



Planetary Engineering

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First Edition, 2012

ISBN 978-81-323-4005-8

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Published by:

White Word Publications

4735/22 Prakashdeep Bldg,

Ansari Road, Darya Ganj,

Delhi - 110002

Email: info@wtbooks.com

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Introduction

Planetary engineering is the application of technology for the purpose of influencing the global properties of a planet. The goal of this theoretical task is usually to make other worlds habitable for life.

Perhaps the best-known type of planetary engineering is terraforming, by which a planet's surface conditions are altered to be more like those of Earth. Other types of planetary engineering include ecopoiesis, the introduction of an ecology to a lifeless environment. Planetary engineering is largely the realm of science fiction at present, although some types of climate change on Earth are recent evidence that humans can cause change on a global scale.

Terraforming

Terraforming is the hypothetical process of deliberately modifying the atmosphere, temperature, or ecology of a planet, moon, or other body to be similar to those of Earth in order to make it habitable by humans.

Geoengineering

Geoengineering is the application of planetary engineering techniques to Earth. Recent geoengineering proposals have principally been methods to tackle human-induced climate change by either removing carbon dioxide from the atmosphere (e.g. using ocean iron fertilisation) or by managing solar radiation (e.g. by using mirrors in space) in order to negate the net warming effect of climate change.

Chapter-1

Terraforming



An artist's conception shows a terraformed Mars in four stages of development.

Terraforming (literally, "Earth-forming") of a planet, moon, or other body is the hypothetical process of deliberately modifying its atmosphere, temperature, surface topography or ecology to be similar to those of Earth to make it habitable by terran organisms.

The term is sometimes used more generally as a synonym for planetary engineering, although some consider this more general usage an error. The concept of terraforming developed from both science fiction and actual science. The term was coined by Jack Williamson in a science-fiction story ("Collision Orbit") published during 1942 in *Astounding Science Fiction*, but the concept may pre-date this work.

Based on experiences with Earth, the environment of a planet can be altered deliberately: however the feasibility of creating an unconstrained planetary biosphere that mimics Earth on another planet has yet to be verified. Mars is considered by many to be the most likely candidate for terraforming. Much study has been done concerning the possibility of heating the planet and altering its atmosphere, and NASA has even hosted debates on the subject. Several potential methods of altering the climate of Mars may fall within humanity's technological capabilities, but at present the economic resources required to do so are far beyond that which any government or society is willing to allocate to the purpose. The long timescales and practicality of terraforming are the subject of debate. Other unanswered questions relate to the ethics, logistics, economics, politics, and methodology of altering the environment of an extraterrestrial world.

History of scholarly study

Carl Sagan, an astronomer, proposed the planetary engineering of Venus in an article published in the journal *Science* in 1961. Sagan imagined seeding the atmosphere of Venus with algae, which would convert water, nitrogen and carbon dioxide into organic compounds. As this process removed carbon dioxide from the atmosphere, the greenhouse effect would be reduced until surface temperatures dropped to "comfortable" levels. The resulting carbon, Sagan supposed, would be incinerated by the high surface temperatures of Venus, and thus be sequestered in the form of "graphite or some involatile form of carbon" on the planet's surface. However, later discoveries about the conditions on Venus made this particular approach impossible. One problem is that the clouds of Venus are composed of a highly concentrated sulfuric acid solution. Even if atmospheric algae could thrive in the hostile environment of Venus' upper atmosphere, an even more insurmountable problem is that its atmosphere is simply far too thick—the high atmospheric pressure would result in an "atmosphere of nearly pure molecular oxygen" and cause the planet's surface to be thickly covered in fine graphite powder. This volatile combination could not be sustained through time. Any carbon that was fixed in organic form would be liberated as carbon dioxide again through combustion, "short-circuiting" the terraforming process.

Sagan also visualized making Mars habitable for human life in "Planetary Engineering on Mars" (1973), an article published in the journal *Icarus*. Three years later, NASA addressed the issue of planetary engineering officially in a study, but used the term

"planetary ecosynthesis" instead. The study concluded that it was possible for Mars to support life and be made into a habitable planet. The first conference session on terraforming, then referred to as "Planetary Modeling", was organized that same year.

In March 1979, NASA engineer and author James Oberg organized the First Terraforming Colloquium, a special session at the Lunar and Planetary Science Conference in Houston. Oberg popularized the terraforming concepts discussed at the colloquium to the general public in his book *New Earths* (1981). Not until 1982 was the word *terraforming* used in the title of a published journal article. Planetologist Christopher McKay wrote "Terraforming Mars", a paper for the *Journal of the British Interplanetary Society*. The paper discussed the prospects of a self-regulating Martian biosphere, and McKay's use of the word has since become the preferred term. In 1984, James Lovelock and Michael Allaby published *The Greening of Mars*. Lovelock's book was one of the first to describe a novel method of warming Mars, where chlorofluorocarbons (CFCs) are added to the atmosphere. Motivated by Lovelock's book, biophysicist Robert Haynes worked behind the scenes to promote terraforming, and contributed the word *ecopoiesis* to its lexicon.

Beginning in 1985, Martyn J. Fogg began publishing several articles on terraforming. He also served as editor for a full issue on terraforming for the *Journal of the British Interplanetary Society* in 1991. In his book *Terraforming: Engineering Planetary Environments* (1995), Fogg proposed the following definitions for different aspects related to terraforming:

- Planetary engineering: the application of technology for the purpose of influencing the global properties of a planet.
- Geoengineering: planetary engineering applied specifically to the Earth. It includes only those macroengineering concepts that deal with the alteration of some global parameter, such as the greenhouse effect, atmospheric composition, insolation or impact flux.
- Terraforming: a process of planetary engineering, specifically directed at enhancing the capacity of an extraterrestrial planetary environment to support life as we know it. The ultimate achievement in terraforming would be to create an open planetary biosphere emulating all the functions of the biosphere of the Earth, one that would be fully habitable for human beings.
- Astrophysical engineering: taken to represent proposed activities, relating to future habitation, that are envisaged to occur on a scale greater than that of "conventional" planetary engineering.

Fogg also devised definitions for candidate planets of varying degrees of human compatibility:

- Habitable Planet (HP): A world with an environment sufficiently similar to the Earth as to allow comfortable and free human habitation.
- Biocompatible Planet (BP): A planet possessing the necessary physical parameters for life to flourish on its surface. If initially lifeless, then such a world

- could host a biosphere of considerable complexity without the need for terraforming.
- Easily Terraformable Planet (ETP): A planet that might be rendered biocompatible, or possibly habitable, and maintained so by modest planetary engineering techniques and with the limited resources of a starship or robot precursor mission.

Fogg suggests that Mars was a biologically compatible planet in its youth, but is not now in any of these three categories, since it could only be terraformed with greater difficulty. Mars Society founder Robert Zubrin produced a plan for a Mars return mission called Mars Direct that would set up a permanent human presence on Mars and steer efforts towards eventual terraformation.

Requirements for sustaining terrestrial life

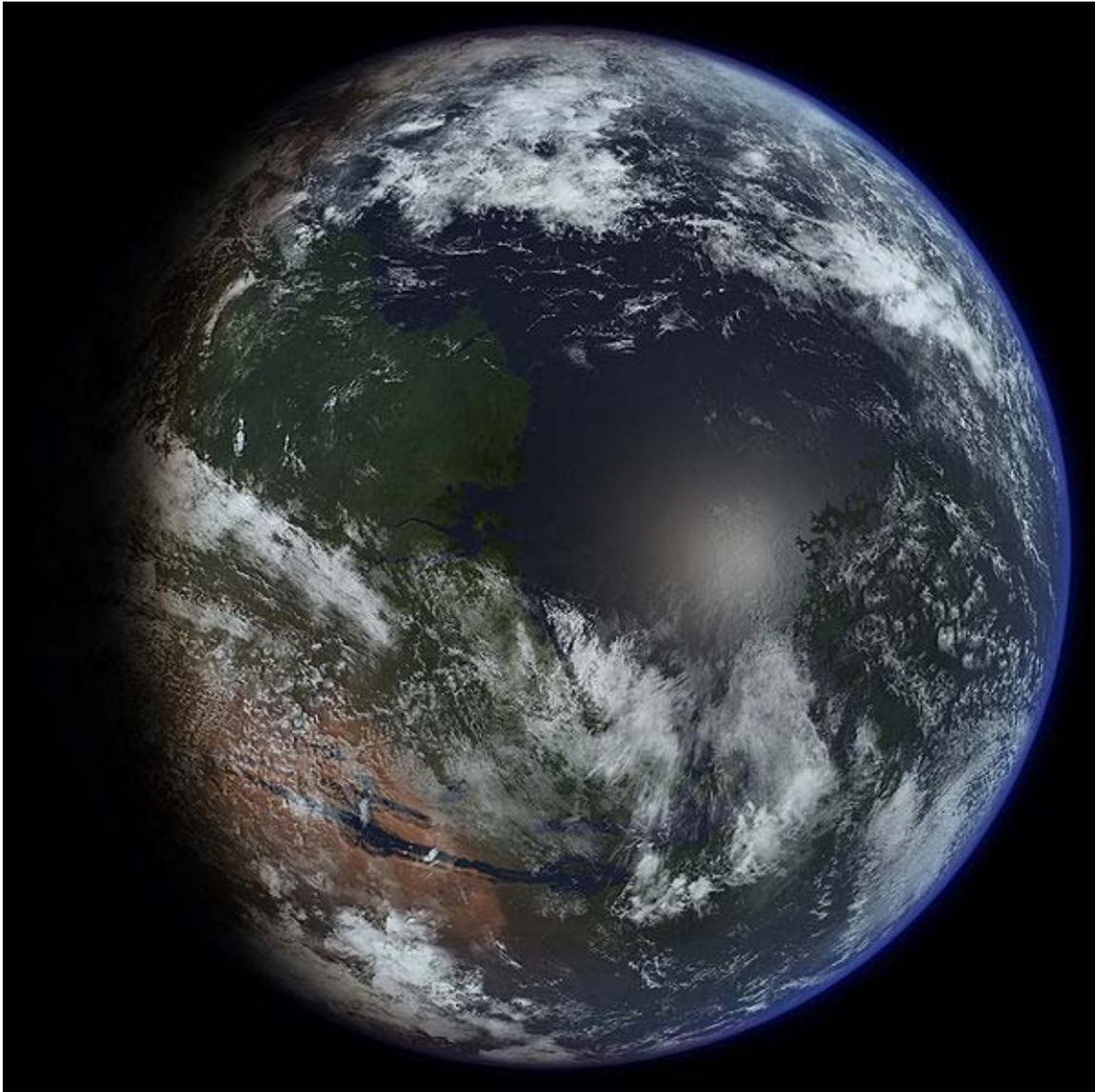
An absolute requirement for life is an energy source, but the notion of planetary habitability implies that many other geophysical, geochemical, and astrophysical criteria must be met before the surface of an astronomical body is able to support life. Of particular interest is the set of factors that has sustained complex, multicellular animals in addition to simpler organisms on this planet. Research and theory in this regard is a component of planetary science and the emerging discipline of astrobiology.

In its astrobiology roadmap, NASA has defined the principal habitability criteria as "extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism."

Preliminary stages of terraforming

Once conditions become more suitable for life, the importation of microbial life could begin. As conditions approach that of Earth, plant life could also be brought in. This would accelerate the production of oxygen, which theoretically would make the planet eventually able to support animal and human life.

Prospective planets



Artist's conception of a terraformed Mars

Mars

In many respects, Mars is the most earthlike of all the other planets in our Solar system. Indeed, it is thought that Mars once did have a more Earth-like environment early in its history, with a thicker atmosphere and abundant water that was lost over the course of hundreds of millions of years.

The exact mechanism of this loss is still unclear, though three mechanisms in particular seem likely: First, whenever surface water is present, carbon dioxide reacts with rocks to form carbonates, thus drawing atmosphere off and binding it to the planetary surface. On Earth, this process is counteracted when plate tectonics works to cause volcanic eruptions

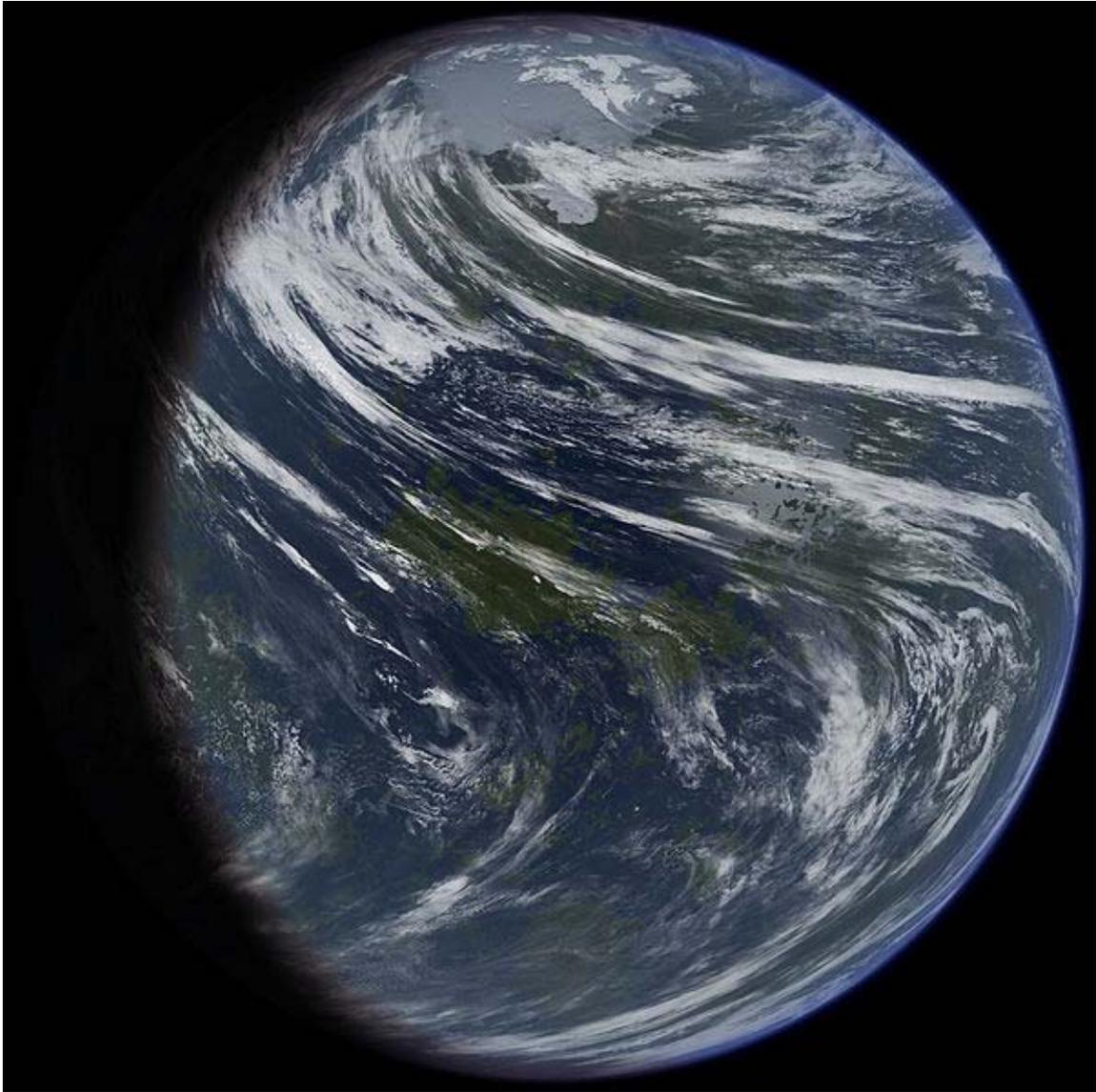
that vent carbon dioxide back to the atmosphere. On Mars, the lack of such tectonic activity worked to prevent the recycling of gases locked up in sediments.

Second, the lack of a magnetosphere surrounding the entire surface of Mars may have allowed the solar wind to gradually erode the atmosphere. Convection within the core of Mars, which is made mostly of iron, originally generated a magnetic field. However the dynamo ceased to function long ago, and the magnetic field of Mars has largely disappeared, probably due to "... loss of core heat, solidification of most of the core, and/or changes in the mantle convection regime." Mars does still retain a limited magnetosphere that covers approximately 40% of its surface. Rather than uniformly covering and protecting the atmosphere from solar wind, however, the magnetic field takes the form of a collection of smaller, umbrella-shaped fields, mainly clustered together around the planet's southern hemisphere. It is within these regions that chunks of atmosphere are violently "blown away", as astronomer David Brain explains:

The joined fields wrapped themselves around a packet of gas at the top of the Martian atmosphere, forming a magnetic capsule a thousand kilometres wide with ionised air trapped inside... Solar wind pressure caused the capsule to 'pinch off' and it blew away, taking its cargo of air with it.

Finally, between approximately 4.1 and 3.8 billion years ago, asteroid impacts during the Late Heavy Bombardment caused significant changes to the surface environment of objects in our Solar system. The low gravity of Mars suggests that these impacts could have ejected much of the Martian atmosphere into deep space.

Terraforming Mars would entail two major interlaced changes: building the atmosphere and heating it. A thicker atmosphere of greenhouse gases such as carbon dioxide would trap incoming solar radiation. Because the raised temperature would add greenhouse gases to the atmosphere, the two processes would augment each other.



Artist's conception of a terraformed Venus

Venus

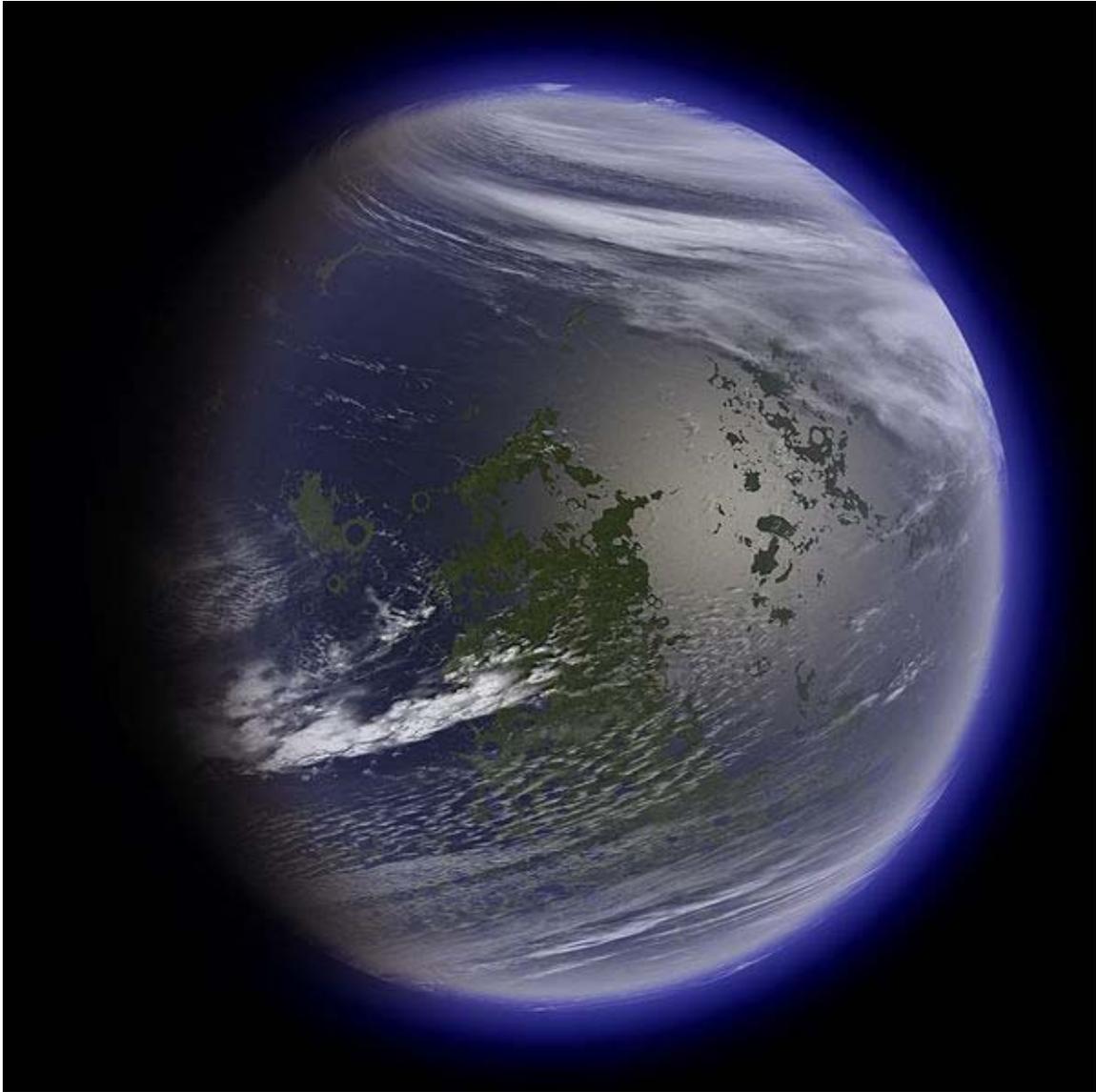
Terraforming Venus requires two major changes; removing most of the planet's dense 9 MPa carbon dioxide atmosphere and reducing the planet's 450 °C (723.15 K) surface temperature. These goals are closely interrelated, since Venus' extreme temperature is thought to be due to the greenhouse effect caused by its dense atmosphere. Sequestering the atmospheric carbon would likely solve the temperature problem as well.



Artist's conception of a terraformed Europa

Europa (moon)

Europa, a moon of Jupiter, is a potential candidate for terraforming. One advantage to Europa is the presence of liquid water which could be extremely helpful for the introduction of any form of life. The difficulties are numerous; Europa is near a huge radiation belt around Jupiter. This would require the building of radiation deflectors, which is currently impractical. Additionally, this satellite is covered in ice and would have to be heated, and there would need to be a supply of oxygen, though this could, at sufficient energy cost, be manufactured locally by electrolysis of the copious water available.



Artist's conception of what the Moon might look like terraformed

Other planets and solar system entities

Other possible candidates for terraforming (possibly only partial or paraterraforming) include Titan, Callisto, Ganymede, the Moon, and even Mercury, Saturn's moon Enceladus and the dwarf planet Ceres. Most, however, have too little mass and gravity to hold an atmosphere indefinitely (although it is possible, but not certain, that an atmosphere could remain for tens of thousands of years or be replenished as needed). In addition, aside from the Moon and Mercury, most of these worlds are so far from the Sun that adding sufficient heat would be much more difficult than even Mars would be. Terraforming Mercury would present a different series of challenges, but in certain aspects would be easier than terraforming Venus. Though not widely discussed, the possibility of terraforming Mercury's poles has been presented. Saturn's Titan offers

several unique advantages, such as an atmospheric pressure similar to Earth and an abundance of nitrogen and frozen water. Jupiter's moons Europa, Ganymede, and Callisto also have an abundance of water ice.

Paraterraforming

Also known as the "worldhouse" concept, or domes in smaller versions, paraterraforming involves the construction of a habitable enclosure on a planet which eventually grows to encompass most of the planet's usable area. The enclosure would consist of a transparent roof held one or more kilometers above the surface, pressurized with a breathable atmosphere, and anchored with tension towers and cables at regular intervals. Proponents claim worldhouses can be constructed with technology known since the 1960s. The Biosphere 2 project built a dome on Earth that contained a habitable environment. The project encountered difficulties in construction and operation.

Paraterraforming has several advantages over the traditional approach to terraforming. For example, it provides an immediate payback to investors (assuming a capitalistic financing model); the worldhouse starts out small in area (a domed city for example), but those areas provide habitable space from the start. The paraterraforming approach also allows for a modular approach that can be tailored to the needs of the planet's population, growing only as fast and only in those areas where it is required. Finally, paraterraforming greatly reduces the amount of atmosphere that one would need to add to planets like Mars to provide Earth-like atmospheric pressures. By using a solid envelope in this manner, even bodies which would otherwise be unable to retain an atmosphere at all (such as asteroids) could be given a habitable environment. The environment under an artificial worldhouse roof would also likely be more amenable to artificial manipulation.

It has the disadvantage of requiring massive amounts of construction and maintenance activity. It also would not likely have a completely independent water cycle, as rainfall may be able to develop with a high enough roof, but still probably not efficiently enough for agriculture or a water cycle. The extra cost might be off-set somewhat by automated manufacturing and repair mechanisms. A worldhouse might also be more susceptible to catastrophic failure if a major breach occurred, though this risk might be reduced by compartmentalization and other active safety precautions. Meteor strikes are a particular concern because without any external atmosphere they would reach the surface before burning up.

Ethical issues

There is a philosophical debate within biology and ecology as to whether terraforming other worlds is an ethical endeavor. From the point of view of a cosmocentric ethic, this involves balancing the need for the preservation of human life against the intrinsic value of existing planetary ecologies. On the pro-terraforming side of the argument, there are those like Robert Zubrin, Martyn J. Fogg, Richard L. S. Taylor and the late Carl Sagan who believe that it is humanity's moral obligation to make other worlds suitable for life, as a continuation of the history of life transforming the environments around it on Earth.

They also point out that Earth would eventually be destroyed if nature takes its course, so that humanity faces a very long-term choice between terraforming other worlds or allowing all terrestrial life to become extinct. Terraforming totally barren planets, it is asserted, is not morally wrong as it does not affect any other life.

Others believe terraforming would be an unethical interference in nature, and that given humanity's past treatment of the Earth, other planets may be better off without human interference. Still others strike a middle ground, such as Christopher McKay, who argues that terraforming is ethically sound only once we have completely assured that an alien planet does not harbor life of its own; but that if it does, while we should not try to reshape the planet to our own use, we should engineer the planet's environment to artificially nurture the alien life and help it thrive and co-evolve, or even co-exist with humans. Even this would be seen as a type of terraforming to the strictest of ecocentrists, who would say that all life has the right, in its home biosphere, to evolve at its own pace as well as its own direction, free of any outside interference, apparently even when it lacks volition of its own, for evolution is not a personally directed process in non-sapient species.

Economic issues

The initial cost of such projects as planetary terraforming would be gargantuan, and the infrastructure of such an enterprise would have to be built from scratch. Such technology is not yet developed, let alone financially feasible at the moment. John Hickman has pointed out that almost none of the current schemes for terraforming incorporate economic strategies, and most of their models and expectations seem highly optimistic. Access to the vast resources of space may make such projects more economically feasible, though the initial investment required to enable easy access to space will likely be tremendous.

Political issues

There are potential political issues arising from terraforming a planet. National pride, rivalries between nations, and the politics of public relations have been a primary motivation for shaping space projects.

