Gaia's comeback: How life shapes the weather

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The world would be warming even faster if forests weren't calling in the clouds. Could it be that Gaia is not be so helpless after all?

YOU'VE done it half a dozen times today without giving it a second thought. If it was chilly in the morning, you may have turned up the heating or put on another layer. As the day got warmer perhaps you opened a window to cool things down. We are adept at controlling our immediate environment.

What about the living planet as a whole? Can the biosphere regulate the environment to suit itself, preventing the planet from freezing or boiling? This is the essence of the Gaia hypothesis proposed in the 1960s by James Lovelock, but climate scientists have never bought into it. They point out that there have been some wild swings in the climate, some of which were caused by life.

But now it appears the world would have warmed a bit more than it has were it not for the aromatic cocktail of chemicals emitted by plants. It turns out this can change the weather – and anything that changes the weather day after day and year after year changes the climate, too. While this new mechanism is nowhere near strong enough to save us from global warming, it may have been stronger in the past when the air was cleaner. So could it be that Gaia is not powerless after all?

There is no doubt that life plays many key roles in the climate system. The air we breathe, rich in oxygen with only traces of carbon dioxide, is created by plants. Trees suck up huge quantities of rainwater that would otherwise flow back into the sea, and release it into the air. Much of the rain in the Amazon may come from the trees themselves.

There are all kinds of other effects. Bacteria have been found growing in clouds, and they may help seed cloud formation. Blooms of plankton in the sea soak up the sun's heat, warming the surface. The list goes on and on.

The question is, how important are these processes? In particular, is life totally at the mercy of external influences such as the sun, or can it control the climate to some extent? Lovelock's suggestion was that living organisms work in concert with nonbiological processes to regulate the environment. He pointed out that over the past 4 billion years the sun has become brighter, and yet the long-term temperature of Earth has remained suitable for life. Life might act as a planetary thermostat, Lovelock said, as well as maintaining the salinity of the oceans and other chemical balances.

To this day, Lovelock regards Gaia's existence as self-evident. "Earth's atmosphere is so massively in chemical disequilibrium, for it to stay stable for any time requires a very powerful regulating system," he says. But even if life does help control the composition of the air and seas, its ability to regulate temperature is much more dubious.

We know now that there have been some violent swings in the climate, including a few "Snowball Earth" phases during which most of the planet froze, almost wiping out life. These super ice ages may well have been triggered by living organisms sucking the carbon dioxide out of the atmosphere and cooling the planet.

It is now thought Earth was saved from an icy doom by a geological thermostat. When the planet gets hot, rocks break down faster, reacting with CO_2 and removing it from the atmosphere. When it cools, this weathering process slows down, and the CO_2 emitted by volcanoes begins to accumulate in the air.

Gaia revisited

This negative feedback keeps temperatures within the "just right" Goldilocks zone, but it takes many millions of years to kick in, which still leaves room for the living part of Gaia to step up. Perhaps life usually helps prevent swings on a shorter timescale, even if things do go catastrophically wrong on occasion? What would make the idea more convincing is a clear-cut mechanism. When the temperature starts to get too high or too low, then living organisms should respond in some way to move it in the opposite direction, back towards a happy medium.

In 1987 Lovelock and others proposed one such mechanism. They pointed out that algae in the sea emit a gas called dimethyl sulphide, which can react with air to form sulphuric acid vapour and condense into small particles, or aerosols. Such aerosols can cool the planet by reflecting sunlight directly and also indirectly by making clouds whiter.

Cloud formation requires more than just cooling moist air. Water droplets do not form and grow unless the air has suitable particles, or nuclei, for the water to condense onto. These nuclei must be upwards of 100 nanometres or so in size. The sulphuric acid aerosols from dimethyl sulphide could be just the ticket if they grow large enough. When temperatures rise, the group reasoned, algae should thrive and emit more dimethyl sulphide, seeding more cloud droplets. More droplets means whiter clouds, which reflect more sunlight and cool things down, completing the negative feedback loop.

