A silver lining to ARCTIC CLOUDS?

The relentless increase in summer sea-ice melt is likely to amplify Arctic warming. But could the same conditions also spur the activity of marine microbiota, increase cloudiness and counteract the melting? **Paty Matrai** and **Caroline Leck** explore.

Kevin Arrigo and colleagues reported recently in *Science* that in July last year, phytoplankton had bloomed strongly beneath Arctic pack ice of the Chukchi Sea. So lush was the bloom that Paula Bontempi, NASA's Ocean Biology and Biogeochemistry Program Manager, likened it to finding the "Amazon rainforest in the middle of the Mojave Desert." Like any plant, the unicellular marine phytoplankton need light to thrive. Old, thick sea ice, especially when covered with snow, is opaque but thinner ice underlying melt ponds is more transparent, and it is under such ice that the blooms reported by Arrigo *et al.* occurred. We know such blooms have occurred before: but, as the Arctic continues to warm faster than any other region on Earth, we can expect them more frequently. In fact, phytoplankton and other marine micro-organisms could ultimately help counter the rapid warming. To find out how, we will need to stick our heads into the Arctic clouds.

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The ever-shrinking area of summer sea ice is one of the most visible manifestations of Arctic climate change. This summer, ice cover melted to its lowest extent in the satellite record, breaking the previous record low observed in 2007. If this trend continues, the region is likely to witness ice-free summers in the near future. Sea ice reflects incoming solar radiation, but the open ocean absorbs and stores solar radiation during the summer. Later, during the autumn, this heat is released and further warms the atmosphere. As more ocean is exposed, a positive feedback loop develops accelerating summer sea-ice melt – attested to by observations in the past decade.

But low-level clouds, which also control the Arctic surface radiation balance, could potentially slow down or even reverse the warming. For most of the summer, such clouds tend to warm the surface. But during the peak-melt season at the end of the summer, the right type of low-level clouds (see Box) could cool the surface and thereby influence the timing of the autumn freeze-up. Earlier freeze-up will cause thicker ice that might melt less during the following summer, surviving into the subsequent winter. If such a process were to recur over several years, it could delay or even prevent sea ice from melting completely during the Arctic summer. In other words, it would constitute a negative feedback.

What are the odds of a negative feedback loop developing? To answer this question we need to know, among other things, what controls the optical properties of Arctic low-level clouds and how they would change in a warming climate. The Arctic's inaccessibility ensures that data remain sparse, and our understanding of the complex relationship between the clouds, sea ice, ocean and atmosphere is still evolving. But the situation is improving. In particular, we are beginning to get a handle on the sources of the small atmospheric particles – cloud condensation nuclei (CCN; see Box) – that eventually spawn clouds. We now know that the greatest number comes from marine micro-organisms (Leck and Bigg 2005a; Orellana *et al.* 2011). How such organisms respond to the melting sea ice, whether in ways reported by Arrigo *et al.* or in other ways, will thus strongly


Marine microbiota in the
icy Arctic Ocean hold the
key to cloud formation.

influence cloud formation and their optical properties, and perhaps the rate of future melting.

Seeding clouds with microgels

Marine microbial food webs produce a gas called dimethyl sulphide (DMS), which is released to the atmosphere from the uppermost ocean. There, it oxidises to form various intermediate products and ultimately sulphate particles. In 1987, Robert J Charlson and colleagues reviewed existing evidence to implicate DMS in the production of oceanic CCN. Thus was born the CLAW hypothesis, named so informally after the paper's authors (Charlson, Lovelock, Andreae and Warren). This provocative hypothesis posits that in the marine realm, DMS emissions would trigger cloud formation, which would cool the ocean surface. This would in turn affect further emissions of DMS by changing the speciation/abundance of marine phytoplankton, leading to a feedback loop.