Chapter-2

Geoengineering



An oceanic phytoplankton bloom in the South Atlantic Ocean, off the coast of Argentina. Encouraging such blooms with iron fertilization could lock up carbon on the seabed.

The modern concept of **geoengineering** (or **climate engineering**) typically proposes to deliberately manipulate the Earth's climate to counteract the effects of global warming

from greenhouse gas emissions. Other uses of the word sometimes occur, meaning geotechnical engineering.

The National Academy of Sciences defined geoengineering as "options that would involve large-scale engineering of our environment in order to combat or counteract the effects of changes in atmospheric chemistry." IPCC (2007) concluded that geoengineering options, such as ocean fertilization to remove CO₂ from the atmosphere, remained largely unproven. It was judged that reliable cost estimates for geoengineering had not yet been published.

Geoengineering accompanies mitigation and adaptation to form a 3-stranded 'MAG' approach to tackling global warming, notably advocated by the Institution of Mechanical Engineers. Some geoengineering techniques are based on carbon sequestration. These techniques seek to reduce greenhouse gases in the atmosphere directly. These include direct methods (e.g. carbon dioxide air capture) and indirect methods (e.g. ocean iron fertilization). These techniques can be regarded as mitigation of global warming. Alternatively, solar radiation management techniques do not reduce greenhouse gas concentrations, and can only address the warming effects of carbon dioxide and other gases; they cannot address problems such as ocean acidification, which are expected as a result of rising carbon dioxide levels. Examples of proposed solar radiation management techniques include the production of stratospheric sulfur aerosols, which was suggested by Paul Crutzen, space mirrors, and cloud reflectivity enhancement. Most techniques have at least some side effects.

To date, no large-scale geoengineering projects have been undertaken. Some limited tree planting and cool roof projects are already underway, and ocean iron fertilization is at an advanced stage of research, with small-scale research trials and global modelling having been completed. Field research into sulfur aerosols has also started. Some commentators have suggested that consideration of geoengineering presents a moral hazard because it threatens to reduce the political and popular pressure for emissions reduction. Typically, the scientists and engineers proposing geoengineering strategies do not suggest that they are an alternative to emissions control, but rather an accompanying strategy. Reviews of geoengineering techniques have emphasised that they are not substitutes for emission controls and have identified potentially stronger and weaker schemes.

Definition

Geoengineering is the idea of applying planetary engineering to Earth. Geoengineering would involve the deliberate modification of Earth's environment on a large scale "to suit human needs and promote habitability". Typically, the term is used to describe proposals to counter the effects of human-induced climate change. However, others define it more narrowly as nature-integrated engineering projects. The term *geoengineering* is distinct from environmental damage and accidental anthropogenic climate change, which are side-effects of human activity, rather than an intended consequence. The global recovery of hydrocarbons from the subsurface using integrated geoscience and engineering

technology has been termed 'petroleum geoengineering' as an activity with global impact. Definitions of the term are not universally accepted.

Background

The field is currently experiencing a surge of interest as it has now become broadly accepted that global warming is both real and dangerous. A degree of urgency in efforts to research and implement potential solutions is based on the historic failure to control emissions, and the possibility that tipping points in the Earth's climate system are close at hand. In particular the Arctic shrinkage is causing accelerated regional warming. Rapid action with geoengineering may be necessary. Other tipping points might be avoided by reducing the impact of global warming in order to stifle positive feedback and prevent the resulting accelerated climate change.

The study of geoengineering is a complex discipline, as it requires the collation of knowledge in:

- scientific disciplines including atmospheric chemistry, ecology, meteorology, plant biology
- engineering disciplines including aeronautical engineering, naval architecture, ballistics
- management and control disciplines such as risk management, operational research, cost-benefit analysis

Several notable organisations have recently, or are soon to, investigate geoengineering with a view to evaluating its potential. Notably, NASA, the Royal Society, the Institute of Mechanical Engineers, and the UK Parliament, have all held inquiries or contests aimed at discovering and evaluating current knowledge of the subject. The Asilomar International Conference on Climate Intervention Technologies was convened to identify and develop risk reduction guidelines for climate intervention experimentation.

The major environmental organisations such as Friends of the Earth and Greenpeace have typically been reluctant to endorse geoengineering. Some have argued that any public support for geoengineering may weaken the fragile political consensus to reduce greenhouse gas emissions.

Proposed strategies

Several geoengineering strategies have been proposed. The documentaries *Five ways to save the world* and *La temperature grimpe* describe many of the most notable projects. IPCC documents also detail several proposed projects.

Solar radiation management

Solar radiation management (SRM) projects seek to reduce the amount of sunlight hitting the Earth and thus counteract global warming. They do not reduce greenhouse gas

concentrations in the atmosphere, and thus do not address problems such as ocean acidification caused by these gases. The phenomenon of global dimming as a side-effect of fossil fuel use is widely known, and is not necessarily a geoengineering technique, also occurring naturally as a result of volcanoes and major forest fires. However, its deliberate manipulation is a tool of the geoengineer.

Solar radiation management projects often have the advantage of speed. While greenhouse gas remediation offers a comprehensive possible solution to climate change, it does not give instant results; for that, solar radiation management is required.

Techniques that fall into this category include:

- Creating stratospheric sulfur aerosols
- Ocean foams
- Cool roof—using pale-coloured roofing and paving materials
- Cloud reflectivity enhancement – using fine sea water spray to whiten clouds and increase cloud reflectivity.
- Space sunshade—obstructing solar radiation with space-based mirrors or other structures
- Cloud seeding of cirrus clouds, possibly using airliners.

Greenhouse gas remediation

Greenhouse gas remediation projects seek to remove greenhouse gases from the atmosphere, and thus tackle the root cause of global warming. They either directly remove greenhouse gases, or alternatively seek to influence natural processes to remove greenhouse gases indirectly. These projects offer a comprehensive solution to the problem of excess greenhouse gases in the atmosphere, but they will take many years to work fully. Many projects overlap with carbon capture and storage and carbon sequestration projects, and may not be considered to be geoengineering by all commentators. Techniques in this category include:

- Ocean nourishment including Iron fertilisation of the oceans
- Creating biochar (anaerobic charcoal) and burying it to create terra preta
- Bio-energy with carbon capture and storage
- Carbon air capture to remove carbon dioxide from ambient air

Arctic geoengineering

Various hydrological geoengineering projects aim to change the climate without directly or indirectly removing greenhouse gases, or directly influencing solar radiation. These principally act by limiting Arctic sea ice loss. Keeping the Arctic ice is seen by many commentators as vital, due to its role in the planet's albedo and in keeping methane, which is an important greenhouse gas, locked up in permafrost.

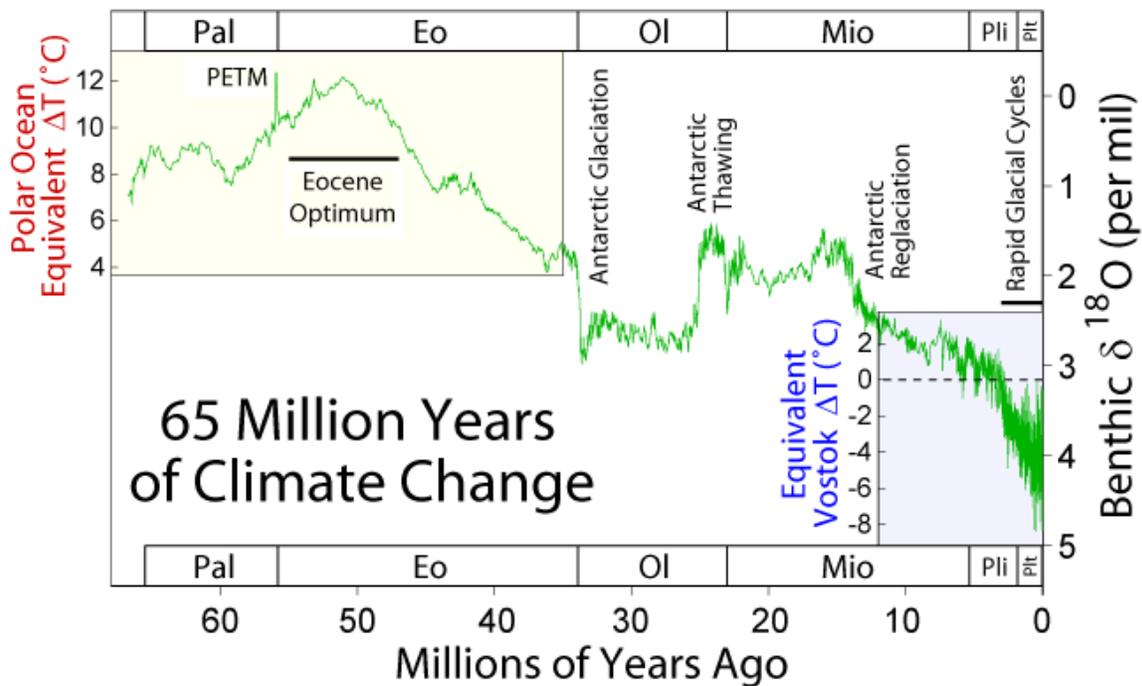
Heat transport

The use of vertical ocean pipes to mix cooler deep water and warmer surface water has been proposed. This technology has also been suggested for the disruption of hurricanes by Bill Gates and others in a recent patent application. Modification of hurricanes may be considered weather modification rather than geoengineering, depending on the definition used.

Justification

The use of geoengineering to tackle climate change is advocated for several specific reasons:

Tipping points and positive feedback



Climate change during the last 65 million years. The Paleocene–Eocene Thermal Maximum is labelled PETM.

It is argued that climate change has already, or is soon to have passed one or more tipping points where aspects of the climate system may 'tip' from one stable state to another stable state, much like a glass tipping over. When the new stable state is reached, it may trigger or accelerate warming positive feedback effects, such as the collapse of Arctic sea ice triggering the release of methane from permafrost in Siberia. The "nightmare scenario" is that a domino effect will occur, with successive parts of the climate system tipping one after the other, with each change being caused by the previous one and causing the next one. Such a situation will lead to spiralling and potentially sudden climate change.

The precise identity of such "tipping points" is not clear, with scientists taking differing views on whether specific systems are capable of "tipping" and the point at which this "tipping" will occur. An example of a previous tipping point is that which preceded the rapid warming leading up to the Paleocene–Eocene Thermal Maximum. Once the tipping point is reached, cuts in greenhouse gas emissions will not be able to reverse the change. Depending on the precise nature of the individual system that "tips", positive feedbacks may occur, with warming causing more warming, which causes yet more warming—a runaway global warming event. Therefore, some commentators suggest that more conservative use of resources is not enough to mitigate global warming. Even if all greenhouse emissions suddenly came to a complete halt, the world would continue to be affected for centuries, and further warming may occur due to positive feedback. Conservation of resources and reduction of greenhouse emissions, used in conjunction with geoengineering, are therefore considered a viable option. Geoengineering offers the hope of temporarily reversing some aspects of climate change and allowing the natural climate to be substantially preserved whilst greenhouse gas emissions are brought under control and removed from the atmosphere by natural or artificial processes.

Precautionary principle

Bearing in mind the threats from climate change, it can be argued that attempting geoengineering represents a lesser risk than not pursuing such strategies. While the understanding of geoengineering techniques is limited, the risks of global warming are at least partially understood, and are severe.

Costs

Some geoengineering techniques, such as the use of pale-coloured materials for roofing and paving, can be achieved at little or no cost, and may even offer a financial payback. IPCC (2007) concluded that reliable cost estimates for geoengineering options had not been published. This finding was based on medium agreement in the literature and limited evidence.

Political viability

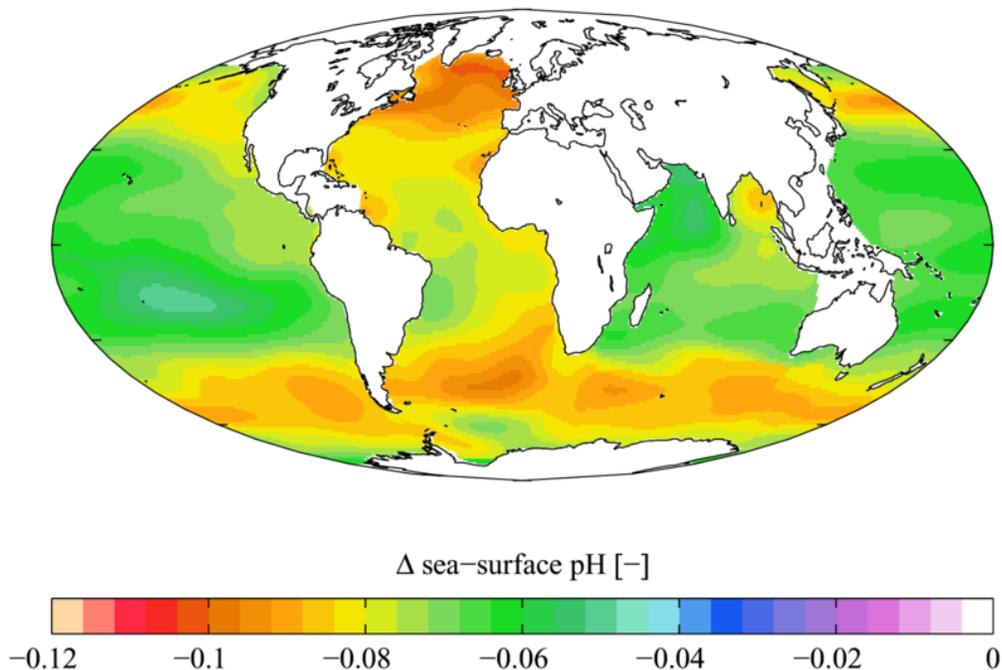
It has been argued that regardless of the economic, scientific and technical aspects, the difficulty of achieving concerted political action on climate change requires other approaches. Those arguing political expediency say the difficulty of achieving meaningful emissions cuts and the effective failure of the Kyoto Protocol demonstrate the practical difficulties of achieving carbon dioxide emissions reduction by the agreement of the international community. However, others point to support for geoengineering proposals among think tanks with a history of climate change skepticism and opposition to emissions reductions as evidence that the prospect of geoengineering is itself already politicized and being promoted as part of an argument against the need for (and viability of) emissions reductions; that, rather than geoengineering being a solution to the difficulties of emissions reductions, the prospect of geoengineering is being used as part of an argument to stall emissions reductions in the first place.

Risks and criticisms

Various criticisms have been made of geoengineering. However, the existence of criticism should not be taken to mean that those raising it are opposed to a particular technique, but rather that they are pointing out a potential disadvantage or downside which may need to be monitored or controlled, or may alternatively weigh against a particular technique. Some commentators appear fundamentally opposed, however. Individuals such as Raymond Pierrehumbert have called for a moratorium on geoengineering techniques.

Ineffectiveness

The effectiveness of the schemes proposed may fall short of predictions. In ocean iron fertilization, for example, the amount of carbon dioxide removed from the atmosphere may be much lower than predicted, as carbon taken up by plankton may be released back into the atmosphere from dead plankton, rather than being carried to the bottom of the sea and sequestered.



Change in sea surface pH caused by anthropogenic CO₂ between the 1700s and the 1990s. This ocean acidification will still be a major problem unless atmospheric CO₂ is reduced.

Incomplete solution to CO₂ emissions

Techniques that do not remove greenhouse gases from the atmosphere may control global warming, but do not reduce other effects from these gases, such as ocean acidification.

While not an argument against geoengineering *per se*, this is an argument against reliance on geoengineering to the exclusion of greenhouse gas reduction.

Control and predictability problems

The full effects of various geoengineering schemes are not well understood. Matthews et al. compared geoengineering to a number of previous environmental interventions and concluded that "Given our current level of understanding of the climate system, it is likely that the result of at least some geoengineering efforts would follow previous ecological examples where increased human intervention has led to an overall increase in negative environmental consequences."

Performance of the systems may become ineffective, unpredictable or unstable as a result of external events, such as volcanic eruptions, phytoplankton blooms, El Niño, solar flares, etc., potentially leading to profound and unpredictable disruption to the climate system.

It may be difficult to predict the effectiveness of projects, with models of techniques giving widely varying results. In the instances of systems which involve tipping points, this may result in irreversible effects. Climate modelling is far from an exact science even when applied to comparatively well-understood natural climate systems, and it is made more complex by the need to understand novel and unnatural processes which by definition lack relevant observation data.

Side effects

The techniques themselves may cause significant foreseen or unforeseen harm. For example, the use of reflective balloons may result in significant litter, which may be harmful to wildlife.

Ozone depletion is a risk of some geoengineering techniques, notably those involving sulfur delivery into the stratosphere.

The active nature of geoengineering may in some cases create a clear division between winners and losers. Most of the proposed interventions are regional, such as albedo modification in the Arctic. Necessarily, such interventions compel those in the affected regions to tolerate the effects of geoengineering for the supposed benefit of the global climate.

There may be unintended climatic consequences, such as changes to the hydrological cycle including droughts or floods, caused by the geoengineering techniques, but possibly not predicted by the models used to plan them. Such effects may be cumulative or chaotic in nature, making prediction and control very difficult.

Unreliable systems

The performance of the interventions may be inconsistent due to mechanical failure, non-availability of consumables or funding problems.

The geoengineering techniques would, in many instances, be vulnerable to being switched off or deliberately destroyed. As examples, cloud making ships could be switched off or sunk and space mirrors could be tilted to make them useless. Anyone capable of exerting such power may seek to abuse it for commercial gain, military advantage or simple terrorism.

Weaponisation

The Environmental Modification Convention generally prohibits weaponising geoengineering techniques. However, this does not eliminate the risk. Geoengineering techniques may serve as weapons of mass destruction, creating droughts or famines designed to destroy or disable an enemy. They could also be used simply to make battlefield conditions more favourable to one side or the other in a war (such as in Operation Popeye). For example, laser-guided weapons are confounded by clouds, and thus switching off cloud machines would favour forces using such weapons, and switching them on would favour ground forces defending against them.

Whilst laws or treaties may prevent the manipulation of the climate as a weapon of war, it could be argued that geoengineering is itself a manipulation, and thus destroying or disabling the geoengineering structures is not prohibited. A new legal framework may be necessary in the event that large-scale geoengineering becomes established.

Carnegie's Ken Caldeira said, "It will make it harder to achieve broad consensus on developing and governing these technologies if there is suspicion that gaining military advantage is an underlying motivation for its development..."

Effect on sunlight, sky and clouds

Managing solar radiation using aerosols or cloud cover will change the ratio between direct and indirect solar radiation. This may affect plant life and solar energy. There will be a significant effect on the appearance of the sky from aerosol projects, notably a hazing of blue skies and a change in the appearance of sunsets. Aerosols may affect the formation of clouds, especially cirrus clouds.

Moral hazard

The existence of such techniques may reduce the political and social impetus to reduce carbon emissions.

Other criticism comes from those who see geoengineering projects as reacting to the symptoms of global warming rather than addressing the real causes of climate change.

Because geoengineering is a form of controlling the risks associated with global warming, it leads to a moral hazard problem. The problem is that knowledge that geoengineering is possible could lead to climate impacts seeming less fearsome, which could in turn lead to a weaker commitment to reducing greenhouse gas emissions.

Lack of global control

Geoengineering opens up various political and economic issues. David Keith argues that the cost of geoengineering the Earth is within the realm of small countries, large corporations, or even very wealthy individuals. Steve Rayner agrees that not all geoengineering possibilities are expensive, and that some, such as ocean iron fertilisation, are within the reach of very wealthy individuals, calling them a "Greenfinger" (after the fictional Goldfinger). David Victor suggests that geoengineering is within the reach of any individual who has a small fraction of the bank account of Bill Gates, who takes it upon him or her self to be the "self-appointed protector of the planet".

This effectively eliminates any control over who gets to decide when to cool the Earth and how often this should be done. The resulting power would be enormous, and could not necessarily be readily controlled by legal, political or regulatory systems. These legal and regulatory systems may themselves be far less powerful than the geoengineers controlling the climate become.

It is quite feasible for carbon offsetting firms to set up unregulated, unsupervised and dangerous geoengineering projects. This may be done in order to sell carbon credits to individuals and firms.

Geoengineering schemes have the potential to cause significant environmental damage, and may even end up releasing further greenhouse gases into the atmosphere. Opposition to some early schemes has been intense, with respected environmental groups campaigning against them.

Rapid warming if stopped

If solar radiation management were to abruptly stop, the climate would rapidly warm. This would cause a sudden rise in global temperatures towards levels which would have existed without the use of the geoengineering technique. The rapid rise in temperature may lead to more severe consequences than a gradual rise of the same magnitude.

Implementation issues

There is no general consensus that geoengineering is safe, appropriate or effective, for the reasons listed above. The issue of moral hazard means that many environmental groups and campaigners are reluctant to advocate geoengineering for fear of reducing the imperative to cut greenhouse gas emissions. Other environmentalists see calls for geoengineering as part of an explicit strategy to delay emissions reductions on the part of those with connections to coal and oil industries.

All proposed geoengineering techniques require implementation on a relatively large scale, in order to make a significant difference to the Earth's climate. The least costly schemes are budgeted at a cost of millions, with many more complex schemes such as space sunshade costing far more.

Many techniques, again such as space sunshade, require a complex technical development process before they are ready to be implemented. There is no clear institutional mechanism for handling this research and development process. As a result, many promising techniques do not have the engineering development or experimental evidence to determine their feasibility or efficacy at present.

Once a technique has been developed and tested, its implementation is still likely to be difficult. Climate change is by nature a global problem, and therefore no one institution, company or government is responsible for it. The substantial costs of most geoengineering techniques therefore cannot currently be apportioned. Roll-out of such technologies is therefore likely to be delayed until these issues can be resolved. A notable exception is the use of small albedo manipulation projects, known as *cool roof*, in which the colour of roofing or paving surfaces can be manipulated to reflect solar radiation back into space. These can be, and are, implemented by individuals, companies and governments without controversy.

Due to the radical changes caused by geoengineering interventions, legal issues are also an impediment to implementation. The changes resulting from geoengineering necessarily benefit some people and disadvantage others. There may therefore be legal challenges to the implementation of geoengineering techniques by those adversely affected by them.

Evaluation of geoengineering

Few field experiments in geoengineering have been carried out. Most of what is known about the suggested techniques is based on small-scale trials and from simulations of global climate models and other computer modelling techniques. Some geoengineering schemes employ methods that have analogues in natural phenomena such as stratospheric sulfur aerosols and cloud condensation nuclei. As such, studies about the efficacy of these schemes can draw on information already available from other research, such as that following the 1991 eruption of Mount Pinatubo. However, comparative evaluation of the relative merits of each technology is complicated, especially given modelling uncertainties and the early stage of engineering development of many geoengineering schemes.

In a 2009 review study, Lenton and Vaughan evaluated a range of geoengineering schemes from those that sequester CO₂ from the atmosphere and decrease longwave radiation trapping, to those that decrease the Earth's receipt of shortwave radiation. In order to permit a comparison of disparate techniques, they used a common evaluation for each scheme based on its effect on net radiative forcing. As such, the review examined the scientific plausibility of schemes rather than the practical considerations such as

engineering feasibility or economic cost. Lenton and Vaughan found that "[air] capture and storage shows the greatest potential, combined with afforestation, reforestation and bio-char production", and noted that "other suggestions that have received considerable media attention, in particular "ocean pipes" appear to be ineffective". They concluded that "[climate] geoengineering is best considered as a potential complement to the mitigation of CO₂ emissions, rather than as an alternative to it".

Reports into geoengineering have also been published in the United Kingdom by the Institution of Mechanical Engineers and the Royal Society. The IMechE report examined a small subset of proposed schemes (air capture, urban albedo and algal-based CO₂ capture schemes), and its main conclusions were that geoengineering should be researched and trialled at the small scale alongside a wider decarbonisation of the economy.

The Royal Society review examined a wide range of geoengineering schemes and evaluated them in terms of effectiveness, affordability, timeliness and safety (assigning qualitative estimates in each assessment). Similarly to Lenton and Vaughan, the report divided schemes into "carbon dioxide removal" (CDR) and "solar radiation management" (SRM) approaches that respectively address longwave and shortwave radiation. The key recommendations of the report were that "Parties to the UNFCCC should make increased efforts towards mitigating and adapting to climate change, and in particular to agreeing to global emissions reductions", and that "[nothing] now known about geoengineering options gives any reason to diminish these efforts". Nonetheless, the report also recommended that "research and development of geoengineering options should be undertaken to investigate whether low risk methods can be made available if it becomes necessary to reduce the rate of warming this century".

Chapter-3

Space Sunshade and Natural Satellite Habitability

Space sunshade

A **space sunshade** or **sunshield** can be described as analogous to a parasol that diverts or otherwise reduces some of a star's rays, preventing them from hitting a planet and thereby reducing its insolation, which results in less heating of the planet.

A sunshade is of particular interest towards mitigating global warming through solar radiation management. Such shades could also be used to produce space solar power, acting as solar power satellites. Proposed shade designs include a single-piece shade and a shade made by a great number of small objects.

Cloud of small spacecraft near L1

One proposed such sunshade for use towards that effect would be composed of 16 trillion small disks at the Sun-Earth L1 Lagrangian point, 1.5 million kilometers above Earth. Each disk is proposed to have a 0.6 meter diameter and a thickness of about 5 microns. The weight of such a sunshade would be about a gram, adding up to a total weight of almost 20 million tonnes. Such a group of small sunshades that blocks 2% of the sunlight, reflecting it off into space, would be enough to halt global warming, giving us ample time to cut our emissions back on earth.

The individual autonomous flyers building up the cloud of sunshades are proposed to not reflect the sunlight but be transparent lenses, deflecting the light slightly so it does not hit earth. This minimizes the effect of solar radiation pressure on the units, requiring less effort to be put into holding them in place at the L1 point. An optical prototype has been constructed by Roger Angel with funding from NIAC.

