques *synergistically* remains to be explored. One might for instance use space mirrors to enhance phytoplankton production in the Antarctic Ocean during dark months and thus improve the performance of the iron fertilization scenario. Similarly, space mirrors that could evaporate polar stratospheric clouds early, or prevent them from performing their chlorine chemistry by maintaining their temperature > 200 K, might tie in with alkane injections to provide a much more effective protection of the ozone layer.
- The environmental risks of planetary engineering on an inhabited world should not be taken lightly. Other complex political, legal, ethical, cultural and financial issues also enter the picture. It is this need to have universal agreement and to satisfy universal requirements on a planet where civilization has no universal agenda that perhaps makes the Earth a poor candidate for planetary engineering.
- The possibility of *creative* planetary engineering on other worlds where there is no life is what makes terraforming so attractive. Many of the planetary engineering techniques and tools discussed in the context of geoengineering are also of relevance to terraforming. This is especially true of extrinsic techniques with their reliance on space-based industry. The difference between geoengineering and terraforming is therefore not so much one of substance, but of degree.

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