Risky business: Altering the atmosphere

Recently revisited as a quick fix for global warming, 'geoengineering' could rapidly cool the climate but might also play havoc with the planet. Hannah Hoag reports.

Back in 1992, as representatives from 154 countries gathered in Rio de Janeiro and agreed to keep greenhouse-gas emissions from getting out of hand, a US National Academy of Sciences report on climate change was receiving its final touches. The study was the consequence of congressional action, and drew on the knowledge of more than 50 experts on climate change, its impacts, mitigation and adaptation. About halfway though the nearly 1,000-page report, the mitigation panel considered a risky and uncertain endeavour to counteract climate change: the large-scale engineering of the Earth's environment.

Since then, there has been a steady stream of geoengineering proposals to manage climate change: iron-seeded oceans coaxed to absorb more carbon dioxide; an armour of mirrors for the Earth to reflect the sunlight into space; hazy mists of saltwater sprayed into the atmosphere to increase cloud formation over the oceans; the injection of sulphate aerosols into the troposphere to block incoming solar radiation. Yet most of the proposals — seemingly cribbed from the pages of science fiction — have rested quietly on the fringes of science for years.

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The eruption of Mount Pinatubo in 1991 spewed millions of tons of aerosols into the stratosphere, cooling the Earth.

QUICK FIX

Recently, though, geoengineering has been experiencing a renaissance[1]. Some of the Earth's carbon sinks, such as the Antarctica's Southern Ocean, are losing their ability to soak up carbon dioxide[2], and as these carbon repositories near capacity more quickly than anticipated, technology may become more important in taming climate change. But some climatologists are cautious as they learn more about what will happen in a world that's cooler, but swathed in carbon dioxide.

Injecting sulphur dioxide into the atmosphere has become the most appealing scheme of the lot because it draws on natural phenomena. In 1991, the eruption of Mount Pinatubo spewed about 30 million tons of aerosols into the stratosphere. The tiny particles scattered some of the solar radiation back into space, cooling the Earth. This aerosol veil and its effects are well documented and considered to be a good natural analogue to injecting sulphur aerosols into the atmosphere.

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>
> Damon Matthews

RAPID RESPONSE

Damon Matthews, of Concordia University in Montreal, and Ken Caldeira, of the Carnegie Institution of Washington recently tested whether a man-made version of the event would yield a similar response. Published last month in the *Proceedings of the National Academy of Science*[3], their study, which modelled the climate response to a geoengineered sunshade, found that sulphur aerosols are effective at blocking the sun's rays and allow surface air temperatures to return to values found in the 1900s. The climate response was almost immediate, says Matthews. "If 50 years from now we found that climate warming was much larger than we anticipated, and there was the danger of imminent climate catastrophe, there is the potential for a quick geoengineered cooling to offset the warming," he says.

Today, the ocean and terrestrial sinks each sop up about two billion tons of carbon per year. According to Matthews' and Caldeira's model, fifty years from now, even in the absence of geoengineering, those sinks are expected to double in response to high carbon dioxide levels. As levels increase, more is soaked up by plants (through faster growth), and by the oceans. But the warming that the Earth is experiencing, and that it is projected to experience in the future, counteracts the effect by suppressing the capacity of carbon sinks to sequester CO_2.

Conversely, the temperature drop induced by geoengineering would expand the Earth's carbon sinks to their full potential. In a geoengineered world, the oceans would be cooler and less stratified, says Caldeira, leading to greater carbon uptake. On land, decomposition rates would slow down and more carbon dioxide would accumulate in the terrestrial biosphere. But because neither oceanic nor land-based carbon sinks would be able to soak up carbon dioxide faster than it is emitted, CO_2 levels would continue to rise, hitting around 800 p.p.m.v. by 2100.

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Some of the Earth's major carbon sinks are losing their ability to soak up carbon dioxide.