The remaining solar pressure and the fact that the L1 point is an unstable position easily disturbed by the wobble of the earth due to gravitational effects from the moon, requires the small autonomous flyers to be capable of maneuvering themselves to keep their

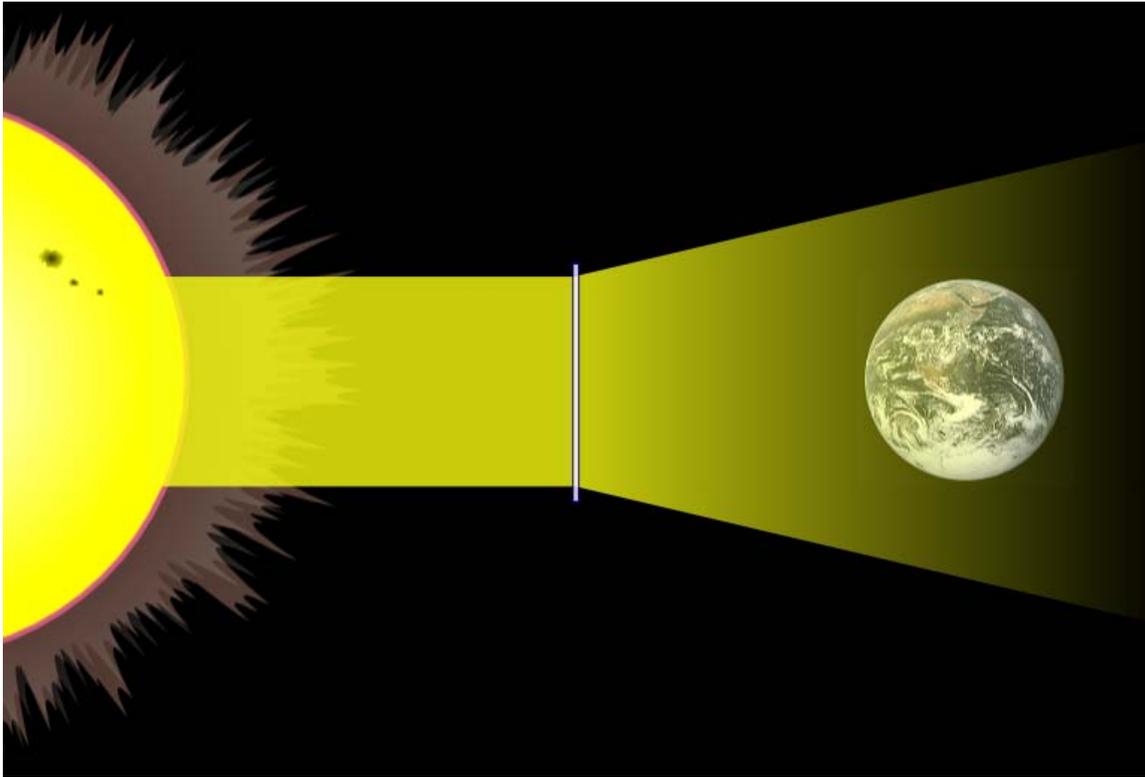
position. A suggested solution to this problem is the placement of mirrors capable of rotation on the surface of the flyers. By using the solar radiation pressure on the mirrors and tilting them in the right direction, the flyer will be capable of altering its speed and direction to keep in position.

Such a group of sunshades would need to occupy an area of about 3.8 square kilometers if placed at the L1 point. The deployment of the flyers is an issue that requires new technology. It has been proposed that this would be accomplished most easily with large railguns or coilguns firing a capsule containing a million shades into space every 5 minutes for 10 years using 20 separate launch sites. The esteemed total cost of such an operation is 5 trillion US dollars, with a believed lifetime of 50 years.

Even so, it would still take years to launch enough of the disks into orbit before they have any effect. Thus, if using this technology should become essential, enough time would be needed to implement it. Rebecca Shafer of Reed College presented the idea for the Sunshade at the U.S. National Academy of Sciences in April, 2006 and won a NASA Institute for Advanced Concepts grant for further research in July, 2006. Her team members working on the grant are David Miller of the Massachusetts Institute of Technology, Nick Woolf of UA's Steward Observatory, and NASA Ames Research Center Director S. Pete Worden.

Creating this sunshade in space was estimated to cost in excess of US\$5 trillion, thus leading Professor Shafer to conclude that "[t]he sunshade is no substitute for developing renewable energy, the only permanent solution. A similar massive level of technological innovation and financial investment could ensure that. But if the planet gets into an abrupt climate crisis that can only be fixed by cooling, it would be good to be ready with some shading solutions that have been worked out."

Sunshade consisting of one Fresnel lens



The basic function of a space lens to mitigate global warming. A 1000 kilometre diameter lens is sufficient, and much smaller than what is shown in this simplified image. As a Fresnel lens it would be only a few millimeters thick.

Several authors have proposed dispersing light before it reaches the Earth by putting a very large lens in space, perhaps at the L₁ point between the Earth and the Sun. This plan was proposed in 1989 by J. T. Early.

In 2004, physicist and science fiction author Gregory Benford calculated that a concave rotating Fresnel lens 1000 kilometres across, yet only a few millimeters thick, floating in space at the L₁ point, would reduce the solar energy reaching the Earth by approximately 0.5% to 1%. Side-effects include that, if this lens were built and global warming were avoided, there would be less incentive to reduce greenhouse gases, and humans might continue to produce too much carbon dioxide until it caused some other environmental catastrophe, such as a chemical change in ocean water that could be disastrous to ocean life.

The cost of such a lens has been disputed. At a global warming summit in 2004, Benford estimated that it would cost around US\$10 billion up front, and another \$10 billion in supportive cost during its lifespan. However, the mass of a 500 km radius circle with a thickness of 2mm at a density of 1 gram/cc would be 1.57 trillion kilograms. To launch that much mass into low earth orbit would require 12,362,000 Saturn V class launch vehicles, which would actually cost much more than 808.93\$ per launch. At a much more

realistic cost of 1 billion dollars per Saturn V class launch, it would cost 12.36 quadrillion dollars to launch the mass for the lens into low earth orbit. This is neglecting the mass of fuel in leo to boost the lens materials from leo to the L1 point. Accounting for the extra mass of fuel for the delta V required would approximately double the number of launches, which means the 10 billion dollar system would actually cost a minimum of 24.7 quadrillion dollars.

Sunshade consisting of one diffraction grating

A similar approach involves placing a very large diffraction grating (thin wire mesh) in space, perhaps at the L1 point between the Earth and the Sun. Such a proposal was made in 1997 by Edward Teller, Lowell Wood, and Roderick Hyde, although in 2002 these same authors argued for blocking solar radiation in the stratosphere rather than in orbit.

Natural satellite habitability



Artist's impression of a hypothetical moon around a Saturn-like exoplanet that could be habitable.

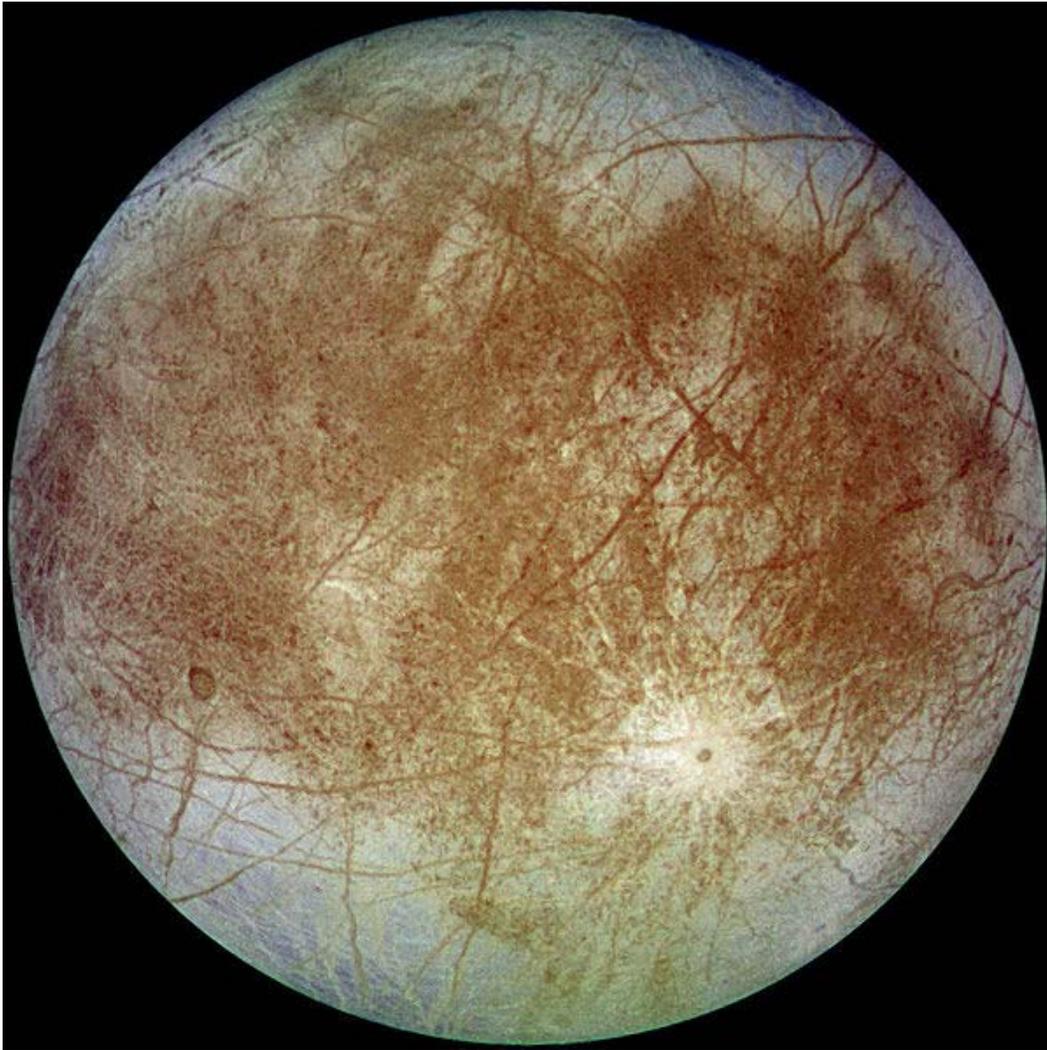
Natural satellite habitability is the measure of a natural satellite's potential to sustain life. Theoretical conditions under which life might on develop natural satellites (moons) are similar to those of planets. More complex orbital arrangements and differences in mass and other bulk criteria are considered by scientists in studying the possibility of habitable satellites.

Scientists generally consider the probability of extraterrestrial life on natural satellites within our own solar system to be remote given the complex conditions required for

abiogenesis. Within our solar system's habitable zone the only such objects are the moon (Luna), Phobos and Deimos and do not have either an atmosphere or water in liquid form. However several candidates have been identified that have some of the ingredients thought necessary for life to exist. The theory of panspermia suggests that life may have been introduced to such environments. The strongest such candidates are satellites of the Jupiter and Saturn. There is also the theoretical possibility of exotic biochemistries within our own solar system. No extrasolar moons are yet known to exist and there is no way of knowing how common they may be or how many could be considered habitable.

Moon habitability is sometimes used in the context of potential candidates for Space colonization by humans. Humans can inhabit moons through artificial environments and have indeed inhabited our moon (Luna) for brief periods of time. However the most Earth-like moon in our solar system is Titan, however it is extremely uninhabitable in this sense. Terraforming of moons may be possible but outside the limits of current technology. Moon habitability for terrestrial life is also a distinct possibility, through either deliberate or accidental future forward-contamination.

Possible habitable moons



Europa, a moon of Jupiter with a possibility of having life

The following is a list of satellites which are possible candidates for life in our solar system in approximate order of probability for harboring life.

Name	System	Notes
Europa	Jupiter	Has an ocean heated by volcanic activity, tidal energy and radiation. Also may have more water and oxygen than Earth, including an oxygen atmosphere

Enceladus	Saturn	Has water and geothermal activity
Titan	Saturn	Considered similar to an early Earth with a thicker atmosphere, hydrocarbon lakes, cryovolcanos, with a remote possibility of an exotic methane-based biochemistry
Rhea	Saturn	Has a thin atmopshere containing oxygen and carbon dioxide
Callisto	Jupiter	Thought to have a sub-surface ocean heated by radiation.
Io	Jupiter	Volcanically active, generating heat energy with a trace atmosphere
Triton	Neptune	Possible layer of liquid water or subterranean ocean.
Charon	Pluto	Possible internal ocean of water and ammonia evidenced by possible cryovolcanic activity.

Conditions for habitability

Several factors are assumed by scientists to be conditions required for a habitable moon.

Stable climate

Orbital stability

For a stable orbit (and thus a stable climate), the ratio between the moon's orbital period around its primary and that of the primary around its sun cannot be too small. Simulations suggest that a moon with an orbital period less than about 45 to 60 days will remain safely bound to a massive giant planet or brown dwarf that orbits 1 AU from a Sun-like star.

Atmosphere

A moon would need at least 7% of Earth's mass to retain most of its atmosphere for 4.6 billion years (Earth's current age) if it had a Mars-like density and an Earth-like

atmospheric temperature structure, because some of the gas atoms at the top of an atmosphere will get kicked by random thermal collisions to faster than the moon's escape velocity and fly away.

The other thing that can make a moon lose its atmosphere is sputtering, a process whereby atoms are ejected from a solid target material due to bombardment of the target by energetic particles. All the gas giants that are in our solar system, and likely others, have magnetospheres with radiation belts potent enough to completely erode an atmosphere of an earth-like moon in just a few hundred million years. One way to decrease loss of atmosphere by sputtering is for the moon to have strong magnetic field. NASA's Galileo's measurements hints large moons can have strong magnetic field. It detected Earth-like magnetic field around Ganymede even though its mass is only 2.5% of Earth's

Length of day

A moon orbiting a gas giant or brown dwarf is likely to be tidally locked to its primary: that is, its day is as long as its orbit. Monoj Joshi and Robert Haberle (NASA/Ames Research Center) and their colleagues modelled the temperature on tide-locked exoplanets in the habitability zone of red dwarfs. They found that an atmosphere with a carbon-dioxide pressure of only 1 to 1.5 atmospheres not only allows habitable temperatures but allows liquid water on the dark side. The temperature range of a moon that is tidally locked to a gas giant should be less extreme than with a planet that locked to a sun. Even though no studies have been done on the subject, just modest amounts of CO₂ would make the temperature habitable.

Chapter-4

Stratospheric Sulfur Aerosols

Stratospheric sulfur aerosols are tiny sulfur-rich particles of solid or liquid, or a mixture of the two, which exist in the stratosphere region of the Earth's atmosphere. When present, after a strong volcanic eruption such as Mount Pinatubo, they produce a cooling effect for a few years before the particles fall out, by reflecting sunlight, and by modifying clouds as they fall out of the stratosphere.

An aerosol is a suspension of fine solid particles or liquid droplets in a gas. The sulfate particles or sulfuric acid droplets in the atmosphere are about 0.1 to 1.0 micrometer (a millionth of a meter) in diameter.

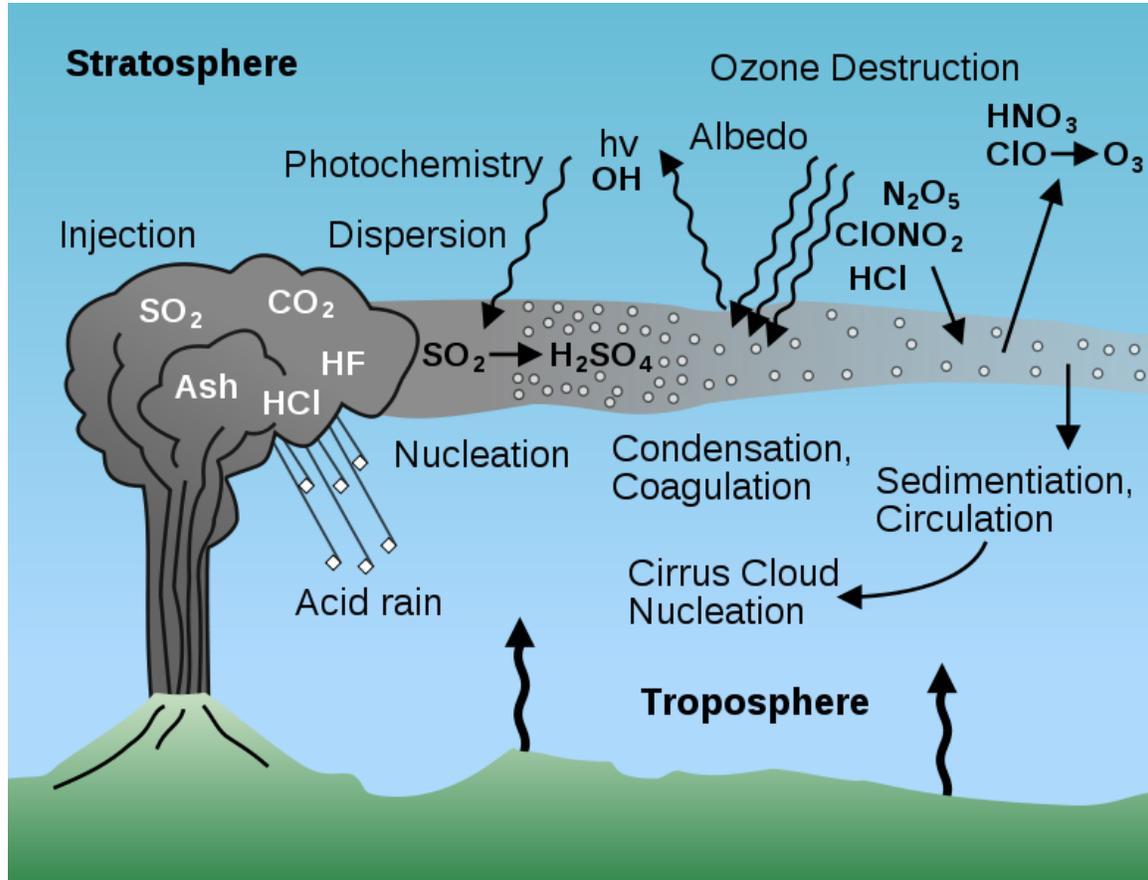
Sulfur aerosols are common in the troposphere as a result of pollution with sulfur dioxide from burning coal, and from natural processes. Volcanos are the major source of particles in the stratosphere as the force of the volcanic eruption propels sulfur-containing gases into the stratosphere.

Creating stratospheric sulfur aerosols deliberately is a proposed geoengineering technique which offers a possible solution to some of the problems caused by global warming. However, this will not be without side effects and it has been suggested that the cure may be worse than the disease.



Pinatubo eruption cloud. This volcano released huge quantities of stratospheric sulfur aerosols and contributed greatly to understanding of the subject.

Origins



Volcanic "injection"

Natural sulfur aerosols are formed in vast quantities from the SO_2 ejected by volcanoes, which may be injected directly into the stratosphere during very large (Volcanic Explosivity Index, VEI, of 4 or greater) eruptions. A comprehensive analysis, dealing largely with tropospheric sulfur compounds in the atmosphere, is provided by Bates et al.

The IPCC AR4 says *explosive volcanic events are episodic, but the stratospheric aerosols resulting from them yield substantial transitory perturbations to the radiative energy balance of the planet, with both shortwave and longwave effects sensitive to the microphysical characteristics of the aerosols*. As of 2009 there have been no explosive and climatically significant volcanic events since Mt. Pinatubo and consequently stratospheric aerosol concentrations are at the lowest concentrations since the satellite era and global coverage began in about 1980.

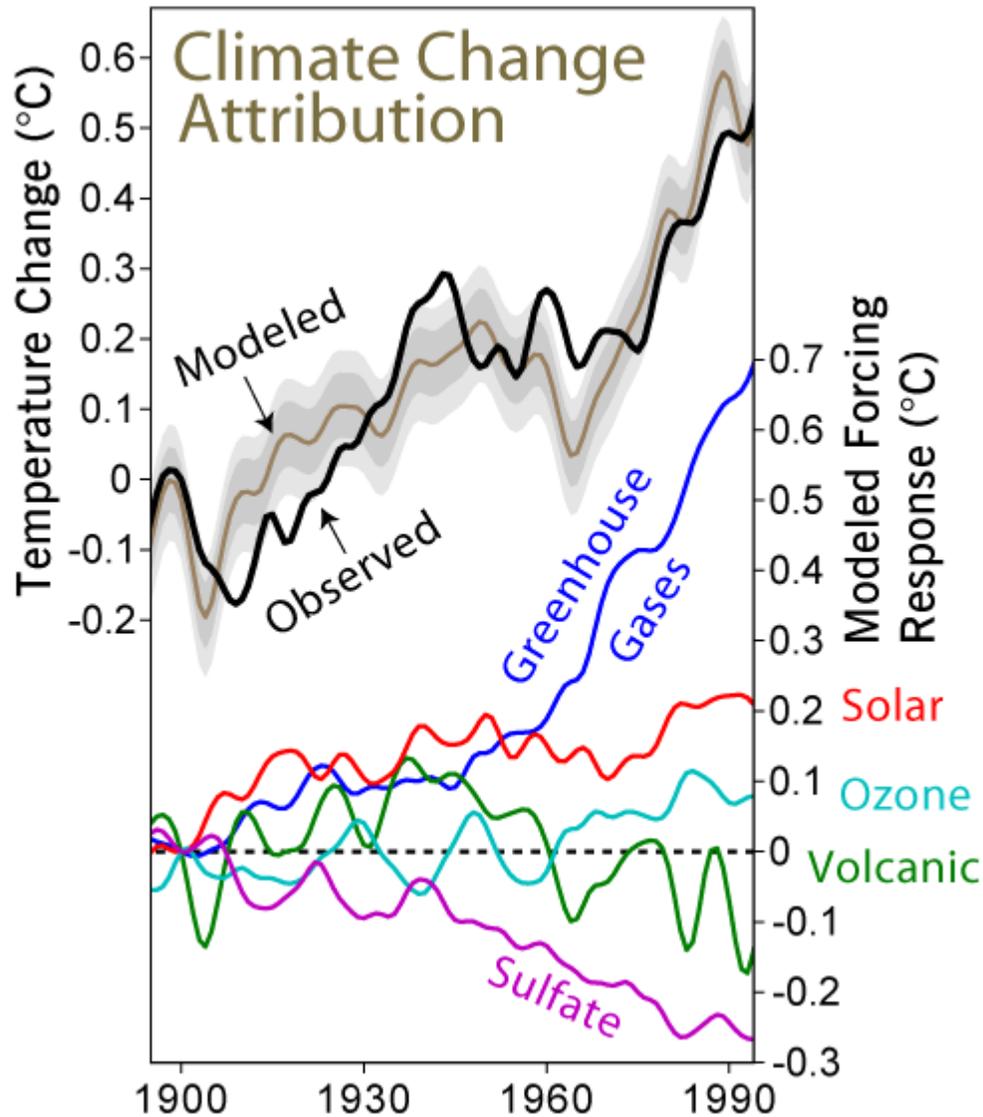
During periods lacking volcanic activity (and thus direct injection of SO_2 into the stratosphere), oxidation of COS (carbonyl sulfide) dominates the production of stratospheric sulfur aerosol.

Chemistry

The chemistry of stratospheric sulfur aerosols varies significantly according to their source. Volcanic emissions vary significantly in composition, and have complex chemistry due to the presence of ash particulates and a wide variety of other elements in the plume.

The chemical reactions affecting both the formation and elimination of sulfur aerosols are not fully understood. It is difficult to estimate accurately, for example, whether the presence of ash and water vapour is important for aerosol formation from volcanic products, and whether high or low atmospheric concentrations of precursor chemicals (such as SO_2 and H_2S) are optimal for aerosol formation. This uncertainty makes it difficult to determine a viable approach for geoengineering uses of sulfur aerosol formation.

Scientific study



Stratospheric sulfates from volcanic emissions cause transient cooling; the purple line showing sustained cooling is from tropospheric sulfate

Understanding of these aerosols comes in large part from the study of volcanic eruptions, notably Mount Pinatubo in the Philippines, which erupted in 1991 when scientific techniques were sufficiently far advanced to study the effects carefully.

The formation of the aerosols and their effects on the atmosphere can also be studied in the lab. Samples of actual particles can be recovered from the stratosphere using balloons or aircraft.

Computer models can be used to understand the behaviour of aerosol particles, and are particularly useful in modelling their effect on global climate.

Biological experiments in the lab, and field/ocean measurements can establish the formation mechanisms of biologically derived volatile sulfurous gases.

Effects

Effect on climate

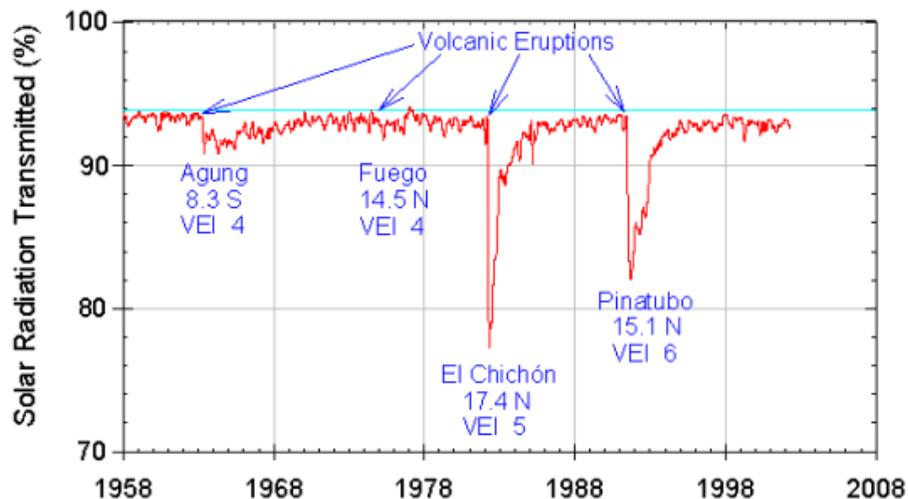
It has been established that emission of precursor gases for sulfur aerosols is the principle mechanism by which volcanoes cause episodic global cooling.

The Intergovernmental Panel on Climate Change AR4 regards stratospheric sulfate aerosols as having a low level of scientific understanding.

The aerosol particles form a whitish haze in the sky. This creates a global dimming effect, where less of the sun's radiation is able to reach the surface of the Earth. This leads to a global cooling effect. In essence, they act as the reverse of a greenhouse gas, which tends to allow visible light from the sun through, whilst blocking infra-red emitted from the Earth's surface and its atmosphere. The particles also radiate infra red energy directly, as they lose heat into space.

Effects on light transmission through the atmosphere

Mauna Loa Observatory Atmospheric Transmission



Solar radiation reduction due to volcanic eruptions

All aerosols both absorb and scatter solar and terrestrial radiation. This is quantified in the *Single Scattering Albedo* (SSA), the ratio of scattering alone to scattering plus absorption (*extinction*) of radiation by a particle. The SSA tends to unity if scattering dominates, with relatively little absorption, and decreases as absorption increases, becoming zero for infinite absorption. For example, sea-salt aerosol has an SSA of 1, as a sea-salt particle only scatters, whereas soot has an SSA of 0.23, showing that it is a major atmospheric aerosol absorber.