This idea, called the CLAW hypothesis after the initials of its four authors, inspired a lot of research – but it appears to be feeble at best. Observations show that as much as 60 per cent of the cloud condensation nuclei above the oceans are provided by salt spray, and most of the rest are solid organic compounds also sprayed directly from the sea surface. That leaves little room for the involvement of sulphate aerosols, as Patricia Quinn and Timothy Bates of the Pacific Marine Environmental Laboratory in Seattle pointed out in a 2011 review (*Nature*, vol 480, p 51).

Another stage in the proposed feedback loop is also doubtful. "People go out on ships and incubate algae to look at their response to an increase in temperature or radiation," says Quinn. The algae do emit more dimethyl sulphide when the sea warms up, but only slightly; not enough to whitewash the sky.

So the CLAW effect seems too weak to pull Earth's climate levers. Maybe that job can be done by a green tendril instead. In 2004 Markku Kulmala at the University of Helsinki suggested a new feedback loop. In a pine forest in southern Finland, he and his team had been measuring the concentration of a group of chemicals called terpenes. Terpenes are produced by many plants and they evaporate readily into the air – they are volatile, in other words. We perceive terpenes as part of that pleasant smell of pine forests, and they are the main constituents of genuine turpentine distilled from pine resin.

As they float about in the air, terpene molecules and other volatile organic compounds become oxidised, making them less volatile. They then condense onto any tiny aerosol particles already in the air, making them larger. That means more aerosols grow to a given size. Over several years, Kulmala's group monitored terpenes and the number of aerosol particles about 3 nanometres across above a Scots pine forest in Finland. They found a strong correlation between the two, with both peaking in summer when plants are growing most vigorously. This led Kulmala to suggest that if the climate warms, plants might emit even more volatiles and make more planet-cooling aerosols – a negative feedback that would counteract the warming.

But this was only an educated guess. Kulmala's studies did not show that forests emit more volatiles as the temperature rises. Nor did it show whether the aerosol particles could grow large enough for them to seed cloud droplets – at least 100 nanometres across. And the data came from just one site – hardly evidence of a worldwide phenomenon.

Meanwhile, far from the forests of Finland, Jasper Kirkby and his team were busy making clouds in a large stainless steel chamber at the CERN particle physics laboratory near Geneva, Switzerland. In some of the experiments, the CERN team tried to recreate the first step in cloud formation: how gases condense to form embryonic aerosol particles. "If you look to the mountains one day after a rainstorm has cleansed the atmosphere, there is already a blue haze. Those are new aerosol particles that have formed from trace gases, scattering light into your eye," says Kirkby. New particles require sulphuric acid vapour to form. That comes from sulphur dioxide, a by-product of human industry as well as those marine algae.

Stick'em together

It had been thought that sulphuric acid vapour could condense on its own, but the results of Kirkby's studies, released in 2011, proved otherwise. A few molecules might stick together, but these embryonic aerosols are unstable. They almost always evaporate instead of growing larger.

When the team added traces of ammonia to the air, however, it stabilised the growing sulphuric acid cluster, increasing the number of viable aerosol particles by as much as 1000 times. Yet this is still just a thousandth of the formation rate of sulphuric acid aerosols actually seen in our atmosphere, so something else must be stabilising their growth.

"After we ruled out ammonia, the only other possibility was organic compounds," says Kirkby. "We have now made a series of measurements with several different organics." Those results are under review, so Kirkby will not comment further except to say that they are "very interesting" and due out later this year.

Nevertheless, his team's published work suggests that volatile organic compounds could have a huge influence on clouds by helping sulphate aerosols to form in the first place, in addition to making existing aerosol particles grow larger.