SERIOUS SIDE EFFECTS

There would be other consequences too in a geoengineered world: acidified oceans and distorted precipitation patterns. Historically, ocean pH has been a slightly basic 8.16. It has crept down by 0.1 units over the last 200 years and may fall by as much as 0.4 units by 2100 if carbon dioxide emissions continue to rise at their current pace. The release of sulphate aerosols into the atmosphere could further increase ocean acidity as the oceanic carbon sink expands.

"There will be huge consequences for the entire marine ecosystem," says Alan Robock, a climatologist at Rutgers University. The decline in pH hampers the ability of marine organisms to build shells and skeletons. Coral reefs may weaken or collapse, and pteropods, oysters, clams and mussels — all creatures with calcium carbonate shells — could be jeopardized, with the risk of changing the biodiversity of the oceans.

Volcanic eruptions show that rainfall patterns across the globe would also be disrupted. Kevin Trenberth, an atmospheric scientist at NCAR, has been reconstructing rainfall and continental runoff patterns following the eruption of Mount Pinatubo in 1991. In the year after the incident, overland precipitation slowed down and the associated runoff and river discharge plummeted[4]. The timing coincided with widespread regions of moderate and severe drought.

> But within about a decade, temperatures return to where they would have been, resulting in very rapid rates of warming.
> Damon Matthews

Other studies of older eruptions show similar patterns. In September, Robock and his colleagues reported that the 1783 eruption of the Icelandic volcano Laki pumped over 100 million tons of sulphur dioxide into the atmosphere and weakened the monsoons in Africa and Asia[5]. Drought and famine soon followed in Egypt. Two other eruptions in the last 2,000 years have produced similar monsoon failure, says Robock.

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Geoengineering could disrupt global rainfall patterns, worsening regional drought.

ABRUPT END

If the potential side effects aren't sufficiently dissuading, the consequences of the abrupt termination or failure of geoengineering schemes just may be. "Within about a decade, temperatures return to where they would have been, and that results in very rapid rates of warming," says Matthews. The terrestrial biomass would begin to decompose and release carbon into the atmosphere, and the warmer oceans would absorb less. The annual temperature rise following failure could be as high as 4 °C per decade — about 20 times the current rate of global warming — and could have severe impacts on humans and the environment.

Among most scientists, cutting greenhouse-gas emissions remains the top choice for reducing global warming. Some say they're not totally against geoengineering, but all admit there are still many more modelling studies to do before it can even be tested.

Hannah Hoag is a freelance science writer.

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Missing carbon mystery: Case solved?

Scientists claim to have located the 'missing carbon sink' in tropical forests that are absorbing around one billion tonnes more carbon than previously thought. Jane Burgermeister investigates.

They looked for it here and they looked for it there, but the carbon had vanished into thin air. So it seemed in the case of the 'missing carbon sink', a billion tonnes of human-generated carbon assumed to be absorbed by northern forests, but unaccounted for in field studies. Scientists now say they have located the missing carbon in tropical forests that are removing much higher quantities of carbon dioxide from the atmosphere than realized.

Of the 8 billion tonnes of carbon that human activity produces each year — 6.4 from fossil-fuel emissions, and 1.6 from deforestation, mainly in the tropics[1] — on average, 3.2 billion tonnes remain in the atmosphere, 2.2 billion tonnes are stored in the oceans and 2.6 billion tonnes are sucked up by land-based carbon sinks, mainly forests. Carbon-uptake models predict that as much as 2.4 billion tonnes of this carbon ends up in northern mid- to high-latitude forests. But scientists searching for it on the ground — measuring trees and carbon exchanges between the vegetation and the atmosphere — have only been able to account for about 0.7 billion tonnes there[2].