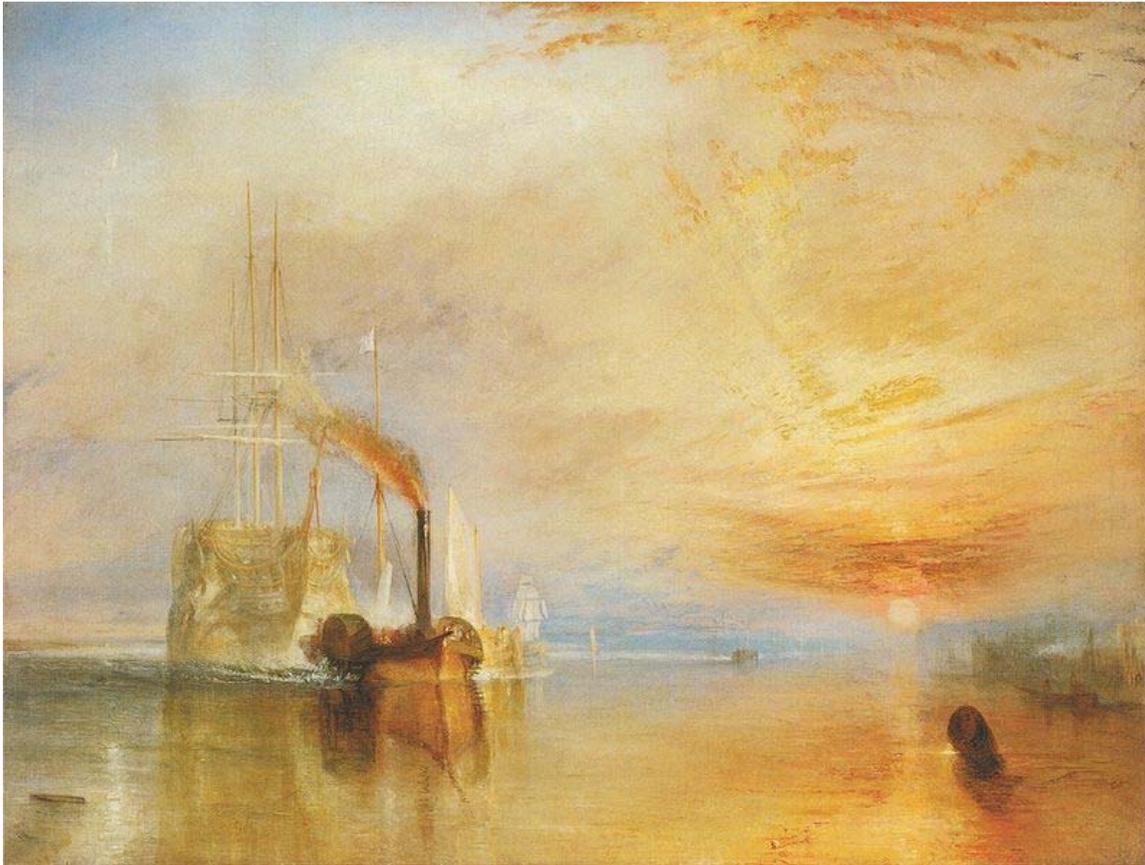
Aerosols, natural and anthropogenic, can affect the climate by changing the way radiation is transmitted through the atmosphere. Direct observations of the effects of aerosols are quite limited so any attempt to estimate their global effect necessarily involves the use of computer models. The Intergovernmental Panel on Climate Change, IPCC, says: *While the radiative forcing due to greenhouse gases may be determined to a reasonably high degree of accuracy... the uncertainties relating to aerosol radiative forcings remain large, and rely to a large extent on the estimates from global modelling studies that are difficult to verify at the present time.* However, they are mostly talking about tropospheric aerosol.

Effect on ozone

The aerosols have a role in the destruction of ozone due to surface chemistry effects. Destruction of ozone has in recent years created large holes in the ozone layer, initially over the Antarctic and then the Arctic. These holes in the ozone layer have the potential to expand to cover inhabited and vegetative regions of the planet, leading to catastrophic environmental damage.

Ozone destruction occurs principally in polar regions, but the formation of ozone occurs principally in the tropics. Ozone is distributed around the planet by the Brewer-Dobson circulation. Therefore, the source and dispersal pattern of aerosols is critical in understanding their effect on the ozone layer.

Effect on sky appearance



Turner was inspired by dramatic sunsets caused by volcanic aerosols.

Aerosols scatter light, which affects the appearance of the sky and of sunsets. Changing the concentration of aerosols in the atmosphere can dramatically affect the appearance of sunsets. A change in sky appearance during the year without a summer (attributed to the eruption of Tambora) was the inspiration for the paintings of J. M. W. Turner. Further volcanic eruptions and geoengineering projects involving sulfur aerosols are likely to affect the appearance of sunsets significantly, and to create a haze in the sky.

Effect on the biosphere

Aerosol particles are eventually deposited from the stratosphere onto land and ocean. Depending on the volume of particles descending, the effects may be significant to ecosystems, or may not be. Modelling of the quantities of aerosols used in likely geoengineering scenarios suggest that effects on terrestrial ecosystems from deposition is not likely to be significantly harmful.

Geoengineering

The ability of stratospheric sulfur aerosols to create this global dimming effect has made them a possible candidate for use in geoengineering projects to limit the effect and impact of climate change due to rising levels of greenhouse gases. Delivery of precursor gases such as H₂S and SO₂ by artillery, aircraft and balloons has been proposed.

Understanding of this proposed technique is partly based on the fact that it is the adaptation of an existing atmospheric process. The technique is therefore potentially better understood than are comparable (but purely speculative) geoengineering schemes. It is also partly based on the speed of action of any such solution deployed, in contrast to carbon sequestration projects such as carbon dioxide air capture which would take longer to work. However, gaps in understanding of these processes exist, for example the effect on stratospheric climate and on rainfall patterns, and further research is needed.

This technique has been studied more extensively than most other geoengineering techniques, and is suggested by commentators including Tom Wigley.

Chapter-5

Planetary Habitability



Understanding planetary habitability is partly an extrapolation of the Earth's conditions, as it is the only planet currently known to support life

Planetary habitability is the measure of a planet's or a natural satellite's potential to sustain life. Life may develop directly on a planet or satellite or be transferred to it from another body, a theoretical process known as panspermia. As the existence of life beyond Earth is currently uncertain, planetary habitability is largely an extrapolation of conditions on Earth and the characteristics of the Sun and solar system which appear

favorable to life's flourishing—in particular those factors that have sustained complex, multicellular organisms and not just simpler, unicellular creatures. Research and theory in this regard is a component of planetary science and the emerging discipline of astrobiology.

An absolute requirement for life is an energy source, and the notion of planetary habitability implies that many other geophysical, geochemical, and astrophysical criteria must be met before an astronomical body can support life. In its astrobiology roadmap, NASA has defined the principal habitability criteria as "extended regions of liquid water, conditions favorable for the assembly of complex organic molecules, and energy sources to sustain metabolism."

In determining the habitability potential of a body, studies focus on its bulk composition, orbital properties, atmosphere, and potential chemical interactions. Stellar characteristics of importance include mass and luminosity, stable variability, and high metallicity. Rocky, terrestrial-type planets and moons with the potential for Earth-like chemistry are a primary focus of astrobiological research, although more speculative habitability theories occasionally examine alternative biochemistries and other types of astronomical bodies.

The idea that planets beyond Earth might host life is an ancient one, though historically it was framed by philosophy as much as physical science.^a The late 20th century saw two breakthroughs in the field. The observation and robotic spacecraft exploration of other planets and moons within the solar system has provided critical information on defining habitability criteria and allowed for substantial geophysical comparisons between the Earth and other bodies. The discovery of extrasolar planets, beginning in the early 1990s and accelerating thereafter, has provided further information for the study of possible extraterrestrial life. These findings confirm that the Sun is not unique among stars in hosting planets and expands the habitability research horizon beyond our own solar system.

Suitable star systems

An understanding of planetary habitability begins with stars. While bodies that are generally Earth-like may be plentiful, it is just as important that their larger system be agreeable to life. Under the auspices of SETI's Project Phoenix, scientists Margaret Turnbull and Jill Tarter developed the "HabCat" (or Catalogue of Habitable Stellar Systems) in 2002. The catalogue was formed by winnowing the nearly 120,000 stars of the larger Hipparcos Catalogue into a core group of 17,000 "HabStars," and the selection criteria that were used provide a good starting point for understanding which astrophysical factors are necessary to habitable planets.

Spectral class

The spectral class of a star indicates its photospheric temperature, which (for main-sequence stars) correlates to overall mass. The appropriate spectral range for "HabStars" is presently considered to be "early F" or "G", to "mid-K". This corresponds to

temperatures of a little more than 7,000 K down to a little more than 4,000 K; the Sun, a G2 star, is well within these bounds. "Middle-class" stars of this sort have a number of characteristics considered important to planetary habitability:

- They live at least a few billion years, allowing life a chance to evolve. More luminous main-sequence stars of the "O," "B," and "A" classes usually live less than a billion years and in exceptional cases less than 10 million.^b
- They emit enough high-frequency ultraviolet radiation to trigger important atmospheric dynamics such as ozone formation, but not so much that ionisation destroys incipient life.
- Liquid water may exist on the surface of planets orbiting them at a distance that does not induce tidal lock. K Spectrum stars may be able to support life for long periods, far longer than our sun.

This spectral range probably accounts for between 5% and 10% of stars in the local Milky Way galaxy. Whether fainter late K and M class red dwarf stars are also suitable hosts for habitable planets is perhaps the most important open question in the entire field of planetary habitability given their ubiquity (habitability of red dwarf systems). Gliese 581 c, a "super-Earth," has been found orbiting in the "habitable zone" of a red dwarf and may possess liquid water. Alternately, a greenhouse effect may render it too hot to support life, while its neighbor, Gliese 581 d, may in fact be a more likely candidate for habitability. In September 2010, the discovery was announced of another planet in an orbit between these two planets.

A stable habitable zone

The habitable zone (HZ) is a theoretical shell surrounding a star in which any planet present would have liquid water on its surface. After an energy source, liquid water is considered the most important ingredient for life, considering how integral it is to all life-systems on Earth. This may reflect the bias of humanity's water-dependent biology, however, and if life is discovered in the absence of water (for example, in a liquid-ammonia solution), the notion of an HZ may have to be greatly expanded or else discarded altogether as too restricting.^c

A "stable" HZ denotes two factors. First, the range of an HZ should not vary greatly over time. All stars increase in luminosity as they age and a given HZ naturally migrates outwards, but if this happens too quickly (for example, with a super-massive star), planets may only have a brief window inside the HZ and a correspondingly weaker chance to develop life. Calculating an HZ range and its long-term movement is never straightforward, given that negative feedback loops such as the carbon cycle will tend to offset the increases in luminosity. Assumptions made about atmospheric conditions and geology thus have as great an impact on a putative HZ range as does Solar evolution; the proposed parameters of the Sun's HZ, for example, have fluctuated greatly.

Secondly, no large-mass body such as a gas giant should be present in or relatively close to the HZ, thus disrupting the formation of Earth-like bodies. The mass of the asteroid

belt, for example, appears to have been unable to accrete into a planet due to orbital resonances with Jupiter; if the giant had appeared in the region that is now between the orbits of Venus and Mars, Earth would almost certainly not have developed its present form. This is somewhat ameliorated by suggestions that a gas giant inside the HZ might have habitable moons under the right conditions.

In the Solar System, the inner planets are terrestrial, the outer ones gas giants, but discoveries of extrasolar planets suggest this arrangement may not be at all common: numerous Jupiter-sized bodies have been found in close orbit about their primary, disrupting potential HZs. However, present data for extrasolar planets is likely to be skewed towards these types (large planets in close orbits) because they are far easier to identify; thus, it remains to be seen which type of planetary system is the norm, or indeed if there is one.

Low stellar variation

Changes in luminosity are common to all stars, but the severity of such fluctuations covers a broad range. Most stars are relatively stable, but a significant minority of variable stars often experience sudden and intense increases in luminosity and consequently the amount of energy radiated toward bodies in orbit. These are considered poor candidates for hosting life-bearing planets as their unpredictability and energy output changes would negatively impact organisms. Particularly, living things adapted to a specific temperature range would probably be unable to survive too great a temperature deviation. Further, upswings in luminosity are generally accompanied by massive doses of gamma ray and X-ray radiation which might prove lethal. Atmospheres do mitigate such effects, but atmosphere retention might not occur on planets orbiting variables, because the high-frequency energy buffeting these bodies would continually strip them of their protective covering.

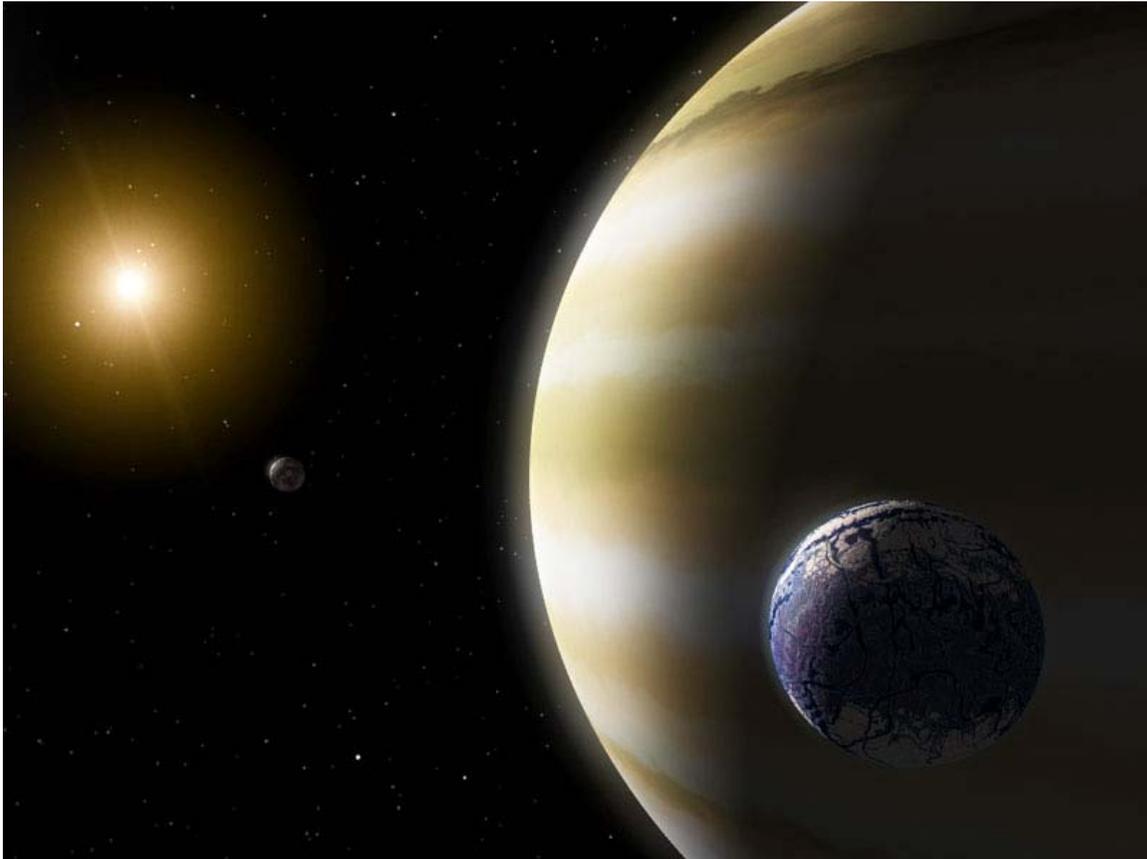
The Sun, as in much else, is benign in terms of this danger: the variation between solar max and minimum is roughly 0.1% over its 11-year solar cycle. There is strong (though not undisputed) evidence that even minor changes in the Sun's luminosity have had significant effects on the Earth's climate well within the historical era; the Little Ice Age of the mid-second millennium, for instance, may have been caused by a relatively long-term decline in the Sun's luminosity. Thus, a star does not have to be a true variable for differences in luminosity to affect habitability. Of known "solar analogs," the one that most closely resembles the Sun is considered to be 18 Scorpii; unfortunately for the prospects of life existing in its proximity, the only significant difference between the two bodies is the amplitude of the solar cycle, which appears to be much greater for 18 Scorpii.

High metallicity

While the bulk of material in any star is hydrogen and helium, there is a great variation in the amount of heavier elements (metals) stars contain. A high proportion of metals in a star correlates to the amount of heavy material initially available in protoplanetary disks.

A low amount of metal significantly decreases the probability that planets will have formed around that star, under the solar nebula theory of planetary systems formation. Any planets that did form around a metal-poor star would probably be low in mass, and thus unfavorable for life. Spectroscopic studies of systems where exoplanets have been found to date confirm the relationship between high metal content and planet formation: "stars with planets, or at least with planets similar to the ones we are finding today, are clearly more metal rich than stars without planetary companions." High metallicity also places a requirement for youth on hab-stars: stars formed early in the universe's history have low metal content and a correspondingly lesser likelihood of having planetary companions.

Planetary characteristics



The moons of some gas giants could potentially be habitable.

The chief assumption about habitable planets is that they are terrestrial. Such planets, roughly within one order of magnitude of Earth mass, are primarily composed of silicate rocks and have not accreted the gaseous outer layers of hydrogen and helium found on gas giants. That life could evolve in the cloud tops of giant planets has not been decisively ruled out,^d though it is considered unlikely given that they have no surface and their gravity is enormous. The natural satellites of giant planets, meanwhile, remain perfectly valid candidates for hosting life.

In February 2011 the Kepler Space Observatory Mission team released a list of 1235 extrasolar planet candidates, including 54 that may be in the habitable zone. Six of the candidates in this zone are smaller than twice the size of Earth. A more recent study found that one of these candidates (KOI 326.01) is in fact much larger and hotter than first reported. Based on the findings, the Kepler Team has estimated "at least 50 billion planets in the Milky Way" of which "at least 500 million" are in the habitable zone.

In analyzing which environments are likely to support life, a distinction is usually made between simple, unicellular organisms such as bacteria and archaea and complex metazoans (animals). Unicellularity necessarily precedes multicellularity in any hypothetical tree of life and where single-celled organisms do emerge there is no assurance that this will lead to greater complexity.^e The planetary characteristics listed below are considered crucial for life generally, but in every case habitability impediments should be considered greater for multicellular organisms such as plants and animals versus unicellular life.

Mass



Mars, with its rarefied atmosphere, is colder than the Earth would be, if it were at a similar distance from the Sun

Low-mass planets are poor candidates for life for two reasons. First, their lesser gravity makes atmosphere retention difficult. Constituent molecules are more likely to reach escape velocity and be lost to space when buffeted by solar wind or stirred by collision. Planets without a thick atmosphere lack the matter necessary for primal biochemistry, have little insulation and poor heat transfer across their surfaces (for example, Mars, with its thin atmosphere, is colder than the Earth would be if it were at a similar distance from the sun), and provide less protection against meteoroids and high-frequency radiation. Further, where an atmosphere is less than 0.006 Earth atmospheres, water cannot exist in liquid form as the required atmospheric pressure, 4.56 mm Hg (608 Pa) (0.18 inch Hg), does not occur. The temperature range at which water is liquid is smaller at low pressures generally.

Secondly, smaller planets have smaller diameters and thus higher surface-to-volume ratios than their larger cousins. Such bodies tend to lose the energy left over from their formation quickly and end up geologically dead, lacking the volcanoes, earthquakes and tectonic activity which supply the surface with life-sustaining material and the atmosphere with temperature moderators like carbon dioxide. Plate tectonics appear particularly crucial, at least on Earth: not only does the process recycle important chemicals and minerals, it also fosters bio-diversity through continent creation and increased environmental complexity and helps create the convective cells necessary to generate Earth's magnetic field.

"Low mass" is partly a relative label; the Earth is considered low mass when compared to the Solar System's gas giants, but it is the largest, by diameter and mass, and densest of all terrestrial bodies.^f It is large enough to retain an atmosphere through gravity alone and large enough that its molten core remains a heat engine, driving the diverse geology of the surface (the decay of radioactive elements within a planet's core is the other significant component of planetary heating). Mars, by contrast, is nearly (or perhaps totally) geologically dead and has lost much of its atmosphere. Thus, it would be fair to infer that the lower mass limit for habitability lies somewhere between that of Mars and Earth or Venus; 0.3 Earth masses has been offered as a rough dividing line for habitable planets. However, a 2008 study by the Harvard-Smithsonian Center for Astrophysics suggests that the dividing line may be higher. Earth may in fact lie on the lower boundary of habitability, since if it were any smaller, plate tectonics would be impossible. Venus, which has 85 percent Earth's mass, shows no signs of tectonic activity. Conversely, "super-Earths", terrestrial planets with higher masses than Earth, would have higher levels of plate tectonics and thus be firmly placed in the habitable range. Exceptional circumstances do offer exceptional cases: Jupiter's moon Io (which is smaller than any of the terrestrial planets) is volcanically dynamic because of the gravitational stresses induced by its orbit, and its neighbor Europa may have a liquid ocean underneath a frozen shell also due to power generated from orbiting a gas giant. Saturn's Titan, meanwhile, has an outside chance of harbouring life, as it has retained a thick atmosphere and biochemical reactions are possible in the liquid methane on its surface. These satellites are exceptions, but they prove that mass as a habitability criterion cannot be considered definitive.

Finally, a larger planet is likely to have a large iron core. This allows for a magnetic field to protect the planet from stellar wind and cosmic radiation, which otherwise would tend to strip away planetary atmosphere and to bombard living things with ionized particles. Mass is not the only criterion for producing a magnetic field—as the planet must also rotate fast enough to produce a dynamo effect within its core—but it is a significant component of the process.

Orbit and rotation

As with other criteria, stability is the critical consideration in determining the effect of orbital and rotational characteristics on planetary habitability. Orbital eccentricity is the difference between a planet's farthest and closest approach to its parent star divided by

the sum of said distances. It is a ratio describing the shape of the elliptical orbit. The greater the eccentricity the greater the temperature fluctuation on a planet's surface. Although they are adaptive, living organisms can only stand so much variation, particularly if the fluctuations overlap both the freezing point and boiling point of the planet's main biotic solvent (e.g., water on Earth). If, for example, Earth's oceans were alternately boiling and freezing solid, it is difficult to imagine life as we know it having evolved. The more complex the organism, the greater the temperature sensitivity. The Earth's orbit is almost wholly circular, with an eccentricity of less than 0.02; other planets in our solar system (with the exception of Mercury) have eccentricities that are similarly benign.

Data collected on the orbital eccentricities of extrasolar planets has surprised most researchers: 90% have an orbital eccentricity greater than that found within the solar system, and the average is fully 0.25.

A planet's movement around its rotational axis must also meet certain criteria if life is to have the opportunity to evolve. A first assumption is that the planet should have moderate seasons. If there is little or no axial tilt (or obliquity) relative to the perpendicular of the ecliptic, seasons will not occur and a main stimulant to biospheric dynamism will disappear. The planet would also be colder than it would be with a significant tilt: when the greatest intensity of radiation is always within a few degrees of the equator, warm weather cannot move poleward and a planet's climate becomes dominated by colder polar weather systems.

If a planet is radically tilted, meanwhile, seasons will be extreme and make it more difficult for a biosphere to achieve homeostasis. Although during the Quaternary higher axial tilt of the Earth coincides with reduced polar ice, warmer temperatures and *less* seasonal variation, scientists do not know whether this trend would continue indefinitely with further increases in axial tilt.

The exact effects of these changes can only be computer modelled at present, and studies have shown that even extreme tilts of up to 85 degrees do not absolutely preclude life "provided it does not occupy continental surfaces plagued seasonally by the highest temperature." Not only the mean axial tilt, but also its variation over time must be considered. The Earth's tilt varies between 21.5 and 24.5 degrees over 41,000 years. A more drastic variation, or a much shorter periodicity, would induce climatic effects such as variations in seasonal severity.

Other orbital considerations include:

- The planet should rotate relatively quickly so that the day-night cycle is not overlong. If a day takes years, the temperature differential between the day and night side will be pronounced, and problems similar to those noted with extreme orbital eccentricity will come to the fore.
- The planet should also rotate quickly enough so that a magnetic dynamo may be started in its iron core to produce a magnetic field.

- Change in the direction of the axis rotation (precession) should not be pronounced. In itself, precession need not affect habitability as it changes the direction of the tilt, not its degree. However, precession tends to accentuate variations caused by other orbital deviations. Precession on Earth occurs over a 26,000 year cycle.

The Earth's Moon appears to play a crucial role in moderating the Earth's climate by stabilising the axial tilt. It has been suggested that a chaotic tilt may be a "deal-breaker" in terms of habitability— i.e. a satellite the size of the moon is not only helpful but required to produce stability. This position remains controversial.^g

Geochemistry

It is generally assumed that any extraterrestrial life that might exist will be based on the same fundamental biochemistry as found on Earth, as the four elements most vital for life, carbon, hydrogen, oxygen, and nitrogen, are also the most common chemically reactive elements in the universe. Indeed, simple biogenic compounds, such as amino acids, have been found in meteorites and in the interstellar medium. These four elements together comprise over 96% of Earth's collective biomass. Carbon has an unparalleled ability to bond with itself and to form a massive array of intricate and varied structures, making it an ideal material for the complex mechanisms that form living cells. Hydrogen and oxygen, in the form of water, compose the solvent in which biological processes take place and in which the first reactions occurred that led to life's emergence. The energy released in the formation of powerful covalent bonds between carbon and oxygen, available by oxidizing organic compounds, is the fuel of all complex life-forms. These four elements together make up amino acids, which in turn are the building blocks of proteins, the substance of living tissue. In addition, neither sulfur, required for the building of proteins, nor phosphorus, needed for the formation of DNA, RNA, and the adenosine phosphates essential to metabolism, are rare.

Relative abundance in space does not always mirror differentiated abundance within planets; of the four life elements, for instance, only oxygen is present in any abundance in the Earth's crust. This can be partly explained by the fact that many of these elements, such as hydrogen and nitrogen, along with their simplest and most common compounds, such as carbon dioxide, carbon monoxide, methane, ammonia, and water, are gaseous at warm temperatures. In the hot region close to the Sun, these volatile compounds could not have played a significant role in the planets' geological formation. Instead, they were trapped as gases underneath the newly formed crusts, which were largely made of rocky, involatile compounds such as silica (a compound of silicon and oxygen, accounting for oxygen's relative abundance). Outgassing of volatile compounds through the first volcanoes would have contributed to the formation of the planets' atmospheres. The Miller-Urey experiment showed that, with the application of energy, amino acids can form from the synthesis of the simple compounds within a primordial atmosphere.