Observations in the early 1990s from the Arctic did indeed show that the intermediate oxidation products provided most of the mass for the CCN-sized particles observed over pack ice (Leck and Persson 1996). The source of most of the DMS, though, was at the fringe of the central Arctic Ocean, just around the hospitable edges of the pack ice. At that time, this suggested that winds carried DMS-rich air towards the North Pole, and oxidation of the DMS led to extremely small sulphuric acid particles. Theoretically, these particles would then grow slowly by further condensation of the acids until they were large enough to serve as CCN.

Surprisingly, it turns out, sulphuric acid had nothing to do with the small precursors of CCN. Observations from the Arctic in the mid-1990s instead showed that these small precursors are mostly five or six-sided insoluble solids (polymers) resembling viruses or microcolloids. Subsequently, researchers detected large numbers of similar particles within the thin surface film at the water-air interface between ice floes. These are often aggregated into <100-nanometre-diameter compact balls, assembled as microgels bound by calcium atoms. The microgels are networks of polymer filaments, only a few nanometres in size, made up of polysaccharides or sugars. In 2011, researchers confirmed that the particles found in the atmosphere behave as microgels and originate in the water (Orellana *et al.* 2011) from the activity of sea-ice algae, phytoplankton and, perhaps, bacteria.

Microgels have the right properties to act as nuclei for clouds.

Across the central Arctic Ocean, the ubiquitous diatoms *Melosira arctica* and *Fragilaryopsis cylindrus* are known for surrounding their cells with polymeric substances, suggesting an important role for them in the production of polymers. Microgels have the right properties to act as nuclei for clouds. Furthermore, they could also provide sites for condensation of the oxidation products of DMS. In 2005, Leck and Bigg tested predominantly airborne sulphate particles for the presence of microgels. They detected water-insoluble marine microgel material in half or more of their samples. The co-occurrence of atmospheric organic material and biologically active marine waters has been confirmed for the high Arctic waters, and has also been documented for temperate waters (Faccini *et al.* 2008, Russell *et al.* 2010). But the universality of such microgels, both in the coastal and open-water regions of the Arctic Ocean and at lower latitude oceans, has not yet been confirmed.

Beyond the CLAW

Observations from the Arctic question the key role attributed to DMS in the CLAW hypothesis (Leck and Bigg 2007). In the emerging picture of the Arctic atmosphere, DMS concentration will determine the mass of the particles by producing material for their growth. But it is the

Getting the clouds right

Clouds, which come in all shapes and sizes, form when water vapour condenses. But vapour needs something to condense on – tiny airborne aerosol particles known as cloud condensation nuclei (CCN). Typically, CCN are about 100 nanometres in diameter. Depending on their properties and heights, clouds can either warm the surface by triggering a localised greenhouse effect or cool it by reflecting solar radiation.

If CCN are scarce, the resulting clouds will contain fewer and larger droplets. Such clouds will reflect little sunlight to space while blocking the escape of heat from Earth's surface, causing it to warm. However, if CCN are plentiful, many fine droplets form and the resultant clouds are better reflectors, which can cool the surface below.

Anthropogenic particles are virtually absent in the summer over the central Arctic, north of latitude 80°N. This "clean" air, with few CCN, makes the summer low-level clouds optically thin, with fewer but larger droplets: a heat trap. But if Arctic warming spurs the activity of microbiota, organic sources of CCN might become more prominent and lead to more reflecting clouds.

number of airborne microgels that will primarily influence the number of CCN and the resulting optical properties of the cloud droplets. Indeed, research during the past two decades – reviewed last year in *Nature* (Quinn and Bates 2011) – does not corroborate the CLAW hypothesis for other regions as well. But this does not rule out a link between marine micro-organisms and climate, especially on a regional scale. From that perspective, the Arctic observations discussed here could provide a more nuanced link between marine biology, cloud properties and climate.