AIRCRAFT ANALYSES

Researchers led by Britton Stephens from the National Center for Atmospheric Research in Boulder, Colorado in the USA have now found an answer to this mystery. In a paper published in *Science*[3], they show that tropical forests are absorbing about one billion tonnes more carbon than previously thought and that northern mid-latitude forests are absorbing 0.9 billion tonnes, or 38%, less than assumed up until now. To test how well models represented carbon sinks, Stephens and his team analysed atmospheric CO_2 from aircraft samples collected twice a week at 12 locations worldwide for up to 27 years. They found that CO_2 levels in northern latitudes were much greater at high altitudes relative to surface levels than predicted by carbon models. They then compared their observations with predictions of the vertical gradients in atmospheric CO_2 concentrations made by 12 computer models for atmospheric transport. When it came to estimating which forests are the main terrestrial carbon sinks, most conventional carbon uptake models were off target because they did not sufficiently account for vertical mixing of CO_2 through the atmosphere as a result of convection and storm systems. Of the 12, three models accurately represented the measured vertical gradient in CO_2 at high altitudes. On average, these three selected models predicted that tropical forests take up much more carbon than previously thought, whereas the opposite was true for forests in the northern latitudes.

> Cutting down tropical forests not only increases carbon emissions but it also removes a strong sink and its potential for offsetting future emissions.
> Britton Stephens

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Tropical forests could be absorbing as much as one billion tonnes more carbon than previously realized.

FERTILIZATION FACTOR

Despite rapid deforestation, Stephen's team also showed that tropical forests are the net source of a mere 100 million tonnes of carbon annually, contrary to previous estimates of 1.8 billion tonnes. This suggests that carbon sequestration in the tropics is substantial enough to almost counterbalance the effects of deforestation. Stephens says "tropical forests are essentially in balance, absorbing as much carbon dioxide as they give off". One reason tropical forests could be absorbing substantially more carbon dioxide than accounted for in the models is the phenomenon known as CO_2 fertilization. Trees take in carbon dioxide to grow and when there is more of it they tend to grow faster, being fertilized by carbon dioxide. Also, as temperatures increase with climate

Airborne over Colorado.

change, soil organic matter decomposes more quickly, freeing up nutrients in the ground for forest growth.

Temperate and boreal forests are also being fertilized indirectly by nitrogen, largely from farming and fuel use, according to a study recently published a study in *Nature*[4], led by Federico Magnani from the University of Bologna. The study suggests that this is contributing to the carbon sink in northern latitudes, but Magnani says the same could not be true for tropical forests, where phosphorous and not nitrogen determines growth. He says that to understand what is happening in the tropics “we need to know how much of the carbon sink is the result of vegetation regrowth following deforestation, and how much of it comes from substantial carbon sequestration by primary forests”. Manuel Gloor of the University of Leeds, UK, also argues that we need more information before any assertions on the whereabouts of the missing carbon sink can be confirmed. “To really settle the question regarding tropical versus northern hemisphere carbon sinks, a substantial amount of atmospheric concentration data over tropical land will be needed”, he says.

ALBEDO EFFECT

Other scientists have also recently come to the conclusion that northern forests, although critically important in maintaining biodiversity, might be less important in slowing climate change than tropical forests. Govindasamy Bala and Ken Caldeira found that tropical forests help cool the Earth in two ways: by storing carbon and also by reflecting the suns warming rays back to space[5]. “Unlike tropical forests, high latitude forests darken the Earth’s surface, causing the earth to absorb more sunlight, an effect that is most pronounced in snowy regions. This darkening of the surface has a warming influence that can be stronger than the cooling influence of carbon storage in these forests,” says Caldeira. This suggests that removing high-latitude forests would have a net cooling effect on the planet, whereas removal of tropical forests would result in warming.

ULTIMATELY ACADEMIC?

Tropical forests are, however, rapidly disappearing. Forests in South America, Central Africa and South-East Asia are being cleared for cropland or cattle pasture, and reduced by the expansion of logging and changing patterns of cultivation. The latest IPCC report on mitigating climate change[6] found that during 2004, the contribution of deforestation — primarily in the tropics — and the decay of biomass to global warming was 17.3% of total global greenhouse-gas emissions. “Cutting down tropical forests not only increases carbon emissions but it also removes a strong sink and its potential for offsetting future emissions,” says Stephens.