Even so, volcanic outgassing could not have accounted for the amount of water in Earth's oceans. The vast majority of the water—and arguably carbon— necessary for life must

have come from the outer solar system, away from the Sun's heat, where it could remain solid. Comets impacting with the Earth in the Solar system's early years would have deposited vast amounts of water, along with the other volatile compounds life requires (including amino acids) onto the early Earth, providing a kick-start to the origin of life.

Thus, while there is reason to suspect that the four "life elements" ought to be readily available elsewhere, a habitable system probably also requires a supply of long-term orbiting bodies to seed inner planets. Without comets there is a possibility that life as we know it would not exist on Earth.

Microenvironments and extremophiles



The Atacama Desert provides an analog to Mars and an ideal environment to study the boundary between sterility and habitability.

One important qualification to habitability criteria is that only a tiny portion of a planet is required to support life. Astrobiologists often concern themselves with "micro-environments," noting that "we lack a fundamental understanding of how evolutionary forces, such as mutation, selection, and genetic drift, operate in micro-organisms that act on and respond to changing micro-environments." Extremophiles are Earth organisms that live in niche environments under severe conditions generally considered inimical to life. Usually (although not always) unicellular, extremophiles include acutely alkaliphilic and acidophilic organisms and others that can survive water temperatures above 100 °C in hydrothermal vents.

The discovery of life in extreme conditions has complicated definitions of habitability, but also generated much excitement amongst researchers in greatly broadening the known range of conditions under which life can persist. For example, a planet that might otherwise be unable to support an atmosphere given the solar conditions in its vicinity, might be able to do so within a deep shadowed rift or volcanic cave. Similarly, craterous terrain might offer a refuge for primitive life. The Lawn Hill crater has been studied as an astrobiological analog, with researchers suggesting rapid sediment infill created a protected microenvironment for microbial organisms; similar conditions may have occurred over the geological history of Mars.

Earth environments that *cannot* support life are still instructive to astrobiologists in defining the limits of what organisms can endure. The heart of the Atacama desert, generally considered the driest place on Earth, appears unable to support life, but it has been subject to study by NASA for that reason: it provides a Mars analog and the moisture gradients along its edges are ideal for studying the boundary between sterility and habitability. The Atacama was the subject of study in 2003 that partly replicated experiments from the Viking landings on Mars in the 1970s; no DNA could be recovered from two soil samples, and incubation experiments were also negative for biosignatures.

Alternative star systems

In determining the feasibility of extraterrestrial life, astronomers had long focused their attention on stars like our own Sun. However, they have begun to explore the possibility that life might form in systems very unlike our own.

Binary systems

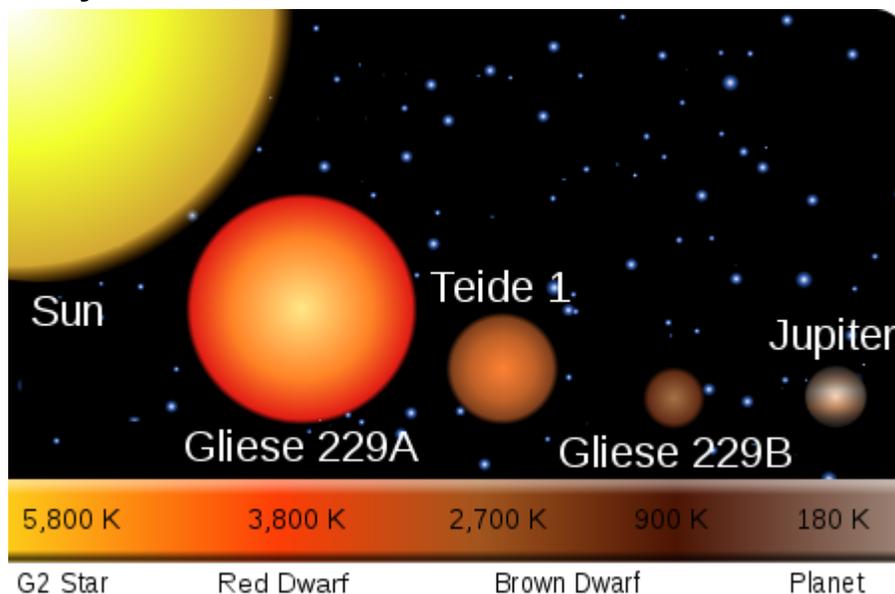
Typical estimates often suggest that 50% or more of all stellar systems are binary systems. This may be partly sample bias, as massive and bright stars tend to be in binaries and these are most easily observed and catalogued; a more precise analysis has suggested that the more common fainter stars are usually singular, and that up to two thirds of all stellar systems are therefore solitary.

The separation between stars in a binary may range from less than one astronomical unit (AU, the Earth-Sun distance) to several hundred. In latter instances, the gravitational effects will be negligible on a planet orbiting an otherwise suitable star and habitability

potential will not be disrupted unless the orbit is highly eccentric. However, where the separation is significantly less, a stable orbit may be impossible. If a planet's distance to its primary exceeds about one fifth of the closest approach of the other star, orbital stability is not guaranteed. Whether planets might form in binaries at all had long been unclear, given that gravitational forces might interfere with planet formation. Theoretical work by Alan Boss at the Carnegie Institution has shown that gas giants can form around stars in binary systems much as they do around solitary stars.

One study of Alpha Centauri, the nearest star system to the Sun, suggested that binaries need not be discounted in the search for habitable planets. Centauri A and B have an 11 AU distance at closest approach (23 AU mean), and both should have stable habitable zones. A study of long-term orbital stability for simulated planets within the system shows that planets within approximately three AU of either star may remain stable (i.e. the semi-major axis deviating by less than 5%). The HZ for Centauri A is conservatively estimated at 1.2 to 1.3 AU and Centauri B at 0.73 to 0.74—well within the stable region in both cases.

Red dwarf systems



Relative star sizes and photospheric temperatures. Any planet around a red dwarf such as the one shown here would have to huddle close to achieve Earth-like temperatures, probably inducing tidal lock.

Determining the habitability of red dwarf stars could help determine how common life in the universe might be, as red dwarfs make up between 70 to 90% of all the stars in the galaxy. Brown dwarfs are probably more numerous than red dwarfs. However, they are not generally classified as stars, and could never support life as we understand it, since what little heat they emit quickly disappears.

Astronomers for many years ruled out red dwarfs as potential abodes for life. Their small size (from 0.1 to 0.6 solar masses) means that their nuclear reactions proceed exceptionally slowly, and they emit very little light (from 3% of that produced by the Sun to as little as 0.01%). Any planet in orbit around a red dwarf would have to huddle very close to its parent star to attain Earth-like surface temperatures; from 0.3 AU (just inside the orbit of Mercury) for a star like Lacaille 8760, to as little as 0.032 AU for a star like Proxima Centauri (such a world would have a year lasting just 6.3 days). At those distances, the star's gravity would cause tidal lock. One side of the planet would eternally face the star, while the other would always face away from it. The only way potential life could avoid either an inferno or a deep freeze would be if the planet had an atmosphere thick enough to transfer the star's heat from the day side to the night side. It was long assumed that such a thick atmosphere would prevent sunlight from reaching the surface in the first place, preventing photosynthesis.

This pessimism has been tempered by research. Studies by Robert Haberle and Manoj Joshi of NASA's Ames Research Center in California have shown that a planet's atmosphere (assuming it included greenhouse gases CO_2 and H_2O) need only be 100 mbs, or 10% of Earth's atmosphere, for the star's heat to be effectively carried to the night side. This is well within the levels required for photosynthesis, though water would still remain frozen on the dark side in some of their models. Martin Heath of Greenwich Community College, has shown that seawater, too, could be effectively circulated without freezing solid if the ocean basins were deep enough to allow free flow beneath the night side's ice cap. Further research—including a consideration of the amount of photosynthetically active radiation—suggested that tidally locked planets in red dwarf systems might at least be habitable for higher plants.

Size is not the only factor in making red dwarfs potentially unsuitable for life, however. On a red dwarf planet, photosynthesis on the night side would be impossible, since it would never see the sun. On the day side, because the sun does not rise or set, areas in the shadows of mountains would remain so forever. Photosynthesis as we understand it would be complicated by the fact that a red dwarf produces most of its radiation in the infrared, and on the Earth the process depends on visible light. There are potential positives to this scenario. Numerous terrestrial ecosystems rely on chemosynthesis rather than photosynthesis, for instance, which would be possible in a red dwarf system. A static primary star position removes the need for plants to steer leaves toward the sun, deal with changing shade/sun patterns, or change from photosynthesis to stored energy during night. Because of the lack of a day-night cycle, including the weak light of morning and evening, far more energy would be available at a given radiation level.

Red dwarfs are far more variable and violent than their more stable, larger cousins. Often they are covered in starspots that can dim their emitted light by up to 40% for months at a time, while at other times they emit gigantic flares that can double their brightness in a matter of minutes. Such variation would be very damaging for life, as it would not only destroy any complex organic molecules that could possibly form biological precursors, but also because it would blow off sizeable portions of the planet's atmosphere. For a planet around a red dwarf star to support life, it would require a rapidly rotating magnetic

field to protect it from the flares. However, a tidally locked planet rotates only very slowly, and so cannot produce a geodynamo at its core. However, the violent flaring period of a red dwarf's life cycle is estimated to only last roughly the first 1.2 billion years of its existence. If a planet forms far away from a red dwarf so as to avoid tidal locking, and then migrates into the star's habitable zone after this turbulent initial period, it is possible that life may have a chance to develop.

There is, however, one major advantage that red dwarfs have over other stars as abodes for life: they live a long time. It took 4.5 billion years before humanity appeared on Earth, and life as we know it will see suitable conditions for at most 1 billion years more. Red dwarfs, by contrast, could live for trillions of years because their nuclear reactions are far slower than those of larger stars, meaning that life would have longer to evolve and survive. Further, while the odds of finding a planet in the habitable zone around any specific red dwarf are slim, the total amount of habitable zone around all red dwarfs combined is equal to the total amount around Sun-like stars given their ubiquity.

Massive stars

Recent research suggests that very large stars, greater than ~100 solar masses, could have planetary systems consisting of hundreds of Mercury-sized planets within the habitable zone. Such systems could also contain brown dwarfs and low-mass stars (~0.1-0.3 solar masses).

The galactic neighborhood

Along with the characteristics of planets and their star systems, the wider galactic environment may also impact habitability. Scientists considered the possibility that particular areas of galaxies (galactic habitable zones) are better suited to life than others; the solar system in which we live, in the Orion Spur, on the Milky Way galaxy's edge is considered to be in a life-favorable spot:

- It is not in a globular cluster where immense star densities are inimical to life, given excessive radiation and gravitational disturbance. Globular clusters are also primarily composed of older, probably metal-poor, stars.
- It is not near an active gamma ray source.
- It is not near the galactic center where once again star densities increase the likelihood of ionizing radiation (e.g., from magnetars and supernovae). A supermassive black hole is also believed to lie at the middle of the galaxy which might prove a danger to any nearby bodies.
- The circular orbit of the Sun around the galactic center keeps it out of the way of the galaxy's spiral arms where once more intense radiation and gravitation may lead to disruption.

Thus, relative loneliness is ultimately what a life-bearing system needs. If the Sun were crowded amongst other systems, the chance of being fatally close to dangerous radiation sources would increase significantly. Further, close neighbours might disrupt the stability

of various orbiting bodies such as Oort cloud and Kuiper Belt objects, which can bring catastrophe if knocked into the inner solar system.

While stellar crowding proves disadvantageous to habitability, so too does extreme isolation. A star as metal-rich as the Sun would probably not have formed in the very outermost regions of the Milky Way given a decline in the relative abundance of metals and a general lack of star formation. Thus, a "suburban" location, such as our Solar System enjoys, is preferable to a Galaxy's center or farthest reaches.

Other considerations

Alternative biochemistries

While most investigations of extraterrestrial life start with the assumption that advanced life-forms must have similar requirements for life as on Earth, the hypothesis of other types of biochemistry suggests the possibility of lifeforms evolving around a different metabolic mechanism. In *Evolving the Alien*, biologist Jack Cohen and mathematician Ian Stewart argue astrobiology, based on the Rare Earth hypothesis, is restrictive and unimaginative. They suggest that Earth-like planets may be very rare, but non-carbon-based complex life could possibly emerge in other environments. The most frequently mentioned alternative to carbon is silicon-based life, while ammonia is sometimes suggested as an alternative solvent to water.

More speculative ideas have focused on bodies altogether different than Earth-like planets. Astronomer Frank Drake, a well-known proponent of the search for extraterrestrial life, imagined life on a neutron star: submicroscopic "nuclear molecules" combining to form creatures with a life cycle millions of times quicker than Earth life. Called "imaginative and tongue-in-cheek," the idea gave rise to science fiction depictions. Carl Sagan, another optimist with regards to extraterrestrial life, considered the possibility of organisms that are always airborne within the high atmosphere of Jupiter in a 1976 paper. Cohen and Stewart also envisioned life in both a solar environment and in the atmosphere of a gas giant.

"Good Jupiters"

"Good Jupiters" are gas giant planets, like the solar system's Jupiter, that orbit their stars in circular orbits far enough away from the habitable zone to not disturb it but close enough to "protect" terrestrial planets in closer orbit in two critical ways. First, they help to stabilize the orbits, and thereby the climates, of the inner planets. Second, they keep the inner solar system relatively free of comets and asteroids that could cause devastating impacts. Jupiter orbits the Sun at about five times the distance between the Earth and the Sun. This is the rough distance we should expect to find good Jupiters elsewhere. Jupiter's "caretaker" role was dramatically illustrated in 1994 when Comet Shoemaker-Levy 9 impacted the giant; had Jovian gravity not captured the comet, it may well have entered the inner solar system.

Early in the Solar System's history, Jupiter played a somewhat contrary role: it increased the eccentricity of asteroid belt orbits and enabled many to cross Earth's orbit and supply the planet with important volatiles. Before Earth reached half its present mass, icy bodies from the Jupiter–Saturn region and small bodies from the primordial asteroid belt supplied water to the Earth due to the gravitational scattering of Jupiter and, to a lesser extent, Saturn. Thus, while the gas giants are now helpful protectors, they were once suppliers of critical habitability material.

In contrast, Jupiter-sized bodies that orbit too close to the habitable zone but not in it (as in 47 Ursae Majoris), or have a highly elliptical orbit that crosses the habitable zone (like 16 Cygni B) make it very difficult for an Earthlike planet to exist in the system.

Life's impact on habitability

A supplement to the factors that support life's emergence is the notion that life itself, once formed, becomes a habitability factor in its own right. An important Earth example was the production of oxygen by ancient cyanobacteria, and eventually photosynthesizing plants, leading to a radical change in the composition of Earth's atmosphere. This oxygen would prove fundamental to the respiration of later animal species.

This interaction between life and subsequent habitability has been explored in various ways. The Gaia hypothesis, a class of scientific models of the geo-biosphere pioneered by Sir James Lovelock in 1975, argues that life as a whole fosters and maintains suitable conditions for itself by helping to create a planetary environment suitable for its continuity; at its most dramatic, Gaia suggests that planetary systems behave similarly to a kind of organism. The most successful life forms change the composition of the air, water, and soil in ways that make their continued existence more certain—a controversial extension of the accepted laws of ecology.

Similarly, David Grinspoon has suggested a "Living Worlds hypothesis" in which our understanding of what constitutes habitability cannot be separated from life already extant on a planet. Planets that are geologically and meteorologically alive are much more likely to be biologically alive as well and "a planet and its life will co-evolve."

In their 2004 book *The Privileged Planet*, astronomer Guillermo Gonzalez and philosopher Jay Richards explore the possible link between the habitability of a planet and its suitability for observing the rest of the universe. The book was criticized as an example of intelligent design and for its lack of scientific credibility.

Chapter-6

Cloud Reflectivity Modification

Cloud reflectivity enhancement is also known as 'marine cloud brightening' or 'cloud whitening' on low cloud. An opposite scheme exists to reduce the reflectivity of higher, colder cirrus clouds. It is a geoengineering technique that works by solar radiation management. By modifying the reflectivity of clouds, the albedo of the Earth is altered. The intention is that this technique, in combination with greenhouse gas emissions reduction (and possibly other geoengineering techniques) will be sufficient to control global warming. Compared to other climate modification strategies, this technique is relatively simple and benign, being based as it is on natural processes of 'ocean spray'. It can therefore be deployed quickly for further research, and can then be rolled out on an effective scale relatively cheaply after that. The effect is expected to be fully reversible, as the cloud condensation nuclei particles precipitate naturally. However, like any planetary-scale project dealing with the complex climate system, there is a non-trivial risk of unintended consequences.

Basic principles

Low level stratocumulus clouds cover approximately one-third of the oceans surface. These clouds possess Albedo levels of 0.3-0.7. The levels of albedo present in the low-level marine stratocumulus clouds create a significant global cooling effect. Theoretically, by increasing the albedo of the clouds, via spraying sea water (NaCl) droplets approximately 1 μm in size, the cooling effects of the clouds are increased and potentially their longevity is enhanced. By creating cloud condensation nuclei, geoengineers can change the albedo of clouds to make them appear whiter. This can be done using a variety of chemicals and techniques, with seawater sprays from ships being a simple example. Broadly speaking, the marine environment has a deficit of cloud condensation nuclei due to lower levels of dust and pollution at sea, so this technique is more effective over the ocean than over land.

Models

HadGAM1 general circulation model

A study by Jones, Latham, and Smith using the Hadley Center's General Circulation Model, suggests that warming due to a x2 increase in CO₂ could potentially be compensated for by a doubling of the droplet concentration number in low-level marine stratocumulus clouds, accounting for anthropogenic aerosol production, in three regions—off the coasts of the Americas and West Africa. The three regions combined cover approximately 3% of the Earth's surface.

Model of marine stratocumulus clouds developed by Bower, Jones and Choulaton

Bower, Jones and Choulaton created a model to analyze the effectiveness of albedo modification on clouds. A 2006 study simplified the model. Their model illustrates the practicality of the technique. It demonstrates droplet size is not of that much importance, that location of clouds is of limited importance, and that significant cooling can be achieved with a level of .03.

Proposed schemes

Seawater spray

Various schemes have been suggested, such as that proposed by John Latham and Stephen Salter, which works by spraying seawater in the atmosphere to increase the reflectiveness of clouds. The extra condensation nuclei created by the spray will change the size distribution of the drops in existing clouds to make them whiter. The sprayers would use a fleet of around 1500 unmanned Rotor ships known as Flettner vessels to spray mist created from seawater into the air to thicken clouds and thus reflect more radiation from the Earth. The whitening is achieved as a result of the Twomey effect. In order to significantly cool the earth, the vessels have to spray sea water droplets at a rate of 50 cubic meter per second over a large portion of the Earth's ocean surface.

This technique can give $>3.7 \text{ W/m}^2$ of globally-averaged negative forcing, which is sufficient to reverse the warming effect of a doubling of CO₂.

Ultrasonic Excitation of a Liquid Using a Piezo-Electric Transducer

This technique works by creating faraday waves at a free surface. If the waves are steep enough the droplets of sea water will be thrown from the crests and particles can enter into the clouds within a predictable area. However, a significant amount of energy is required.

Electrostatic Atomisation of Seawater Drops

This technique utilizes mobile spray platforms which move to adjust to changing weather conditions. A proposed idea is to use unmanned ships that shoot sea spray into the air.

Cloud Seeding Yachts

Stephen Salter developed an unmanned yacht that uses Flettner rotors for propulsion. The rotors are vertical cylinders located on the deck of the yacht. The spray the tiny water droplets into the low level clouds to enhance their reflectivity. The power for the rotors and the ship is generated from underwater turbines. Approximately 1,500 of these ships would be required for the scheme to effectively cool the planet. The Royal Society states that "approximately 1500 spray vessels would be required to produce a negative forcing of -3.7 W m^{-2} . Each vessel would require approximately 150 kW of electrical energy to atomize and disseminate seawater at the necessary continuous rate (as well as to support navigation, controls, communications, etc.), so that the global power requirement is approximately 2.3×10^8 Watts." This technique requires far less energy compared to many other geoengineering techniques.

Ocean Sulfur Cycle Enhancement

Enhancing the natural sulfur cycle in the Southern Ocean by fertilizing a small portion with iron in order to enhance dimethyl sulfide production and cloud reflectivity. The goal is to slow Antarctic ice from melting and raising sea level. Such techniques also tend to sequester carbon, but in this specific project the enhancement of cloud albedo was both the desired outcome and measured result.

This technique can give only 0.016 W/m^2 of globally-averaged negative forcing, which is practically insignificant as a contribution to reducing global warming. However, as it is a regionally-acting technique its effects are concentrated in an influence on the climate of Antarctica.

Advantages and Disadvantages

Advantages

- The techniques use natural and reusable resources i.e sea water and wind
- You can monitor cloud albedo levels via satellite and adjust the sea spraying mechanisms to fit the data.
- Albedo enhancement is considerably cheaper than many other geoengineering techniques.
- It utilizes already existing technologies to send sea water droplets into low level oceanic clouds.
- The location of the albedo enhancement of clouds can be controlled and localized. This could prevent ecological problems.

- Cooling can happen in only the places in which it is required.

Disadvantages

- Most of the information on albedo enhancement on clouds is from models and computer simulations. The actual results from spraying sea water into low level clouds may differ from the predicted effect.
- Currently the two most commonly proposed plans for sea water dispersal are airplanes and turbine powered ships. The use of airplanes will be time consuming, labor intensive, and result in a large amount of carbon emissions. Turbine powered un-manned ships are the most ecologically friendly, but their capacity to fulfill the role is still not known.
- The technique is strongly dependent on wind patterns.
- The meteorological affects cannot be known until real world testing is conducted.
- If CO₂ increases beyond the predicted rate then albedo enhancement of clouds may not be strong enough to cool the Earth.
- The effect of aerosols and its impact on albedo enhancement of clouds has not been significantly researched.

Further research

- The amount of water droplets that enter clouds and form additional droplets is not currently known and is affected largely by meteorological factors. Research must be done to assess what percentage of particles will be successful and what the effect of the weather is.
- Charging sea water particles to utilize the Earth's electric field may be beneficial.
- Climatological and meteorological ramifications must be studied as the technique will alter rainfall, temperature, static stability, and ocean currents.
- The effect of aerosols on low level clouds must be better understood. The aerosols may negatively impact efforts to enhance the albedo of clouds.

Reducing cirrus reflectivity

Cirrus clouds are capable of modification to reduce their reflectivity (opposite to the low-cloud scheme), using seeding mechanisms distributed by airliners. The climatic effects of this modification operate in the opposite direction to that of the lower, warmer clouds modified in the cloud brightening scheme. This authors calculate that this scheme is sufficient to reverse the warming caused by a doubling of CO₂.

Chapter-7

Iron Fertilization



An oceanic phytoplankton bloom in the South Atlantic Ocean, off the coast of Argentina covering an area about 300 miles by 50 miles

Iron fertilization is the intentional introduction of iron to the upper ocean to stimulate a phytoplankton bloom. This is intended to enhance biological productivity, which can benefit the marine food chain and remove carbon dioxide from the atmosphere. Iron is a trace element necessary for photosynthesis in all plants. It is highly insoluble in sea water and is often the limiting nutrient for phytoplankton growth. Large phytoplankton blooms can be created by supplying iron to iron-deficient ocean waters. A number of ocean labs, scientists and businesses are exploring fertilization as a means to sequester atmospheric carbon dioxide in the deep ocean, and to increase marine biological productivity which is likely in decline as a result of climate change. Since 1993, thirteen international research teams have completed ocean trials demonstrating that phytoplankton blooms can be stimulated by iron addition. However, controversy remains over the effectiveness of atmospheric CO₂ sequestration and ecological effects. The most recent open ocean trial of ocean iron fertilization, dubbed LOHAFEX, was conducted from January to March 2009 in the South Atlantic.

Fertilization also occurs naturally when upwellings bring nutrient-rich water to the surface, as occurs when ocean currents meet an ocean bank or a sea mount. This form of fertilization produces the world's largest marine habitats. Fertilization can also occur when weather carries wind blown dust long distances over the ocean, or iron-rich minerals are carried into the ocean by glaciers, rivers and icebergs.

History

Consideration of iron's importance to phytoplankton growth and photosynthesis dates back to the 1930s when English biologist Joseph Hart speculated that the ocean's great "desolate zones" (areas apparently rich in nutrients, but lacking in plankton activity or other sea life) might simply be iron deficient. Little further scientific discussion of this issue was recorded until the 1980s, when oceanographer John Martin renewed controversy on the topic with his marine water nutrient analyses. His studies indicated it was indeed a scarcity of iron micronutrients that was limiting phytoplankton growth and overall productivity in these "desolate" regions, which came to be called "High Nutrient, Low Chlorophyll" (HNLC) zones.

Martin's famous 1991 quip at Woods Hole Oceanographic Institution, "Give me a half a tanker of iron and I will give you another ice age", drove a decade of research whose findings suggested that iron deficiency was not merely impacting ocean ecosystems, it also offered a key to mitigating climate change as well.

Perhaps the most dramatic support for Martin's hypothesis was seen in the aftermath of the 1991 eruption of Mount Pinatubo in the Philippines. Environmental scientist Andrew Watson analyzed global data from that eruption and calculated that it deposited approximately 40,000 tons of iron dust into the oceans worldwide. This single fertilization event generated an easily observed global decline in atmospheric CO₂ and a parallel pulsed increase in oxygen levels.

Experiments

Martin hypothesized that increasing phytoplankton photosynthesis could slow or even reverse global warming by sequestering enormous volumes of CO₂ in the sea. He died shortly thereafter during preparations for Ironex I, a proof of concept research voyage, which was successfully carried out near the Galapagos Islands in 1993 by his colleagues at Moss Landing Marine Laboratories. Since then 9 international ocean studies have examined the fertilization effects of iron:

- Ironex II, 1995
- SOIREE (Southern Ocean Iron Release Experiment), 1999
- EisenEx (Iron Experiment), 2000
- SEEDS (Subarctic Pacific Iron Experiment for Ecosystem Dynamics Study), 2001
- SOFeX (Southern Ocean Iron Experiments - North & South), 2002
- SERIES (Subarctic Ecosystem Response to Iron Enrichment Study), 2002
- SEEDS-II, 2004
- EIFEX (European Iron Fertilization Experiment), 2004
- CROZEX (CROZet natural iron bloom and Export experiment), 2005
- LOHAFEX (Indian and German Iron Fertilization Experiment), 2009

Despite widespread opposition to LOHAFEX, on 26 January 2009 the German Federal Ministry of Education and Research (BMBF) gave clearance for this fertilization experiment to commence. The experiment was carried out in waters low in silicic acid which is likely to affect the efficacy of carbon sequestration. A 900 square kilometres (350 sq mi) portion of the southwest Atlantic Ocean was fertilized with iron sulfate. A large phytoplankton bloom was triggered, however this bloom did not contain diatoms because the fertilized location was already depleted in silicic acid, an essential nutrient for diatom growth. In the absence of diatoms, a relatively small amount of carbon was sequestered, because other phytoplankton are vulnerable to predation by zooplankton and do not sink rapidly upon death. These poor sequestration results have caused some, including members of the LOHAFEX research team, to suggest that ocean iron fertilization is not an effective carbon mitigation strategy *in general*, however prior ocean fertilization experiments in high silica locations have observed much higher carbon sequestration rates because of diatom growth. LOHAFEX has just confirmed that the carbon sequestration potential depends strongly upon careful choice of location.