And volatile organic compounds could influence clouds in a third way, according to Gordon McFiggans's team at the University of Manchester, UK. As cloud-condensation nuclei collect water and grow into a droplet, volatiles are absorbed along with the water, changing the chemistry of the drop to attract more water. In May this year, the team published a paper showing that this effect might substantially increase the number of droplets (*Nature Geoscience*, vol 6, p 443). And a cloud with more droplets per cubic metre is a whiter, fluffier cloud, reflecting more solar heat away from the Earth.

McFiggans is now starting experiments in Manchester to try to find out more. "We have a new photochemical chamber where we can process an atmospheric soup of gases, hit it with an arc lamp to mimic sunlight and cook up an aerosol population, then squirt it into a cloud chamber," he says. "Then we should see if we get denser clouds in the presence of organic vapours."

So several lines of evidence suggest organic compounds might have a big effect on clouds (see diagram). The clincher comes from a study involving 11 weather stations around the planet. A team including Kulmala and led by Pauli Paasonen, also at Helsinki, sampled aerosols at these stations, counting the concentration of particles large enough to form a cloud droplet. They also monitored levels of a range of volatile organic compounds.

In April, the team reported that they had found a strong pattern (*Nature Geoscience*, vol 6, p 438). In places such as Finland and eastern Siberia, where the air is clean, the number of cloud condensation nuclei rose markedly when the temperature went up. Paasonen calculates that over these unpolluted regions, the cooling effect could be powerful, offsetting up to a third of any local temperature rise. This might be enough to protect some forested areas from the worst climate swings.

"But in more polluted areas, the feedback is not significant," says Paasonen. That makes sense, as in these spots there is already a dense haze of aerosols. The volatiles would make those particles slightly larger but have little affect on the overall number.

Curiously, terpenes are thought to be involved in protecting individual plants from heat stress, because their release is so strongly linked to temperature. So it seems a strange coincidence that collectively they might act to cool an entire region. "It's as if we could cool the weather by sweating," says Paasonen. "That would be useful!"

Lovelock thinks it could be an evolutionary adaptation, as organisms that can regulate their climate should boost their survival. "If successful, they will spread," he says.

Globally, this cooling power of plants may not be so profound. Paasonen estimates that the feedback should offset around 1 per cent of global warming, although there is a huge uncertainty because the full effect on clouds is not well understood, and its global importance will not be clear until more sites have been studied. The true figure could be as high as 5 or 10 per cent, or much less than 1 per cent.

"It does not save us, that's for certain," says Paasonen. Nor will it be easy to indulge in a little geoengineering to boost this effect by planting certain kinds of plants, as his results suggest that the effect is just as strong over farmland as over virgin forest. But once upon a time, before human pollution overwhelmed this feedback in many parts of the world, it could have been more powerful. "One thing the authors don't go into is deep prehistory," says Tim Lenton of the University of Exeter, UK. "When land plants first evolved, this could have had a significant cooling effect."

And there may be other feedbacks working in the same direction. "When you add them up it begins to amount to something," says Lovelock. For example, volatiles may play a role at sea as well as over land, says Quinn. Salt spray is still likely to be the dominant source of cloud nuclei, but organic vapours could condense onto small salt particles to boost them to an effective size. A few teams have made observations at sea, but it is difficult to get the kind of long-term coverage that enabled Paasonen to spot the feedback on land.

So in a small way at least, Gaia can influence the temperature. Unfortunately, not only have we poisoned her and sapped her power, we have also unleashed her evil twin. As the Arctic warms, vegetation is starting to replace snow and ice, and dark vegetation soaks up more of the sun's heat – a positive feedback that is accelerating the warming in the Arctic. According to a study out earlier this year, this feedback is much stronger than previously thought (*Nature Climate Change*, doi.org/k27).

It is not clear how all this stacks up. The positive feedbacks involving living organisms may well outweigh the negative ones, undermining the notion of life making a cosy nest for itself. And even if Gaia turns out to have more power than we realised, we cannot rely on her helping hand – we still to have to save ourselves.

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