Whether tropical or northern forests store more carbon might ultimately be academic, though, when it comes to mitigating climate change. Stephens believes that “relying on trees to mitigate climate change is not a good long-term strategy, because the carbon they store gets returned to the atmosphere on a timescale of around 30 years when they die and decompose. Afforestation and reforestation can provide short-term sinks to slow warming and possibly give us more time to find solutions, but ultimately we need to get the carbon into the ocean or geologic reservoirs, or not emit it in the first place”.

Jane Burgermeister is a freelance science writer.

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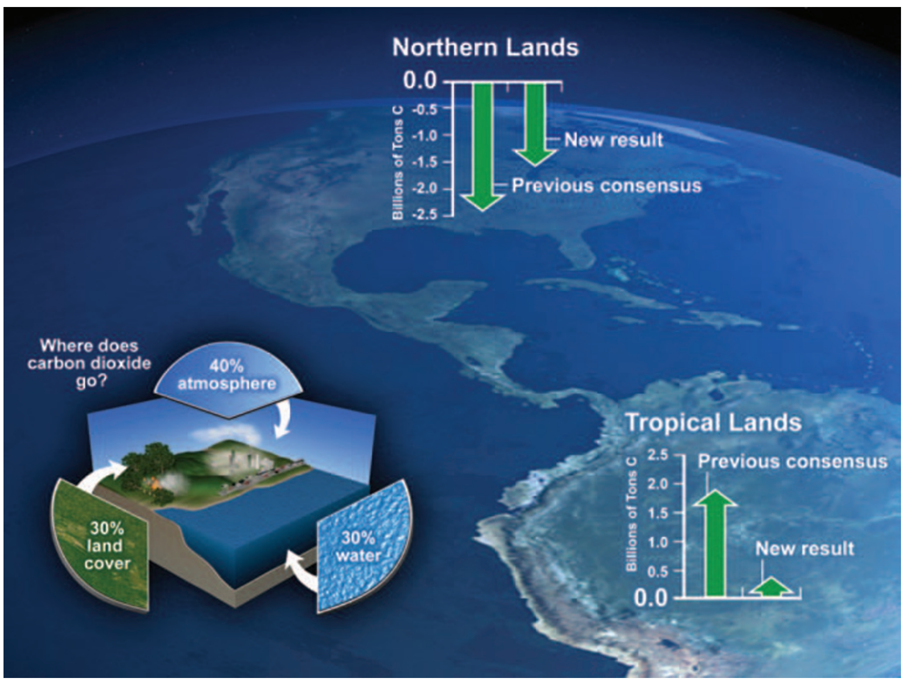

Locating the ‘missing carbon sink’ in the tropics has implications for the entire global carbon cycle.

Not as pure as snow

DAN WHIPPLE

Wind-blown dust from the Southwest US is shortening seasonal snow cover in Colorado's ski resorts.

Snow cover, it appears, is not as pure as the driven snow. A recent paper in *Geophysical Research Letters*[1] found that dust blown up from the Colorado Plateau in the American Southwest is accelerating snowmelt hundreds of miles away in the San Juan Mountains.

An earlier snowmelt is not just a cosmetic issue in the American West, where the ski industry is an irreplaceable attraction for tourists. Snowpack provides late season water supplies for irrigation, livestock watering and for the millions inhabiting cities such as Los Angeles, Phoenix and Denver.

Now, Tom Painter, of the University of Colorado's Snow and Ice Data Center and colleagues have found that snowmelt can occur almost a month earlier than usual under dry conditions as a result of dust blown in from the Four Corners area of Colorado, Arizona, Utah and New Mexico. Previous studies have shown that dust absorbs solar radiation and increases snowmelt[2], but this is the first to quantify dust cover and rates of melt *in situ*.

The Colorado Mountains, where the ski industry is an irreplaceable attraction for tourists.