The maximum possible result from iron fertilization, assuming the most favourable conditions and disregarding practical considerations, is 0.29W/m² of globally-averaged negative forcing, which is almost sufficient to reverse the warming effect of about 1/6 of current levels of anthropogenic CO₂ emissions. It is notable, however, that CO₂ levels will have risen by the time this could be achieved.

Science

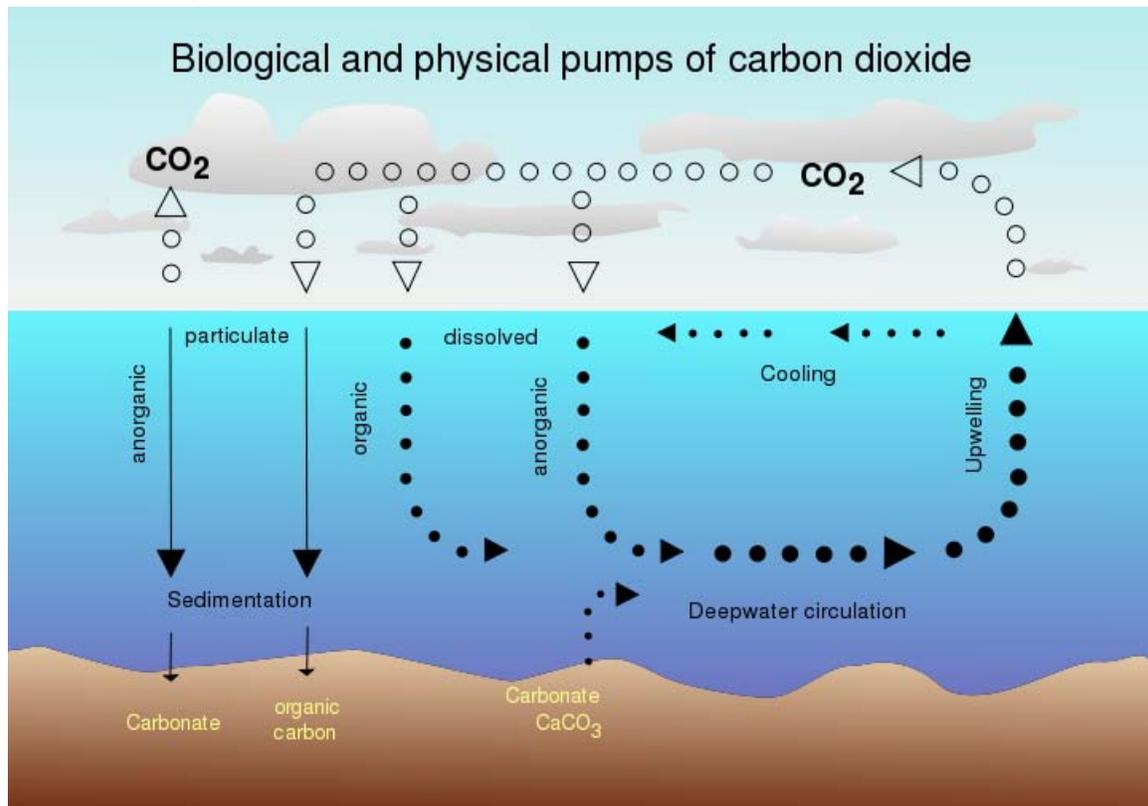
The role of iron

About 70% of the world's surface is covered in oceans, and the upper part of these (where light can penetrate) is inhabited by algae. In some oceans, the growth and reproduction of these algae is limited by the amount of iron in the seawater. Iron is a vital micronutrient for phytoplankton growth and photosynthesis that has historically been delivered to the pelagic sea by dust storms from arid lands. This Aeolian dust contains 3–5% iron and its deposition has fallen nearly 25% in recent decades.

The Redfield ratio describes the relative atomic concentrations of critical nutrients in plankton biomass and is conventionally written "106 C: 16 N: 1 P." This expresses the fact that one atom of phosphorus and 16 of nitrogen are required to "fix" 106 carbon atoms (or 106 molecules of CO₂). Recent research has expanded this constant to "106 C: 16 N: 1 P: .001 Fe" signifying that in iron deficient conditions each atom of iron can fix 106,000 atoms of carbon, or on a mass basis, each kilogram of iron can fix 83,000 kg of carbon dioxide. The 2004 EIFEX experiment reported a carbon dioxide to iron export ratio of nearly 3000 to 1. The atomic ratio would be approximately: "3000 C: 58,000 N: 3,600 P: 1 Fe".

Therefore small amounts of iron (measured by mass parts per trillion) in "desolate" HNLC zones can trigger large phytoplankton blooms. Recent marine trials suggest that one kilogram of fine iron particles may generate well over 100,000 kilograms of plankton biomass. The size of the iron particles is critical, however, and particles of 0.5–1 micrometer or less seem to be ideal both in terms of sink rate and bioavailability. Particles this small are not only easier for cyanobacteria and other phytoplankton to incorporate, the churning of surface waters keeps them in the euphotic or sunlit biologically active depths without sinking for long periods of time.

Carbon sequestration



Air-sea exchange of CO₂

Previous instances of biological carbon sequestration have triggered major climatic changes, such as the Azolla event. Plankton that generate calcium or silicon carbonate skeletons, such as diatoms, coccolithophores and foraminifera, account for most direct carbon sequestration. When these organisms die their carbonate skeletons sink relatively quickly and form a major component of the carbon-rich deep sea precipitation known as marine snow. Marine snow also includes fish fecal pellets and other organic detritus, and can be seen steadily falling thousands of meters below active plankton blooms.

Of the carbon-rich biomass generated by plankton blooms, half (or more) is generally consumed by grazing organisms (zooplankton, krill, small fish, etc.) but 20 to 30% sinks below 200 meters (656 ft) into the colder water strata below the thermocline. Much of this fixed carbon continues falling into the abyss, but a substantial percentage is redissolved and remineralized. At this depth, however, this carbon is now suspended in deep currents and effectively isolated from the atmosphere for centuries. (The surface to benthic cycling time for the ocean is approximately 4,000 years.)

Analysis and quantification

Evaluation of the biological effects and verification of the amount of carbon actually sequestered by any particular bloom requires a variety of measurements, including a

combination of ship-borne and remote sampling, submarine filtration traps, tracking buoy spectroscopy and satellite telemetry. Unpredictable ocean currents have been known to remove experimental iron patches from the pelagic zone, invalidating the experiment.

The potential of iron fertilization as a geoengineering technique to tackle global warming is illustrated by the following figures. If phytoplankton converted all the nitrate and phosphate present in the surface mixed layer across the entire Antarctic circumpolar current into organic carbon, the resulting carbon dioxide deficit could be compensated by uptake from the atmosphere amounting to about 0.8 to 1.4 gigatonnes of carbon per year. This quantity is comparable in magnitude to annual anthropogenic fossil fuels combustion of approximately 6 gigatonnes. It should be noted that the Antarctic circumpolar current region is only one of several in which iron fertilization could be conducted—the Galapagos islands area being another potentially suitable location.

Dimethyl sulfide and clouds

Some species of plankton produce dimethyl sulfide (DMS), a portion of which enters the atmosphere where it is oxidized by hydroxyl radicals (OH), atomic chlorine (Cl) and bromine monoxide (BrO) to form sulfate particles and ultimately clouds. This may increase the albedo of the planet and so cause cooling. This is the basic tenet of the Gaia hypothesis and was presented in James Lovelock's first paper published on this topic.

During the Southern Ocean Iron Enrichment Experiments (SOFeX), DMS concentrations increased by a factor of four inside the fertilized patch. Widescale iron fertilization of the Southern Ocean could lead to significant sulfur-triggered cooling in addition to that due to the increased CO₂ uptake and that due to the ocean's albedo increase, however the amount of cooling by this particular effect is very uncertain.

Financial opportunities

Since the advent of the Kyoto Protocol, several countries and the European Union have established carbon offset markets which trade certified emission reduction credits (CERs) and other types of carbon credit instruments internationally. In 2007 CERs sell for approximately €15–20/ton CO₂e and European analysts project these prices will nearly double by 2012. Iron fertilization is relatively inexpensive compared to scrubbing, direct injection and other industrial approaches, and can theoretically sequester for less than €5/ton CO₂, creating a substantial return. In August, 2010, Russia established a minimum price of €10/ton for offsets to reduce uncertainty for offset providers. Scientists have reported a minimum 6–12% decline in global plankton production since 1980. A full-scale international plankton restoration program could regenerate approximately 3–5 billion tons of sequestration capacity worth €50–100 billion in carbon offset value. Given this potential return on investment, carbon traders and offset customers are watching the progress of this technology with interest.

Multilateral reaction

The parties to the London Dumping Convention (Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972) adopted a non-binding resolution in 2008 on fertilization (labeled LC-LP.1(2008)). The resolution states that ocean fertilization activities, other than legitimate scientific research, "should be considered as contrary to the aims of the Convention and Protocol and do not currently qualify for any exemption from the definition of dumping".

An Assessment Framework for Scientific Research Involving Ocean Fertilization, regulating the dumping of wastes at sea (labeled LC-LP.2(2010)) was adopted by the Contracting Parties to the Convention in October 2010 (LC 32/LP 5).

Sequestration definitions

Carbon is not considered "sequestered" unless it settles to the ocean floor where it remains for eons. Most of the carbon that sinks beneath plankton blooms is dissolved and remineralized well above the seafloor and will eventually (days to centuries) return to the atmosphere, negating the original effect.

Advocates argue that modern climate scientists and Kyoto Protocol policy makers define sequestration in much shorter time frames. For example, they recognize trees and grasslands as important carbon sinks. Forest biomass only sequesters carbon for decades, but carbon that sinks below the marine thermocline (100–200 meters) is effectively removed from the atmosphere for hundreds of years, whether it is remineralized or not. Since deep ocean currents take so long to resurface, their carbon content is effectively sequestered by the criterion in use today.

Debate

While many advocates of ocean iron fertilization see it as modern society's last best hope to slow global warming, some academics, deep greens and proponents of competing technologies cite a variety of concerns.

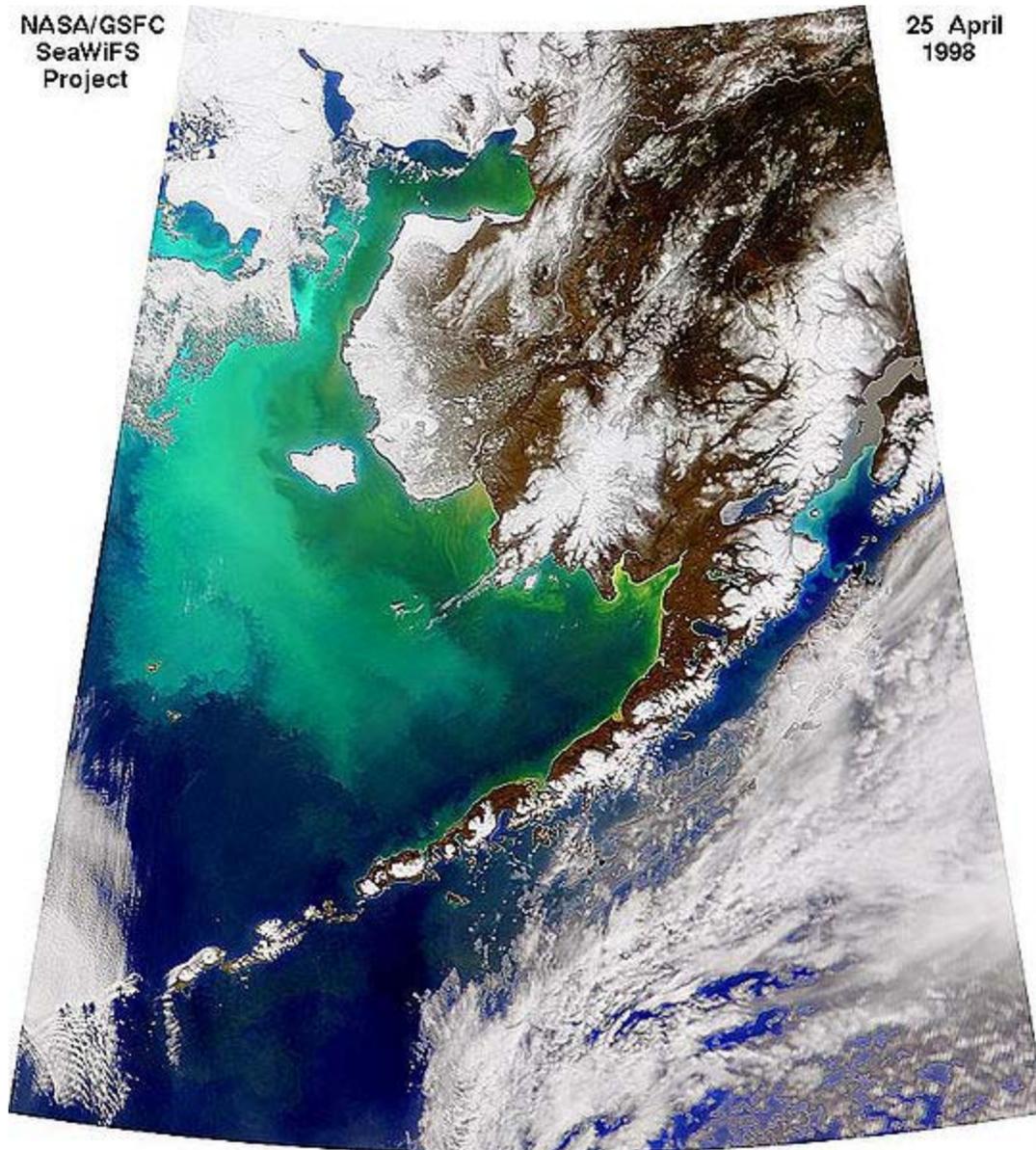
Precautionary principle

The *precautionary principle* (PP) states that if an action or policy has a suspected risk of causing harm, in the absence of scientific consensus, the burden of proof that it is not harmful falls on those who would take the action. The side effects of large-scale iron fertilization are not yet known. Creating phytoplankton blooms in naturally iron-poor areas of the ocean is like watering the desert: in effect it changes one type of ecosystem into another. Such large and rapid conversions have no precedent.

The argument can be applied in reverse, by considering emissions to be the action and remediation an attempt to partially offset the damage.

20th century phytoplankton decline

While advocates argue that iron addition would help to reverse a supposed decline in phytoplankton, this decline may not be real. One study reported a decline in ocean productivity comparing the 1979–1986 and 1997–2000 periods, but two others found *increases* in phytoplankton.



Satellite image of a large, natural, coccolithophore bloom in the Bering Sea in 1998.

Comparison to prior phytoplankton cycles

Fertilization advocates respond that similar algal blooms have occurred naturally for millions of years with no observed ill effects. The Azolla event occurred around 49

million years ago and accomplished what fertilization is intended to achieve (but on a larger scale).

Sequestration efficiency

Fertilization may sequester too little carbon per bloom, supporting the food chain rather than raining on the ocean floor, and thus require too many seeding voyages to be practical. A 2009 Indo-German team of scientists examined the potential of the southwestern Atlantic to sequester significant amounts of carbon dioxide, but found few positive results.

The counter-argument to this is that the low sequestration estimates that emerged from some ocean trials are largely due to these factors:

1. **Data:** none of the ocean trials had enough boat time to monitor their blooms for more than 27 days, confining their measurements to that period. Blooms generally last 60–90 days with the heaviest "precipitation" occurring during the last two months.
2. **Scale:** most trials used less than 1,000 kilograms (2,205 lb) of iron and thus created small blooms that were quickly devoured by opportunistic zooplankton, krill, and fish that swarmed into the seeded region.

Some ocean trials reported positive results. IronEx II reported conversion of 1,000 kilograms (2,205 lb) to carbonaceous biomass equivalent to one hundred full-grown redwoods within two weeks. Eifex recorded fixation ratios of nearly 300,000 to 1.

Current estimates of the amount of iron required to restore all the lost plankton and sequester 3 gigatons/year of CO₂ range widely, from approximately 2 hundred thousand tons/year to over 4 million tons/year. The latter scenario involves 16 supertanker loads of iron and a projected cost of approximately €20 billion (\$27 billion).

Ecological issues

Algal blooms



A "red tide" off the coast of La Jolla, San Diego, California.

Critics are concerned that fertilization will create *harmful algal blooms* (HAB). The species that respond most strongly to fertilization vary by location and other factors and could possibly include species that cause red tides and other toxic phenomena. These factors affect only near-shore waters, although they show that increased phytoplankton populations are not universally benign.

Most species of phytoplankton are harmless or beneficial, given that they constitute the base of the marine food chain. Fertilization increases phytoplankton only in the deep oceans (far from shore) where iron deficiency is the problem. Most coastal waters are replete with iron and adding more has no useful effect.

A 2010 study of iron fertilization in an oceanic high-nitrate, low-chlorophyll environment, however, found that fertilized *Pseudo-nitzschia* diatom spp., which are generally nontoxic in the open ocean, began producing toxic levels of domoic acid. Even short-lived blooms containing such toxins could have detrimental effects on marine food webs.

Deep water oxygen levels

When organic bloom detritus sinks into the abyss, a significant fraction will be devoured by bacteria, other microorganisms and deep sea animals which also consume oxygen. A large enough bloom could render certain regions of the sea deep beneath it anoxic and threaten other benthic species.

The largest plankton replenishment projects under consideration are less than 10% the size of most natural wind-fed blooms. In the wake of major dust storms, natural blooms have been studied since the beginning of the 20th century and no such deep water dieoffs have been reported.

Ecosystem effects

Depending upon the composition and timing of delivery, iron infusions could preferentially favor certain species and alter surface ecosystems to unknown effect. Population explosions of jellyfish, disturbance of the food chain impacting whale populations or fisheries are potential risks.

A 2010 study shows that iron enrichment stimulates toxic diatom production in high-nitrate, low-chlorophyll areas, which, the authors argue, raises "serious concerns over the net benefit and sustainability of large-scale iron fertilizations".

However, CO₂-induced surface water heating and rising carbonic acidity are *already* shifting population distributions for phytoplankton, zooplankton and many other creatures. Optimal fertilization could potentially help restore lost/threatened ecosystem services.

Conclusion and further research

Critics and advocates generally agree that most questions on the impact, safety and efficacy of ocean iron fertilization can only be answered by much larger studies.

A statement published in *Science* in 2008 maintained that it would be

premature to sell carbon offsets from the first generation of commercial-scale OIF experiments unless there is better demonstration that OIF effectively removes CO₂, retains that carbon in the ocean for a quantifiable amount of time, and has acceptable and predictable environmental impacts.

One pilot project planned by Planktos, a U.S. company, was cancelled in 2008 for lack of funding. The company blamed environmental organisations for the failure.

Chapter-8

Terraforming of Mars



Artist's conception of the process of terraforming Mars.

The **terraforming of Mars** is the hypothetical process by which the climate, surface, and known properties of Mars would be deliberately changed with the goal of making it

habitable by humans and other terrestrial life, thus providing the possibility of safe and sustainable colonization of large areas of the planet. The concept is reliant on the assumption that the environment of a planet can be altered through man-made means; the feasibility of creating an unconstrained planetary biosphere is undetermined. There are several proposed methods, some of which present prohibitive economic and natural resource costs, and others which may be currently technologically achievable.

Reasons for terraforming

In the future, population growth and demand for resources may create pressure for humans to colonize new habitats such as Mars, the Moon, and nearby planets, as well as harvest the Solar System's energy and material resources. Terraforming Mars would hypothetically make Mars habitable to humans.

Terraforming Mars may allow for preservation of Earth's species in the event of a catastrophic extinction event, such as the meteor commonly believed to have killed off the dinosaurs 65 million years ago. Additionally, in approximately 7.6 billion years the Sun will enter a red giant phase, as the hydrogen fuel in the core is completely consumed causing the Sun's core to contract and the outer layers to expand. At this point, the Sun's upper atmosphere will extend as far as 1.2 AU, out past the present orbit of the Earth. This expansion will likely destabilize the orbits of the inner planets, causing them to spiral in towards the sun and be destroyed. The Sun will lose a significant fraction of its mass in the process of becoming a red giant, and this may cause a widening of the orbits of the other planets. Earth could technically achieve a widening of its orbit and could potentially maintain a sufficiently high angular velocity to keep it from being engulfed. In order to do so, its orbit would need to increase to between 1.3 AU and 1.7 AU.

It is speculated that Earth will be out of its habitable zone before the Sun enters its Red Giant phase. Astronomers estimate that the Sun will be 33% more luminous in three billion years. The warming Sun and increased solar radiation will cause the Earth's oceans to evaporate, and the Earth to eventually become molten again. The habitable zone would move farther out from the Sun, giving potential Mars colonists some thousands of additional years to develop further space technology to settle elsewhere in the Solar System.

Background

Mars already consists of many soil minerals that could theoretically be used for terraforming. Large amounts of water ice exist below the Martian surface, as well as on the surface at the poles, where it is mixed with dry ice, frozen CO₂. It has been found that significant amounts of water are stored in the south pole of Mars, and if all of this ice suddenly melted, it would form a planetwide ocean 11 meters deep. Frozen carbon dioxide (CO₂) at the poles sublimates into the atmosphere during the Martian summer, and small amounts of water residue are left behind, which fast winds sweep off the poles at speeds approaching 250 mph (400 km/h). This seasonal occurrence transports large

amounts of dust and water vapor into the atmosphere, giving potential for Earth-like cirrus clouds.

Most of the elemental oxygen in the Martian atmosphere is present as carbon dioxide (CO₂), the main atmospheric component; molecular oxygen (O₂) only exists in trace amounts. Large amounts of elemental oxygen can be also found in metal-oxides on the Martian surface, and in the soil, in the form of per-nitrates. An analysis of soil samples taken by the Phoenix lander indicated the presence of perchlorate, which has been used to liberate oxygen in chemical oxygen generators. Electrolysis could be employed to separate water on the planet into oxygen and hydrogen if sufficient liquid water and electricity were available.

It has been suggested that Mars once had an environment relatively similar to that of Earth during an earlier stage in its development. While water once appears to have existed on the Martian surface, it now only appears to exist at the poles and just below the planetary surface as permafrost. Gravity of Mars today indicates that lighter gases in the upper atmosphere could have contributed to the thinning of the atmosphere, with the excess atoms escaping into space; also the evident lack of plate tectonics on Mars would in theory slow the recycling of gases from being locked in sediments back into the atmosphere, and the high amounts of Solar Wind on Mars are other plausible contributing factors. The lack of a magnetic field and geologic activity may both be a result of Mars' smaller size, which allows its interior to cool more quickly than Earth's, though the details of such a process are still not well understood.

Changes required

Comparison of dry atmosphere

	Mars	Earth
Pressure	0.6 kPa (0.087 psi)	101.3 kPa (14.69 psi)
Carbon dioxide (CO₂)	95.32%	0.04%
Nitrogen (N₂)	2.70%	78.08%
Argon (Ar)	1.60%	0.93%
Oxygen (O₂)	0.13%	20.94%

Terraforming Mars would entail three major interlaced changes: building up the atmosphere, keeping it warm, and keeping the atmosphere from being lost into outer space. The atmosphere of Mars is relatively thin and thus has a very low surface pressure of 0.6 kilopascals (0.087 psi); compared to Earth with 101.3 kilopascals (14.69 psi) at sea level and 0.86 kilopascals (0.125 psi) at an altitude of 32 kilometres (20 mi). The atmosphere on Mars consists of 95% carbon dioxide (CO₂), 3% nitrogen, 1.6% argon, and contains only traces of oxygen, water, and methane. Since its atmosphere consists mainly of CO₂, a known greenhouse gas, once the planet begins to heat, more CO₂ enters the atmosphere from the frozen reserves on the poles, adding to the greenhouse effect. This means that the two processes of building the atmosphere and heating it would augment one another, favoring terraforming. However, on a large scale, controlled

application of certain techniques (*explained below*) over enough time to achieve sustainable changes would be required to make this hypothesis a reality.

Building the atmosphere, water content

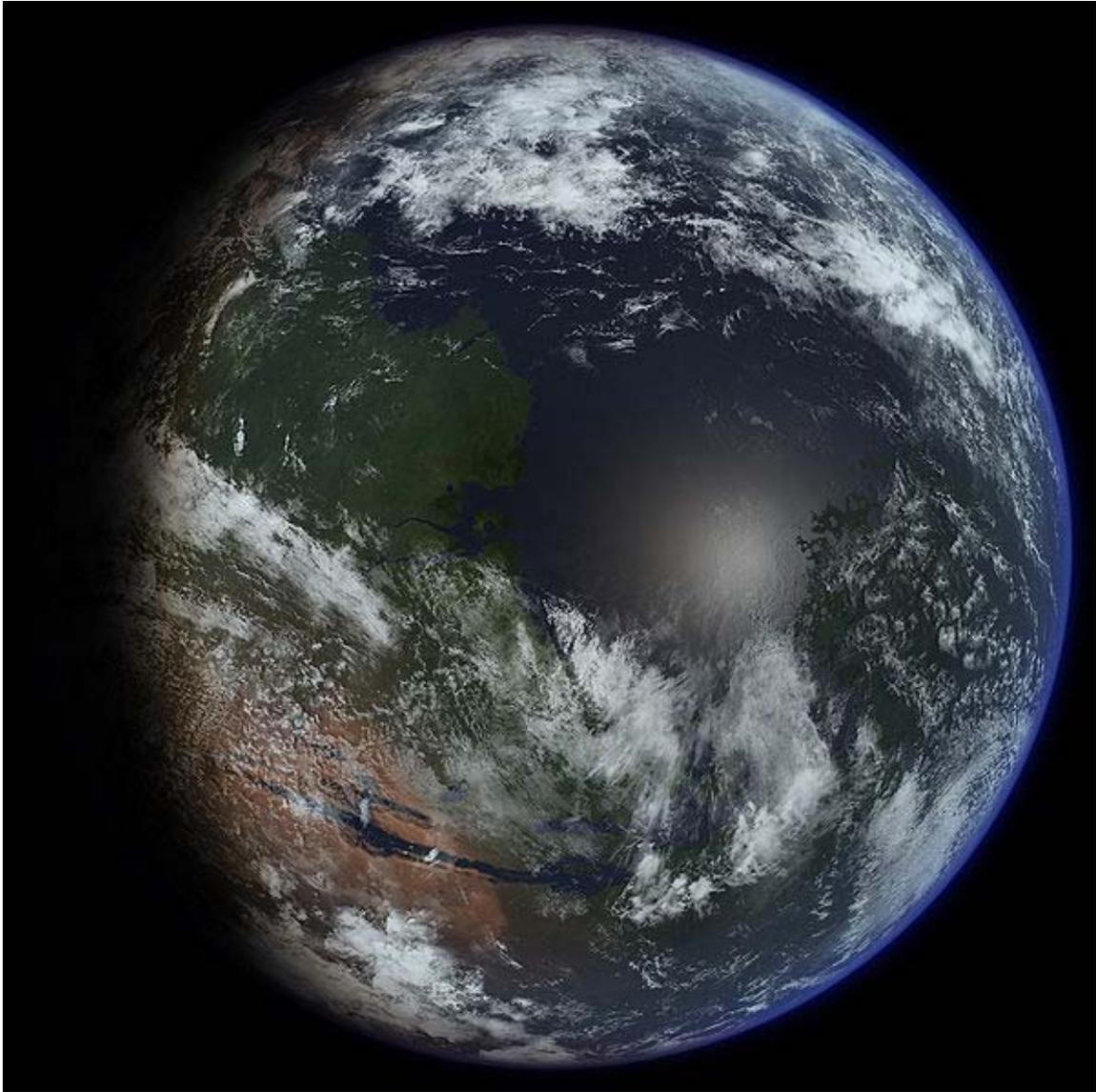


Artist's conception of a terraformed Mars centered on the Tharsis region.