The Arctic low-level clouds have a pronounced influence on the surface energy budget. In summer, a scarcity of CCN leads to optically thin clouds. The sources of these CCN are mostly located along the marginal ice zone and north thereof towards the pole. Marine micro-organisms are the primary contributors to CCN, and hence an important control on the optical properties. Their response to the changing Arctic climate is thus key to a possible negative feedback that would slow down the melting of summer sea ice. We know that the immobile ice algae as well as the floating phytoplankton are likely to be strongly affected by changing sea-ice conditions (Wassman and Reigstad 2011). But whereas both generate dissolved organic matter and are hence a potential source of airborne microgels, their relative importance is not fully understood.

The recent report of a sub-ice phytoplankton bloom by Arrigo and colleagues, in conjunction with previous and current observations, strongly suggest increased activity as the Arctic warms. If they are found to be a strong contributor of microgels, phytoplankton might facilitate an enhanced reflectivity of the low-level clouds that help counteract increased ice melt.

The melting of sea ice might reduce or even eliminate the habitat of ice algae. And it might have indirect effects. The presence of sea ice has prevented, or significantly controlled, wind-driven mixing of the surface layer of the Arctic Ocean. This has kept the floating phytoplankton mostly at the surface. Thinner ice or more open ocean areas would allow the wind to stir the surface ocean, deepen or break the mixed layer, thereby reducing algal growth. If organic matter derived from ice algae was confirmed to be a major source of the microgels throughout the Arctic, future warming might imply reduced supply of CCN and thus very optically thin clouds with enhanced surface warming. On the other hand, ice formation during freeze-up excludes salt brine and other substances, including dissolved organic matter likely assembled as gels. These gels can end up in both the surrounding water and the atmosphere during this crucial period.

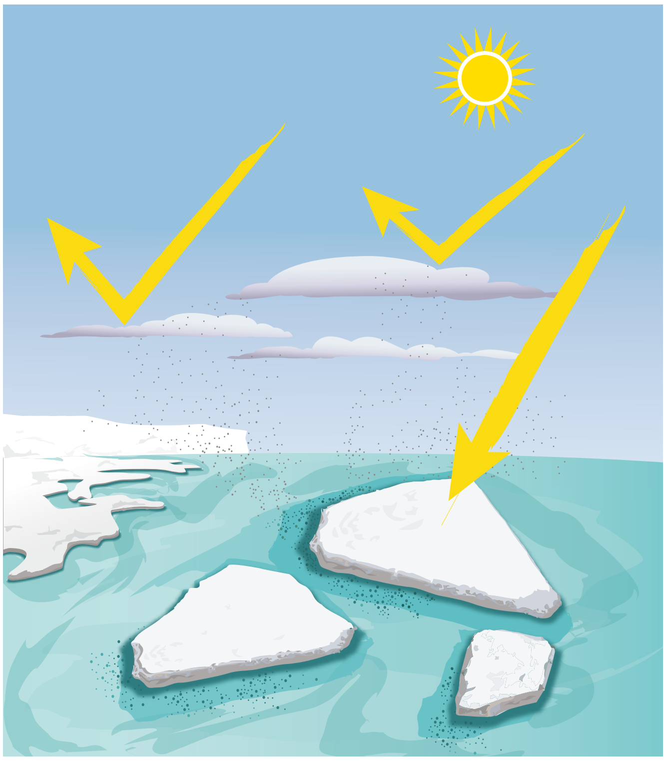

Figure 1. Schematic sketch (not to scale) depicting the negative feedback. Melting sea ice spurs the activity of marine microbiota, thereby increasing the availability of the polymeric sugar precursors (grey dots) of CCN. The low-level clouds thus formed reflect some of the incoming solar radiation and cause surface cooling. This process can hasten the autumn freeze-up.

But this does not rule out a link between marine micro-organisms and climate.

Clearly, there are too many unknowns at this stage to fully assess the likelihood of a negative feedback involving micro-organisms and clouds. But given how sensitive the Arctic is to climate change and how important it is for the regional and global radiation balance, there is a strong rationale for continued research to test this hypothesis. ▮

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