> There will be a drying and warming in the southwest United States. This leads us to think that we may get greater dust emissions in the future.
>
> Tom Painter

SNOWBALL EFFECT

Snow has the highest albedo, or reflectivity, of any naturally occurring surface on earth. The albedo of pure white snow is 0.92, meaning that it reflects back into the atmosphere roughly 92% of the energy it receives. As the snow extent declines, the earth absorbs more heat, rather than reflecting it back into space, which in turn speeds melting.

Painter's group measured 2005–2006 snowmelt at two locations in the San Juan mountains — one alpine and one subalpine — and compared the observed dates of melting with predictions of the aptly named snow energy balance model, or SNOBAL. The researchers found that snow albedo dropped dramatically in two periods of the winter and spring of 2005 from 0.85 to 0.45 in the subalpine region and to 0.51 in the alpine region. There were similar, though smaller, declines in albedo in the 2006 season. "Snowmelt simulations indicate that in 2005 the subalpine snow melted out 22 to 32 days earlier and alpine snow cover melted out 23 to 33 days earlier than dust free snow," say the authors. There was less snow in 2006, with the effect that snow cover melted even faster under the influence of the dust events.

WEAKEST LINK

David Robinson, a climatologist with New Jersey's Rutgers University who has worked extensively on snow cover says of the influence of dust, "theoretically, it makes some sense, but observationally, that's going to be next to impossible to prove. We've seen some snowpacks darken, and the models suggest there may be some impacts, but the observation of soot, dust and dirt on snow is probably the weakest link." He notes that consistent measurements of surface albedo over large areas are lacking.

Nonetheless, Robinson says, there has been an undeniable reduction of snow cover in the northern hemisphere over the last 45 years or so. According to satellite and station observations, the extent of snow cover in the spring has declined quite significantly. There was a marked reduction in spring snow extent in the mid-1980s and it's stayed low since then, he says. During that period, snow cover decreased by about two million square kilometres, from an average of about 31.5 million to 29.5 million square kilometres. But Robinson maintains that the reasons for the reduced snow cover are uncertain. "We don't understand that completely at this point."

Estimates of how much dust results from human activities vary widely, according to the latest report[3] on the science of global warming from the Intergovernmental Panel on Climate Change. But all of the global climate models, Painter says, "show that there will be a drying and warming in the southwest United States. This leads us to think that we may get greater dust emissions in the future". Painter and colleagues say that "the phenomenon of increasing dust emissions exists beyond the western US and is global in nature". In China, for instance, the frequency of large dust storms from the Taklimakan and Gobi deserts was one event every 35 years prior to 1949. But after 1990, the events were occurring annually. Increased dust emissions are evident in Tibet and drying of the Aral Sea region has increased dust deposition in the Tien Shan, Pamir, Himalaya and Altai mountains, says Painter. In a report presented to the UN in June[4], experts from the United Nations University said that desertification, exacerbated by climate change, represents "the greatest environmental challenge of our times".

DRIER, NOT DUSTIER

Not all lines of evidence are pointing at greater amounts of dust in the atmosphere, however, even under a warming regime. Natalie Mahowald, meteorologist at the National Center for Atmospheric Research in Boulder, Colorado, recently co-authored a paper in *Atmospheric Chemistry and Physics*[5] that examines global changes in visibility resulting from dust emissions. For the Aral Sea region, one of their study sites, she says "even thought it's gotten much drier, it's not clear it's gotten much dustier".

> Even thought it's gotten much drier, it's not clear it's gotten much dustier.
>
> Natalie Mahowald

Mahowald maintains that it's possible, because of increased fertilization from carbon dioxide emissions, that plants will adapt rapidly to climate change, dealing better with water stress. This increase in plant vitality could result in more vegetation, thus retaining more soil and actually reducing the amount of dust. But the likely future impact of CO_2 fertilization remains an open question. "What we'd really like to be able to say is, 'What have humans done so far?'" Mahowald says. "But people don't tend to live in desert areas, and they don't happen to leave really good records."

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