An important step in building the martian atmosphere would be the importation of water, that can be obtained, for example, from ice asteroids or from ice moons of Jupiter or Saturn, beyond the water ice already present at the Martian north pole.

Sources of water

A substantial, nearby source of water is the dwarf planet Ceres, which, according to various studies accounts for 25% to 33% of the mass of the Asteroid Belt. Ceres' mass is approximately 9.43×10^{20} kg. Estimates of how much of Ceres is water varies widely but 20% is a typical estimate and it is thought that much of the water forms the outer or near-surface level. The mass of Ceres' water equals approximately 1.9×10^{20} kg using the previous estimates. The total mass of Mars is approximately 6.42×10^{23} kg. Therefore a very rough estimate is that the amount of water on Ceres equals approximately 0.03 % of the total mass of Mars. Transporting a significant portion of this water, or water from any of the icy moons, could prove difficult. Any attempt to perturb the orbit of Ceres in order to add it whole to Mars (similar to the strategy of using a gravitational tractor for asteroid deflection,) must account for any resultant perturbation of the martian orbit and account for prolonged geological tumult, such as reestablishment of hydrostatic equilibrium, that could result from impact.



Artist's conception of a terraformed Mars. This portrayal is approximately centered on the prime meridian and 30° North latitude, and a hypothesized ocean with a sea level at approximately two kilometers below average surface elevation. The ocean submerges what are now Vastitas Borealis, Acidalia Planitia, Chryse Planitia, and Xanthe Terra; the visible landmasses are Tempe Terra at the left, Aonia Terra at the bottom, Terra Meridiani at the lower right, and Arabia Terra at the upper right. Rivers that feed the ocean at the lower right occupy what are now Valles Marineris and Ares Vallis, while the large lake at the lower right occupies what is now Aram Chaos.

Carbon dioxide sublimation

There is presently enough carbon dioxide (CO₂) as ice in the Martian south pole and absorbed by regolith (soil) around the planet that, if sublimated to gas by a climate warming of only a few degrees, would increase the atmospheric pressure to 300 millibars,

which is comparable to that at the peak of Mount Everest. While this would not be comfortably breathable by humans, it would eliminate the present need for pressure suits, melt the water ice at Mars' north pole (flooding the northern basin), and bring the year-round climate above freezing over approximately half of Mars' surface. This would enable the introduction of plant life, particularly plankton in the new northern sea, to start converting the atmospheric CO₂ into oxygen.

Ammonia importation

Another, more intricate method, uses ammonia as a powerful greenhouse gas (as it is possible that large amounts of it exist in frozen form on asteroidal objects orbiting in the outer Solar System), it may be possible to move these (for example, by using very large nuclear bombs to blast them in the right direction) and send them into Mars' atmosphere. Since ammonia (NH₃) is high in nitrogen it might also take care of the problem of needing a buffer gas in the atmosphere. Sustained smaller impacts will also contribute to increases in the temperature and mass of the atmosphere.

The need for a buffer gas is a challenge that will face any potential atmosphere builders. On Earth, nitrogen is the primary atmospheric component making up 77% of the atmosphere. Mars would require a similar buffer gas component although not necessarily as much. Still, obtaining significant quantities of nitrogen, argon or some other comparatively inert gas is difficult.

Hydrocarbons importation

Another way would be to import methane or other hydrocarbons, which are common in Titan's atmosphere (and on its surface). The methane could be vented into the atmosphere where it would act to compound the greenhouse effect.

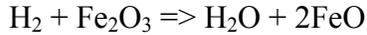
Methane (or other hydrocarbons) also can be helpful to produce a quick increase for the insufficient martian atmospheric pressure. These gases also can be used for production (at the next step of terraforming of Mars) of water and CO₂ for martian atmosphere, by reaction:



This reaction could probably be initiated by heat or by martian solar UV-irradiation. Large amounts of the resulting products (CO₂ and water) are necessary to initiate the photosynthetic processes.

Hydrogen importation

Hydrogen importation could also be done for atmospheric and hydrospheric engineering. For example, hydrogen could react with iron(III) oxide from the martian soil, that would give water as a product:



Depending on the level of carbon dioxide in the atmosphere, importation and reaction of hydrogen would produce heat, water and graphite via the Bosch reaction. Alternatively, reacting hydrogen with the carbon dioxide atmosphere via the Sabatier reaction would yield methane and water.

Using fluorine compounds

Since long-term climate stability would be required for sustaining a human population, the use of especially powerful fluorine-bearing greenhouse gases possibly including sulfur hexafluoride or halocarbons such as chlorofluorocarbons (or CFCs) and perfluorocarbons (or PFCs) has been suggested. These gases are the most cited candidates for artificial insertion into the Martian atmosphere because of their strong effect as a greenhouse gas. This can conceivably be done relatively cheaply by sending rockets with a payload of compressed CFCs on a collision course with Mars. When the rocket crashes onto the surface it releases its payload into the atmosphere. A steady barrage of these "CFC rockets" would need to be sustained for a little more than a decade while the planet changes chemically and becomes warmer.

In order to sublimate the south polar CO₂ glaciers, Mars would require the introduction of approximately 0.3 microbars of CFC (chloro-fluoro-carbons) into Mars' atmosphere. CFC are powerful greenhouse gases that are thousands of times more effective at warming than CO₂. The 0.3 microbars needed would mass approximately 39 million metric tonnes, which is about three times the amount of CFC manufactured on Earth from 1972 to 1992 when CFC production was banned by international treaty. Mineralogical surveys of Mars have found significant amounts of the ores necessary to produce the amount of CFC gas required.

A proposal to mine fluorine-containing minerals as a source of CFCs and PFCs is supported by the belief that since the quantities present are expected to be at least as common on Mars as on Earth, this process could sustain the production of sufficient quantities of optimal greenhouse compounds (CF₃SCF₃, CF₃OCF₂OCF₃, CF₃SCF₂SCF₃, CF₃OCF₂NFCF₃) to maintain Mars at 'comfortable' temperatures, as a method of maintaining an Earth-like atmosphere produced previously by some other means.

Adding heat

Adding heat and conserving the heat present is a particularly important stage of this process, as heat from the Sun is the primary driver of planetary climate. As the planet would become warmer through various methods the CO₂ on the polar caps would sublime into the atmosphere and would further contribute to the warming effect. The tremendous air currents generated by the moving gasses would create large, sustained dust storms, which would heat (through absorbing solar radiation) the molecules in the atmosphere.

Orbiting mirrors

Mirrors made of thin aluminized PET film could be placed in orbit around Mars to increase the total insolation it receives. This would direct the sunlight onto the surface and could increase the planet's surface temperature directly. The mirror could be positioned as a statite, using its effectiveness as a solar sail to orbit in a stationary position relative to Mars, near the poles, to sublimate the CO₂ ice sheet and contribute to the warming greenhouse effect.

Albedo

Reducing the albedo of the Martian surface would also make more efficient use of incoming sunlight. This could be done by spreading dark dust from Mars' moons, Phobos and Deimos, which are among the blackest bodies in the Solar System; or by introducing dark extremophile microbial life forms such as lichens, algae and bacteria. The ground would then absorb more sunlight, warming the atmosphere.

If algae or other green life were established, it would also contribute a small amount of oxygen to the atmosphere, though not enough to allow humans to breathe.

Asteroid impact

Another way to increase the temperature could be to direct small cosmic bodies (asteroids) onto the Martian surface; the impact energy would be released as heat and could vaporize Martian water ice to steam, which is also a greenhouse gas. Asteroids could also be chosen for their composition, such as Ammonia, which would then disperse into the atmosphere on impact, adding greenhouse gases to the atmosphere. Lightning may have built up nitrate beds in the soil over the life of the planet. Impacting asteroids on these nitrate beds would release additional nitrogen and oxygen into the atmosphere.

Magnetic field and solar radiation

Earth abounds with water because its ionosphere is permeated with a magnetic field. The hydrogen ions present in its ionosphere move very fast due to their small mass, but they cannot escape to outer space because their trajectories are deflected by the magnetic field. Venus has a dense atmosphere, but only traces of water vapor (20 ppm) because it has no magnetic field. The Martian atmosphere also loses water to space.

Earth's ozone layer provides additional protection. Ultraviolet light is blocked before it can dissociate water into hydrogen and oxygen. Since little water vapor rises above the troposphere and the ozone layer is in the upper stratosphere, little water is dissociated into hydrogen and oxygen.

It is believed that Mars would be uninhabitable to most life-forms due to high solar radiation levels. Because of the planet's lack of a magnetosphere, the Sun is thought to have thinned the Martian atmosphere to its current state; the solar wind adding a

significant amount of energy to the atmosphere's top layers which enables the atmospheric particles to reach escape velocity and leave Mars. Indeed, this effect has even been detected by Mars-orbiting probes. Another theory is that solar wind rips the atmosphere away from the planet as it becomes trapped in bubbles of magnetic fields called plasmoids.

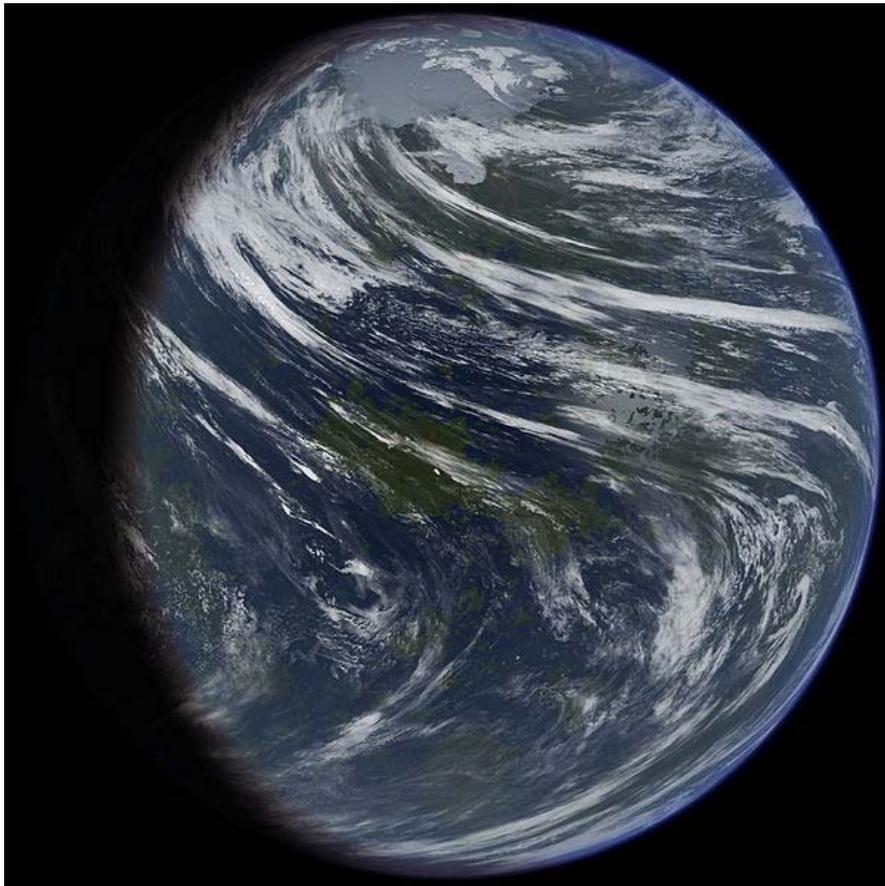
Venus, however, shows that the lack of a magnetosphere does not preclude a dense (albeit dry) atmosphere. A thick atmosphere could also provide solar radiation protection to the surface, similar to Earth's. In the past, Earth has regularly had periods where the magnetosphere changed direction and collapsed for some time.

The lack of a protective magnetic field would also have possible health effects on colonists due to increased cosmic ray flux. The health threat depends on the flux, energy spectrum, and nuclear composition of the rays. The flux and energy spectrum depend on a variety of factors, which are incompletely understood. The Mars Radiation Environment Experiment (MARIE) was launched in 2001 in order to collect more data. Estimates are that humans unshielded in interplanetary space would receive annually roughly 400 to 900 milli-Sieverts (mSv) (compared to 2.4 mSv on Earth) and that a Mars mission (12 months in flight and 18 months on Mars) might expose shielded astronauts to ~500 to 1000 mSv. These doses approach the 1 to 4 Sv career limits advised by the National Council on Radiation Protection and Measurements for Low Earth orbit activities.

Shielding from cosmic rays can be accomplished by placing habitation modules either within lava tubes or under igloo structures built from sintered regolith bricks.

Chapter-9

Terraforming of Venus



Artist's conception of a terraformed Venus. The cloud formations are depicted assuming the planet's rotation has not been sped up.

Terraforming of Venus is the hypothetical process of engineering the global environment of the planet Venus in such a way as to make it suitable for human habitation. Terraforming Venus was first seriously proposed by the astronomer Carl Sagan in 1961. The minimum adjustments to the existing environment of Venus to support human life would require three major changes to the planet:

- Reducing Venus's 450°C (850°F) surface temperature.
- Eliminating most of the planet's dense 9 MPa (~90 atm) carbon dioxide atmosphere, via removal or conversion to some other form.
- Addition of breathable oxygen to the atmosphere.

These three goals are closely interrelated, since Venus's extreme temperature is due to the greenhouse effect caused by its dense carbon-dioxide atmosphere. In addition, two additional changes would be highly desirable:

- Establishing a day/night light cycle shorter than Venus's current solar day (currently equal to 116.75 Earth days).
- Establishing a planetary magnetic field or substitute for protection against solar and cosmic radiation.

Solar shades

Venus receives about twice the sunlight that Earth does, which is thought to have contributed to its runaway greenhouse effect. Terraforming Venus will likely involve reducing the insolation at Venus' surface to prevent the planet from heating up again.

Space based

Solar shades could be used to reduce the total insolation received by Venus, cooling the planet somewhat. A shade placed in the Sun-Venus L_1 Lagrange point also serves to block the solar wind, removing the radiation exposure problem on Venus.

Construction of a suitably large solar shade is a daunting task. The size of the shade would be four times the diameter of Venus itself if at the L_1 point. This size would necessitate construction in space. There would also be the difficulty of balancing a thin-film shade perpendicular to the Sun's rays at the Sun-Venus Lagrangian point with the incoming radiation pressure, which would tend to turn the shade into a huge solar sail. If the shade were left at the L_1 point, the pressure would add force to the sunward side and necessitate moving the shade even closer to the Sun than the L_1 point.

Modifications to the L_1 solar shade design have been suggested to solve the solar sail problem. One suggested method is to use polar orbiting, solar-synchronous mirrors that reflect light toward the back of the sunshade, from the non-sunward side of Venus. Photon pressure would push the support mirrors to an angle of 30 degrees away from the sunward side.

Paul Birch proposed a slatted system of mirrors near the L_1 point between Venus and the Sun. The shade's panels would not be perpendicular to the sun's rays, but instead at an angle of 30 degrees, such that the reflected light would strike the next panel, negating the photon pressure. Each successive row of panels would be +/- 1 degree off the 30-degree deflection angle, causing the reflected light to be skewed 4 degrees from striking Venus.

Another possibility, suggested by Bradley C. Edwards, is to put into orbit around Venus a belt of material, blocking a portion of sunlight. Multiple thinner belts may be used, and may be composed of a thin net of fibers spaced so that certain wavelengths could not get through while using less material.

Solar shades could also serve as solar power generators. Space-based solar shade techniques, and thin-film solar sails in general, are only in an early stage of development. The vast sizes require a quantity of material that is many orders of magnitude greater than any man-made object that has ever been brought into space or constructed in space.

Atmospheric or surface-based

Cooling could also be effected by placing reflectors in the atmosphere or on the surface. Reflective balloons floating in the upper atmosphere could create shade. The number and/or size of the balloons would necessarily be great. Geoffrey A. Landis has suggested that if enough floating cities were built, they could form a solar shield around the planet, and could simultaneously be used to process the atmosphere into a more desirable form, thus combining the solar shield theory and the atmospheric processing theory with a scalable technology that would immediately provide living space in the Venerian atmosphere. If made from carbon nanotubes (recently fabricated into sheet form) or graphene (a sheet-like carbon allotrope), then the major structural materials can be produced using carbon dioxide gathered in situ from the atmosphere. The recently synthesised amorphous carbonia might prove a useful structural material if it can be quenched to STP conditions, perhaps in a mixture with regular silica glass. According to Birch's analysis such colonies and materials would provide an immediate economic return from colonizing Venus, funding further terraforming efforts.

Increasing the planet's albedo by deploying light color or reflective material on the surface could help keep the atmosphere cool. The amount would be large and would have to be put in place after the atmosphere had been modified already, since Venus's surface is currently completely shrouded by clouds.

An advantage of atmospheric and surface cooling solutions is that they take advantage of existing technology. A disadvantage is that Venus already has highly reflective clouds (giving it an albedo of 0.65), so any approach would have to significantly surpass this to make a difference.

Eliminating the dense carbon dioxide atmosphere

Biological approaches

A method proposed in 1961 by Carl Sagan involves the use of genetically engineered bacteria to fix carbon into organic forms. Although this method is still commonly proposed in discussions of Venus terraforming, later discoveries showed it would not be successful. The production of organic molecules from carbon dioxide requires an input of hydrogen, which on Earth is taken from its abundant supply of water but which is nearly

nonexistent on Venus. Since Venus lacks a magnetic field, the upper atmosphere is exposed to direct erosion by solar wind and has lost most of its original hydrogen to space.

Furthermore, any carbon that was bound up in organic molecules would quickly be converted to carbon dioxide again by the hot surface environment. Venus would not begin to cool down until after most of the carbon dioxide has already been removed. Twenty-three years later, in *Pale Blue Dot*, Sagan conceded that his original proposal for terraforming would not work because the atmosphere of Venus is far denser than was known in 1961.

Floating colonies could gradually transform the Venerian atmosphere: for example, their reflectivity could alter the overall albedo of Venus. Colonies could also grow plant matter, if water or another source of hydrogen were imported, which would gradually sequester carbon dioxide in the air. However, it would take an enormous number of such colonies, and large quantities of introduced hydrogen, to have a significant atmospheric impact, as there is over 1.2×10^{20} kg of carbon in Venus's atmosphere.

Introduction of hydrogen

Bombarding Venus with hydrogen, possibly from some outer solar system source, and reacting with carbon dioxide, could produce elemental carbon (graphite) and water by the Bosch reaction. It would take about 4×10^{19} kg of hydrogen to convert the whole Venerian atmosphere. (Loss of hydrogen due to the solar wind is unlikely to be significant on the timescale of terraforming.) Due to the relatively flat surface, this water would cover about 80% of the surface compared to 70% for Earth, even though it would amount to only roughly 10% of the water found on Earth.

The remaining atmosphere, at around 3 bars (about three times that of Earth), will mainly be composed of nitrogen, some of which will dissolve into the new oceans of water, reducing atmospheric pressure further, in accordance with Henry's law.

Capture in carbonates

Bombardment of Venus with refined magnesium and calcium metal could sequester carbon dioxide in the form of calcium and magnesium carbonates. About 8×10^{20} kg of calcium or 5×10^{20} kg of magnesium would be required, which would entail a great deal of mining and mineral refining. 8×10^{20} kg is a few times the mass of the asteroid 4 Vesta (more than 300 miles in diameter).

Modelling by Mark Bullock of Venus' atmospheric evolution suggests that existing surface minerals, particularly calcium and magnesium oxides, could serve as a sink of carbon dioxide and sulphur dioxide. If these could be exposed to the atmosphere then the planet would cool and its atmospheric pressure decline somewhat. One of the possible end states modelled by Bullock was a 43 bar atmosphere and 400 K surface temperature.

Direct liquefaction and sequestration

Birch's proposal involves using a solar shade to cool Venus down sufficiently to permit liquefaction, from a temperature less than 304.18 K and partial pressures of CO₂ down to 73.8 bar (carbon dioxide's critical point) and then down to 5.185 bar and 216.85 K (carbon dioxide's triple point). Below that temperature, freezing of atmospheric carbon dioxide into dry ice will cause it to deposit onto the surface, after which the frozen CO₂ would be buried and maintained in that condition by pressure, or shipped off-world. After this process was complete, the shades could be removed or solettas added, allowing the planet to partially warm again to temperatures comfortable for Earth life. A source of hydrogen or water would still be needed, and some of the remaining 3.5 bar of atmospheric nitrogen would need to be fixed into the soil. Birch suggests disrupting an ice-moon of Saturn and bombarding Venus with its fragments to provide perhaps an average depth of 100 meters of water over the whole planet.

Removing atmosphere

The removal of Venus's atmosphere could be attempted by a variety of methods, possibly in combination. Directly lifting atmospheric gas from Venus into space would likely prove difficult. Venus has sufficiently high escape velocity to make blasting it away with asteroid impacts impractical. Pollack and Sagan calculated in 1993 that an impactor of 700 km diameter striking Venus at greater than 20 km/s, would eject all the atmosphere above the horizon as seen from the point of impact, but since this is less than a thousandth of the total atmosphere and there would be diminishing returns as the atmosphere's density decreased a very great number of such giant impactors would be required. Smaller objects would not work either, requiring even more. The violence of the bombardment could well result in significant outgassing that replaces removed atmosphere. Most of the ejected atmosphere would go into solar orbit near Venus, and, without further intervention, could be captured by Venus' gravitational field and become part of the atmosphere once again.

Removal of atmospheric gas in a more controlled manner could also prove difficult. Venus's extremely slow rotation means that space elevators would be very difficult to construct as the planet's geostationary orbit lies an impractical distance above the surface; and the very thick atmosphere to be removed makes mass drivers useless for removing payloads from the planet's surface. Possible workarounds include placing mass drivers on high-altitude balloons or balloon-supported towers extending above the bulk of the atmosphere, using space fountains, or rotovators.

Rotation

Venus rotates once every 243 days – by far the slowest rotation period of any of the major planets. A Venerian sidereal day thus lasts more than a Venerian year (243 versus 224.7 Earth days). However, the length of a solar day on Venus is significantly shorter than the sidereal day; to an observer on the surface of Venus the time from one sunrise to the next would be 116.75 days. Nevertheless, Venus's extremely slow rotation rate would

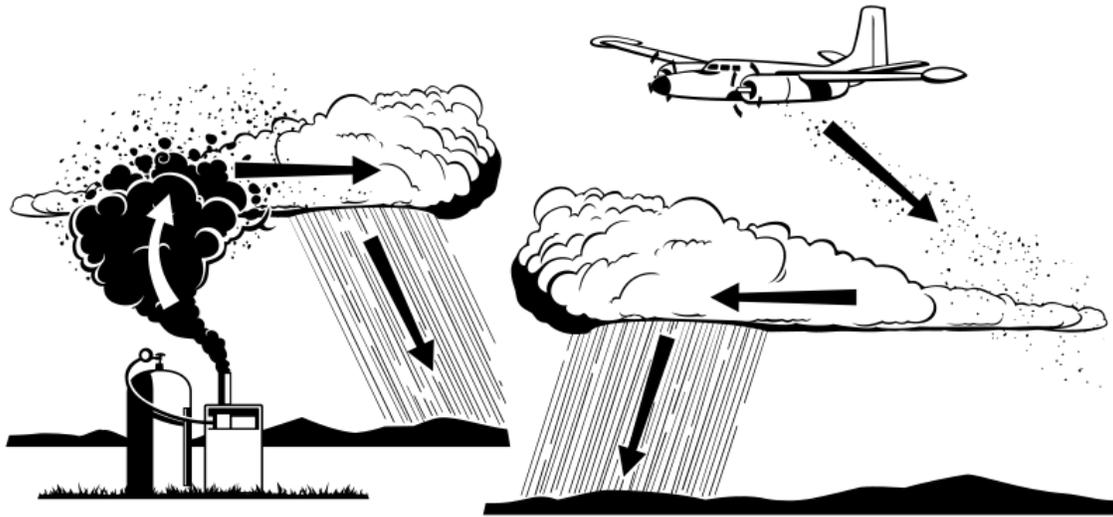
result in extremely long days and nights, which could prove difficult for most known Earth species of plants and animals to adapt to. The slow rotation also likely accounts for the lack of a significant magnetic field.

One proposal is a system of orbiting solar mirrors which might be used to provide sunlight to the night side of Venus and possibly shade to the day side surface. In addition to his suggestion of slatted system of mirrors near the L_1 point between Venus and the Sun, Paul Birch has proposed a rotating soletta mirror in a polar orbit, which would produce a 24-hour light cycle.

Increasing the speed of Venus's rotation would require many orders of magnitude greater amounts of energy than construction of orbiting solar mirrors, or even than the removal of Venus's atmosphere. Recent scientific research suggests that close fly-bys of asteroids or cometary bodies larger than 60 miles across could be used to move a planet in its orbit, or increase the speed of rotation. G. David Nordley has suggested, in fiction, that Venus might be spun-up to a day-length of 30 Earth-days by exporting the atmosphere of Venus into space via mass drivers. This concept was also explored more rigorously by Birch.

Chapter-10

Cloud Seeding

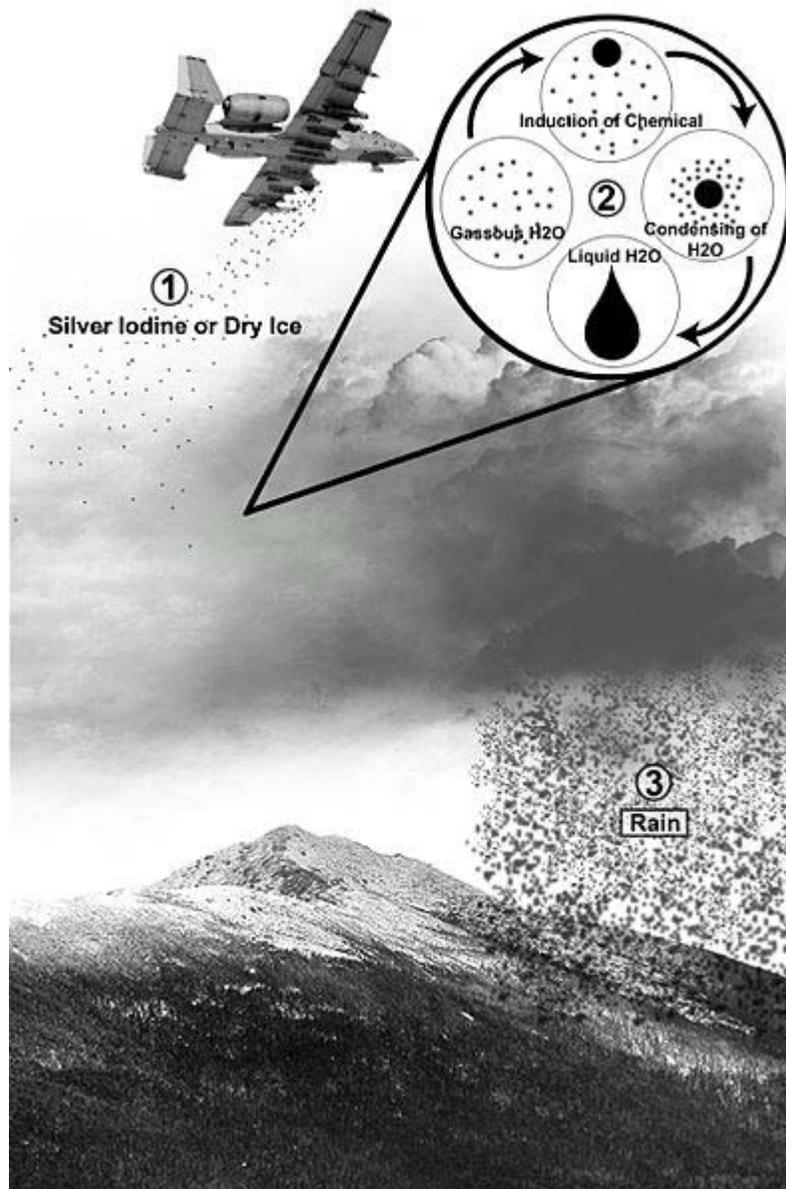


Cloud seeding can be done by ground generators, plane, or rocket (not shown).

Cloud seeding, a form of weather modification, is the attempt to change the amount or type of precipitation that falls from clouds, by dispersing substances into the air that serve as cloud condensation or ice nuclei, which alter the microphysical processes within the cloud. The usual intent is to increase precipitation (rain or snow), but hail and fog suppression are also widely practiced in airports.

Terpenes are released by trees more actively during warmer weather, acting as a natural form of cloud seeding. The clouds reflect sunlight, allowing the forest to regulate its temperature.

How cloud seeding works



This image explaining cloud seeding shows the chemical either silver iodine or dry ice being dumped onto the cloud which then becomes a rain shower. The process shown in the upper right is what is happening in the cloud and the process of condensation to the introduced chemicals.

The most common chemicals used for cloud seeding include silver iodide and dry ice (frozen carbon dioxide). The expansion of liquid propane into a gas has also been used and can produce ice crystals at higher temperatures than silver iodide. The use of hygroscopic materials, such as salt, is increasing in popularity because of some promising research results.

Seeding of clouds requires that they contain supercooled liquid water—that is, liquid water colder than zero degrees Celsius. Introduction of a substance such as silver iodide, which has a crystalline structure similar to that of ice, will induce freezing nucleation. Dry ice or propane expansion cools the air to such an extent that ice crystals can nucleate spontaneously from the vapor phase. Unlike seeding with silver iodide, this spontaneous nucleation does not require any existing droplets or particles because it produces extremely high vapor supersaturations near the seeding substance. However, the existing droplets are needed for the ice crystals to grow into large enough particles to precipitate out.

In mid-latitude clouds, the usual seeding strategy has been predicated upon the fact that the equilibrium vapor pressure is lower over ice than over water. When ice particles form in supercooled clouds, this fact allows the ice particles to grow at the expense of liquid droplets. If there is sufficient growth, the particles become heavy enough to fall as snow (or, if melting occurs, rain) from clouds that otherwise would produce no precipitation. This process is known as "static" seeding.

Seeding of warm-season or tropical cumulonimbus (convective) clouds seeks to exploit the latent heat released by freezing. This strategy of "dynamic" seeding assumes that the additional latent heat adds buoyancy, strengthens updrafts, ensures more low-level convergence, and ultimately causes rapid growth of properly selected clouds.

Cloud seeding chemicals may be dispersed by aircraft (as in the second figure) or by dispersion devices located on the ground (generators, as in first figure, or canisters fired from anti-aircraft guns or rockets). For release by aircraft, silver iodide flares are ignited and dispersed as an aircraft flies through the inflow of a cloud. When released by devices on the ground, the fine particles are carried downwind and upwards by air currents after release.

An electronic mechanism was tested in 2010, when infrared laser pulses were directed to the air above Berlin by researchers from the University of Geneva. The experimenters posited that the pulses would encourage atmospheric sulfur dioxide and nitrogen dioxide to form particles that would then act as seeds.

Effectiveness

Referring to the 1903, 1915, 1919 and 1944 and 1947 weather modification experiments, the Australian Federation of Meteorology discounted "rain making." By the 1950s the CSIRO Division of Radiophysics switched to investigating the physics of clouds and had hoped by 1957 to better understand these processes. By the 1960s the dreams of weather making had faded only to be re-ignited post-corporatisation of the Snowy Mountains Scheme in order to achieve "above target" water. This would provide enhanced energy generation and profits to the public agencies who are the principal owners. Cloud seeding has been shown to be effective in altering cloud structure and size and in converting supercooled liquid water to ice particles. The amount of precipitation due to seeding is difficult to quantify. Cloud seeding may also suppress precipitation.

A key challenge is in discerning how much precipitation would have occurred had clouds not been seeded. Overall, there is general expectation that winter cloud seeding over mountains will produce snow, expressed by professional organizations. There is statistical evidence for seasonal precipitation increases of about 10% with winter seeding.

The US government through its National Center for Atmospheric Research has analyzed seeded and unseeded clouds to understand the differences between them, and has conducted seeding research in other countries.

Clouds were seeded during the 2008 Summer Olympics in Beijing using rockets, so that there would be no rain during the opening and closing ceremonies. although others dispute their claims of success.

Impact on environment and health

With an NFPA 704 rating of Blue 2, silver iodide can cause temporary incapacitation or possible residual injury to humans and mammals with intense or continued but not chronic exposure. However, there have been several detailed ecological studies that showed negligible environmental and health impacts. The toxicity of silver and silver compounds (from silver iodide) was shown to be of low order in some studies. These findings likely result from the minute amounts of silver generated by cloud seeding, which are 100 times less than industry emissions into the atmosphere in many parts of the world, or individual exposure from tooth fillings.

Accumulations in the soil, vegetation, and surface runoff have not been large enough to measure above natural background. A 1995 environmental assessment in the Sierra Nevada of California and a 2004 independent panel of experts (an overview only is presented in the executive summary of the research) in Australia confirmed these earlier findings.

Cloud seeding over Kosciuszko National Park - a Biosphere Reserve - is problematic in that several rapid changes of environmental legislation were made to enable the "trial." Environmentalists are concerned about the uptake of elemental silver in a highly sensitive environment affecting the pygmy possum amongst other species as well as recent high level algal blooms in once pristine glacial lakes. The ABC program Earthbeat on 17 July 2004 heard that not every cloud has a silver lining where concerns for the health of the pygmy possums was raised. Research 50 years ago and analysis by the former Snowy Mountains Authority led to the cessation of the cloud seeding program in the 1950s with non-definitive results. Formerly, cloud seeding was rejected in Australia on environmental grounds because of concerns about the protected species, the pygmy possum. Since silver iodide and not elemental silver is the cloud seeding material, the claims of negative environmental impact are disputed by peer-reviewed research as summarized by the international weather modification association.

History



Cessna 210 with cloud seeding equipment

Vincent Schaefer (1906–1993) discovered the principle of cloud seeding in July 1946 through a series of serendipitous events. Following ideas generated between himself and Nobel laureate Irving Langmuir while climbing Mt. Washington in New Hampshire, Schaefer, Langmuir's research associate, created a way of experimenting with supercooled clouds using a deep freeze unit of potential agents to stimulate ice crystal growth, *i.e.*, salt, talcum powder, soils, dust and various chemical agents with minor effect. Then one hot and humid July 14, 1946, he wanted to try a few experiments at General Electric's Schenectady Research Lab. He was dismayed to find that the deep freezer was not cold enough to produce a "cloud" using breath air. He decided to move the process along by adding a chunk of dry ice just to lower the temperature of his experimental chamber. To his astonishment, as soon as he breathed into the deep freezer, a bluish haze was noted, followed by an eye-popping display of millions of microscopic ice crystals, reflecting the strong light rays from the lamp illuminating a cross-section of the chamber. He instantly realized that he had discovered a way to change supercooled water into ice crystals. The experiment was easily replicated and he explored the temperature gradient to establish the -40°C limit for liquid water.

Within the month, Schaefer's colleague, the noted atmospheric scientist Dr. Bernard Vonnegut (brother of novelist Kurt Vonnegut) is credited with discovering another

method for "seeding" supercooled cloud water. Vonnegut accomplished his discovery at the desk, looking up information in a basic chemistry text and then tinkering with silver and iodide chemicals to produce silver iodide. Together with Dr. Vonnegut, Professor Henry Chessin, SUNY Albany, a crystallographer, co-authored a publication in *Science Magazine* and received a patent in 1975. Both methods were adopted for use in cloud seeding during 1946 while working for the General Electric Corporation in the state of New York. Schaefer's altered a cloud's heat budget, Vonnegut's altered formative crystal structure – an ingenious property related to a good match in lattice constant between the two types of crystal. (The crystallography of ice later played a role in Kurt Vonnegut's novel *Cat's Cradle*.) The first attempt to modify natural clouds in the field through "cloud seeding" began during a flight that began in upstate New York on 13 November 1946. Schaefer was able to cause snow to fall near Mount Greylock in western Massachusetts, after he dumped six pounds of dry ice into the target cloud from a plane after a 60-mile easterly chase from the Schenectady County Airport.

Dry ice and silver iodide agents are effective in changing the physical chemistry of supercooled clouds, thus useful in augmentation of winter snowfall over mountains and under certain conditions, and lightning and hail suppression. While not a new technique, hygroscopic seeding for enhancement of rainfall in warm clouds is enjoying a revival, based on some positive indications from research in South Africa, Mexico, and elsewhere. The hygroscopic material most commonly used is salt. It is postulated that hygroscopic seeding causes the droplet size spectrum in clouds to become more maritime (bigger drops) and less continental, stimulating rainfall through coalescence. From March 1967 until July 1972, the U.S. military's Operation Popeye cloud-seeded silver iodide to extend the monsoon season over North Vietnam, specifically the Ho Chi Minh Trail. The operation resulted in the targeted areas seeing an extension of the monsoon period an average of 30 to 45 days. The 54th Weather Reconnaissance Squadron carried out the operation to "make mud, not war".

In 1969 at the Woodstock Festival, various people claimed to have witnessed clouds being seeded by the U.S. military. This was said to be the cause of the rain which lasted throughout most of the festival.

One private organization which offered, during the 1970s, to conduct weather modification (cloud seeding from the ground using silver iodide flares) was *Irving P. Krick and Associates* of Palm Springs, California. They were contracted by the Oklahoma State University in 1972 to conduct such a seeding project to increase warm cloud rainfall in the Lake Carl Blackwell watershed. That lake was, at that time (1972–73), the primary water supply for Stillwater, Oklahoma and was dangerously low. The project did not operate for a long enough time to show statistically any change from natural variations. However, at the same time, seeding operations have been ongoing in California since 1948.

An attempt by the United States military to modify hurricanes in the Atlantic basin using cloud seeding in the 1960s was called Project Stormfury. Only a few hurricanes were tested with cloud seeding because of the strict rules that were set by the scientists of the

project. It was unclear whether the project was successful; hurricanes appeared to change in structure slightly, but only temporarily. The fear that cloud seeding could potentially change the course or power of hurricanes and negatively affect people in the storm's path stopped the project.

Two federal agencies have supported various weather modification research projects, which began in the early 1960s: The United States Bureau of Reclamation (Reclamation; Department of the Interior) and the National Oceanic and Atmospheric Administration (NOAA; Department of Commerce). Reclamation sponsored several cloud seeding research projects under the umbrella of Project Skywater from 1964 to 1988, and NOAA conducted the Atmospheric Modification Program from 1979 to 1993. The sponsored projects were carried out in several states and two countries (Thailand and Morocco), studying both winter and summer cloud seeding. More recently, Reclamation sponsored a small cooperative research program with six Western states called the Weather Damage Modification Program, from 2002–2006.

Funding for research in the United States has declined in the last two decades. The Bureau of Reclamation sponsored a six-state research program from 2002–2006, however, called the "Weather Damage Modification Program". A 2003 study by the United States National Academy of Sciences urges a national research program to clear up remaining questions about weather modification's efficacy and practice.

In Australia, CSIRO conducted major trials between 1947 and the early 1960s:

- 1947 – 1952: CSIRO scientists dropped dry ice into the tops of cumulus clouds. The method worked reliably with clouds that were very cold, producing rain that would not have otherwise fallen.
- 1953 – 1956: CSIRO carried out similar trials South Australia, Queensland and other States. Experiments used both ground-based and airborne silver iodide generators.
- Late 1950s and early 1960s: Cloud seeding in the Snowy Mountains, on the Cape York Peninsula in Queensland, in the New England district of New South Wales, and in the Warragamba catchment area west of Sydney.

Only the trial conducted in the Snowy Mountains produced statistically significant rainfall increases over the entire experiment.

An Austrian study to use silver iodine seeding for hail prevention ran during 1981–2000, and the technique is still actively deployed there.

Modern uses

Asia

The largest cloud seeding system in the world is that of the People's Republic of China, which believes that it increases the amount of rain over several increasingly arid regions, including its capital city, Beijing, by firing silver iodide rockets into the sky where rain is desired. There is even political strife caused by neighboring regions which accuse each other of "stealing rain" using cloud seeding. About 24 countries currently practice weather modification operationally. China used cloud seeding in Beijing just before the 2008 Olympic Games in order to clear the air of pollution, but there are disputes regarding the Chinese claims. In February 2009, China also blasted iodide sticks over Beijing to artificially induce snowfall after four months of drought, and blasted iodide sticks over other areas of northern China to increase snowfall. The snowfall in Beijing lasted for approximately three days and led to the closure of 12 main roads around Beijing. At the end of October 2009 Beijing claimed it had its earliest snowfall since 1987 due to cloud seeding.

In Southeast Asia, open burning produces haze that pollutes the regional environment. Cloud-seeding has been used to improve the air quality by encouraging rainfall. In India, cloud seeding operations were conducted during the years 2003 and 2004 through U.S. based Weather Modification Inc. in state of Maharashtra. In 2008, there are plans for 12 districts of state of Andhra Pradesh.

North America

In the United States, cloud seeding is used to increase precipitation in areas experiencing drought, to reduce the size of hailstones that form in thunderstorms, and to reduce the amount of fog in and around airports. Cloud seeding is also occasionally used by major ski resorts to induce snowfall. Eleven western states and one Canadian province (Alberta) have ongoing weather modification operational programs . In January 2006, an \$8.8 million cloud seeding project began in Wyoming to examine the effects of cloud seeding on snowfall over Wyoming's Medicine Bow, Sierra Madre, and Wind River mountain ranges.

A number of commercial companies, such as Aero Systems Incorporated , Atmospherics Incorporated , North American Weather Consultants , Weather Modification Incorporated , Weather Enhancement Technologies International , Seeding Operations and Atmospheric Research (SOAR) , offer weather modification services centered on cloud seeding. The USAF proposed its use on the battlefield in 1996, although the U.S. signed an international treaty in 1978 banning the use of weather modification for hostile purposes.



This Cessna 441 is used to conduct cloud-seeding flights on behalf of Hydro Tasmania

During the sixties, Irving P. Krick & Associates operated a successful cloud seeding operation in the area around Calgary, Alberta. This utilized both aircraft and ground-based generators that pumped silver iodide into the atmosphere in an attempt to reduce the threat of hail damage. Ralph Langeman, Lynn Garrison, and Stan McLeod, all ex-members of the RCAF's 403 Squadron, attending the University of Alberta, spent their summers flying hail suppression. A number of surplus Harvard aircraft were fitted with racks under each wing containing 32 railroad fuzes that were impregnated with silver iodide. These could be ignited individually or all at once, depending upon the threat. In coordination with ground units, the aircraft would lay a plume of silver iodide in front of approaching cumulo-nimbus clouds with noticeable effect. Large, active CBs were reduced to nothing. Heavy hail storms were reduced in intensity. This effective program was funded by farmer contributions and government grants.

Europe

Cloud seeding was begun in France during the 1950s with the intent of reducing hail damage to crops. The ANELFA project consists of local agencies acting within a non-profit organization. A similar project in Spain is managed by the Consorcio por la Lucha Antigranizo de Aragon. The success of the French program was supported by insurance data; that of the Spanish program in studies conducted by the Spanish Agricultural Ministry.

Russian military pilots seeded clouds over Belarus after the Chernobyl disaster to remove radioactive particles from clouds heading toward Moscow. At the July 2006 G8 Summit, President Putin commented that air force jets had been deployed to seed incoming clouds so they rained over Finland. Rain drenched the summit anyway. In Moscow, the Russian Airforce tried seeding clouds with bags of cement on June 17, 2008. One of the bags did not pulverize and went through the roof of a house. In October 2009, the Mayor of Moscow promised a "winter without snow" for the city after revealing efforts by the Russian Air Force to seed the clouds upwind from Moscow throughout the winter.

Australia

In Australia, CSIRO's activities in Tasmania in the 1960s were successful. Seeding over the Hydro-Electricity Commission catchment area on the Central Plateau achieved rainfall increases as high as 30% in autumn. The Tasmanian experiments were so successful that the Commission has regularly undertaken seeding ever since in mountainous parts of the State.

In 2004, Snowy Hydro Limited began a trial of cloud seeding to assess the feasibility of increasing snow precipitation in the Snowy Mountains in Australia. The test period, originally scheduled to end in 2009, was later extended to 2014. The New South Wales (NSW) Natural Resources Commission, responsible for supervising the cloud seeding operations, believes that the trial may have difficulty establishing statistically whether cloud seeding operations are increasing snowfall. This project was discussed at a summit in Narrabri, NSW on 1 December 2006. The summit met with the intention of outlining a proposal for a 5 year trial, focussing on Northern NSW.

The various implications of such a widespread trial were discussed, drawing on the combined knowledge of several worldwide experts, including representatives from the Tasmanian Hydro Cloud Seeding Project however does not make reference to former cloud seeding experiments by the then Snowy Mountains Authority which rejected weather modification. The trial required changes to NSW environmental legislation in order to facilitate placement of the cloud seeding apparatus. The modern experiment is not supported for the Australian Alps.

In December 2006, the Queensland government of Australia announced A\$7.6 million in funding for "warm cloud" seeding research to be conducted jointly by the Australian Bureau of Meteorology and the United States National Center for Atmospheric Research. Outcomes of the study are hoped to ease continuing drought conditions in the states South East region.

Chapter-11

Ocean Nourishment

Ocean Nourishment is a type of geoengineering based on the purposeful introduction of nutrients to the upper ocean to increase marine food production and to sequester carbon dioxide from the atmosphere. Fertilization can also potentially create sulfur aerosols which reduce the rate of global warming. The marine food chain is based on photosynthesis by marine phytoplankton which combine carbon with inorganic nutrients to produce organic matter. The production of organic matter is limited in general by the availability of nutrients, most commonly nitrogen or iron. Numerous experiments have been carried out demonstrating how iron fertilization can increase phytoplankton productivity. Nitrogen is a limiting nutrient over much of the ocean and can be supplied by from a number of sources including fixation by cyanobacteria. Carbon-to-iron ratios in phytoplankton are much larger than carbon-to-nitrogen or carbon-to-phosphorus ratios, so iron has the highest potential for sequestration per unit mass added.

Ocean Nourishment offers the prospect of both reducing the concentration of atmospheric greenhouse gases with the aim of avoiding rapid climate change and at the same time increasing the sustainable fish stocks. It promises to do this by increasing the ocean primary production.

Ocean Nourishment promises to be a way of creating low cost protein in sufficient quantity to supply the needs of the additional two billion people expected to populate the earth before the population stabilizes at values near eight billion. While manipulation of the land ecosystem in support of agriculture for the benefit of humans has long been accepted it is a new concept to enhance the large scale ocean productivity and so creates some apprehension.

Phosphorus fertilization

This technique can give 0.83W/m^2 of globally-averaged negative forcing, which is sufficient to reverse the warming effect of about half the current levels of anthropogenic CO_2 emissions. It is notable, however, that CO_2 levels will have risen by the time this could be achieved.

Nitrogen fertilization

Proposed by Ian Jones with the purpose to fertilize the ocean with urea, a nitrogen rich substance, to encourage phytoplankton growth. Also considered by Karl.

An Australian company, Ocean Nourishment Corporation (ONC), plans to sink hundreds of tonnes of urea into the ocean, in order to boost the growth of CO₂-absorbing phytoplankton, as a way to combat climate change. In 2007, Sydney-based ONC completed an experiment involving one tonne of nitrogen in the Sulu Sea off the Philippines.

This technique can give 0.38W/m² of globally-averaged negative forcing, which is sufficient to reverse the warming effect of current levels of around a quarter of anthropogenic CO₂ emissions. It is notable, however, that CO₂ levels will have risen by the time this could be achieved.

Sulu sea urea fertilization advantages and disadvantages

Advantages

"Ocean Nourishment Corporation has claimed that in the long run, beyond Sulu Sea trials, "One Ocean Nourishment plant will remove approximately 5-8 million tonnes of CO₂ from the atmosphere for each year of operation, equivalent to offsetting annual emissions from a typical 1200 MW coal-fired power station or the short-term sequestration from million hectares of new growth forest".

Disadvantages

Nitrogen fertilization is not as efficient as iron fertilization.

Algal cell chemical composition is 106 carbon: 16 nitrogen: 1 phosphorus: 0.0001 iron. In other words for each atom of iron there are 1060000 atoms of carbon are captured, however for one nitrogen atom only 6 atoms of carbon are captured.

Urea fertilization may not benefit fisheries

It has been said that addition of urea to the ocean can cause blooms of phytoplankton that is source of food of fish. However, if cyanobacteria and dinoflagellates dominate the phytoplankton assemblage that are considered poor quality food for fish then fish quantity cannot be counted as rising. Another disadvantage is the fact that fossil fuels are used to produce urea. The fossil fuels contain buried CO₂, so using them is not benign from the environmental point of view.

Sulu sea biodiversity

In Sulu Sea Tubbataha's marine biodiversity is virtually unparalleled by any other in the world today and nitrogen loading in coral reef areas can lead to community shifts towards algal overgrowth of corals and ecosystem disruption. This makes Sulu sea unlikely candidate for urea fertilization experiment.

Ocean nourishment and International Law

Iron, urea, or phosphorus fertilization of ocean is thought to be dilemma looking from international law perspective. From one perspective United Nations Framework Convention on Climate Change (UNFCCC 1992) has accepted to make mitigation acts if amount exceeds normal quantity where climate change can adapt. On the other hand international law protects and preserve marine environment from scientific uncertainty. Some commercial companies like Climos and GreenSea Ventures, and Australian based Ocean Nourishment Corporation, are to engage in urea and iron fertilization process. These companies invite green co-sponsors to finance their activities in return for provision of carbon credits to offset investors' CO₂ emissions.

According to David Freestone and Rosemary Rayfuse in June 2007 London convention issued a Statement of concern noting 'the potential for large scale ocean iron fertilization to have negative impacts on the marine environment and human health'. But word 'large scale' was not defined properly. It is believed that large scale would refer to operations on the scale then planned by Planktos. Planktos is USA-based company, recently abandoned its plans to conduct 6 fertilization cruises from 2007 2009, each of which would have dissolved up to 100 t of iron over a 10,000 km² tract of ocean.

UN Intergovernmental Panel on Climate Change has examined the ocean fertilization issue and determined that it should not be pursued because there is very little documented increase in actual long-term sequestration of CO₂ in the deep waters or sediments.

To reduce carbon and greenhouse gas emissions any country should meet UNFCCC and Kyoto Protocol criteria. However Kyoto protocol do not accept any form of carbon sink projects except the forestation and reforestation projects.

Law of sea issues

According to United Nations Convention on the Law of the Sea (LOSC 1982), all states are obliged to take individually and jointly all measures necessary to prevent, reduce and control pollution of the marine environment, to prohibit the transfer, either directly or indirectly, of damage or hazards from one area to another, and to prohibit the transformation of one type pollution to another. Now, without deep research it is not clear to say that fertilization of oceans are safe way to fight against carbon and greenhouse gas emissions.

Solar radiation management

As well as carbon sequestration, ocean fertilization can also be used to create sulfate aerosols which reflect sunlight and modify the Earth's albedo, this creating a cooling effect which reduces some of the effects of climate change. Enhancing the natural sulfur cycle in the Southern Ocean ocean by fertilizing a small portion with iron in order to enhance dimethyl sulfide production and cloud reflectivity achieves this. The goal is to slow Antarctic ice from melting and raising sea level. Such techniques also tend to sequester carbon, but in this specific project the enhancement of cloud albedo was both the desired outcome and measured result.