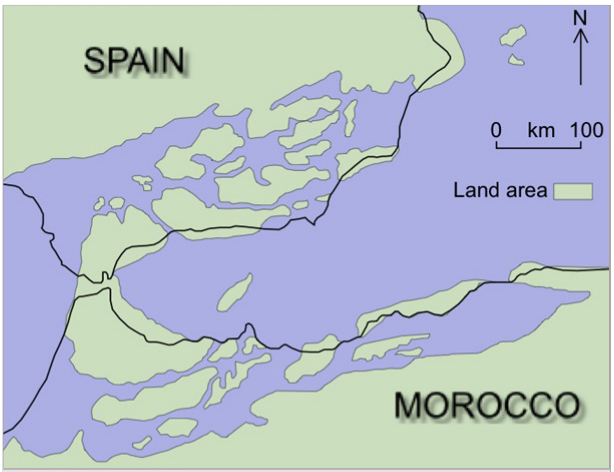
A small sea at large: Mediterranean controls on global climate

In the late 1990s, R. G. Johnson noted that the Aswan Dam on the river Nile was causing the Mediterranean Sea to become more saline. He suggested far-reaching implications for global climate, including the formation of a new ice sheet in Canada – all because of the saltier water flowing from the Mediterranean into the Atlantic. In fact, he went so far as to propose a dam across the Strait of Gibraltar to stop this from happening.

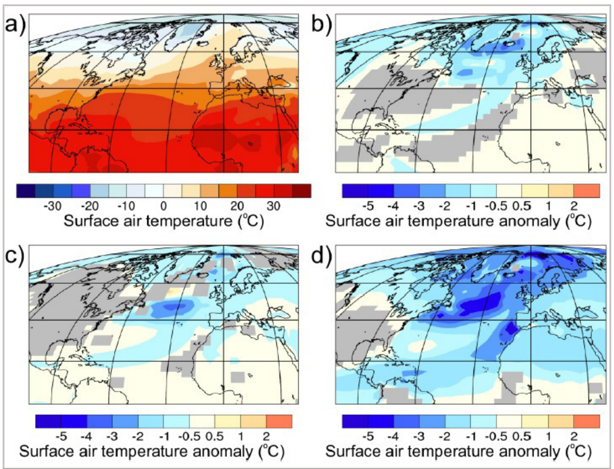
Oceans form an integral part of the global carbon cycle and also serve as a major heat sink – clearly, they play a pivotal role in the global climate system. But can a change in the salinity of a small sea such as the Mediterranean really bring about climatic change on a global scale?

Models of the present day suggest that this is indeed possible. Relatively warm, saline (and therefore dense) Mediterranean outflow water enters the Atlantic at depth and strengthens the deep-ocean part of the thermohaline circulation, the 'global conveyor belt' of currents that move water around the world. The long timescales (centuries) on which the thermohaline circulation changes, however, mean that past events may yield useful insights about potential consequences of fluctuations in Mediterranean outflow water.

Ruza Ivanovic and her team have investigated a particularly pertinent case study of how changes in the Mediterranean have driven global climate in the past. During the so-called Messinian Salinity Crisis (MSC) between 5.96 and 5.33 million years ago, sediments show that the Mediterranean Sea underwent severe fluctuations in temperature and salinity. It may even have dried up completely at several points during this period! The team use a sophisticated general circulation model (GCM) to simulate changes in Mediterranean outflow water into the Atlantic and their global-scale climatic impact during the MSC. The results are published in Climate of the Past.



The Messinian Salinity Crisis is thought to have been caused by extreme restriction of the exchange between the Mediterranean and the Atlantic. The black lines show the present-day Strait of Gibraltar as delineated by the coasts of Spain and Morocco. During the salinity crisis, the green land areas limited flow. (Credit: Ivanovic)



Surface air temperatures during the initial steady state are shown here in panel a). Panels b) and c) show changes relative to this steady state in two different scenarios with elevated Mediterranean salinity levels, while panel d) shows what happens if the Mediterranean freshens. (Credit: Ivanovic et al., 2014)

Ivanovic and her colleagues had to calibrate their GCM to simulate what Earth was like over 5 million years ago. Back then, our planet was warmer and wetter on average and the Himalayas and Rocky Mountains were lower, so the distribution of vegetation – an important carbon sink – was different. The Antarctic and Greenland ice sheets were smaller than they are today, so sea levels were 25 m higher. Finally, the Central American Seaway between North and South America was still open and the thermohaline circulation was weaker. All these changes mean that fluctuations in the Mediterranean had a greater impact on global climate back then than they would today.

The researchers first ran their 'Messinian' GCM for a period of 2,400 years to allow a steady state to emerge. From this steady state, they simulated several different extreme scenarios of Mediterranean hypersalinity, freshening (becoming less saline) and different outflow strengths, and compared their outcomes to a control scenario with no changes.

Ivanovic and her team found that if the Mediterranean were to dry up so that no water enters the Atlantic, the Labrador Sea east of Newfoundland would become warmer, raising temperatures across Canada. In the Messinian, then, damming the Mediterranean as Johnson proposed would indeed have prevented the formation of a new Canadian ice sheet.

Increasing Mediterranean salinity (and therefore increasing density) produces marked cooling in the north Atlantic and over Canada, Greenland and Europe. Dense, deep water normally flowing south from the far northern Atlantic is essentially replaced by Mediterranean outflow water so that the northern latitudes remain cooler.

Conversely, a freshening Mediterranean becomes less dense than the Atlantic, meaning that water flows into the ocean at the surface rather than at depth. The entire Atlantic water column freshens, with extreme and widespread consequences. The thermohaline circulation breaks down completely in the Atlantic, so warm, tropical water no longer reaches higher latitudes. Cool, fresh water even spreads into the Pacific through the Central American Seaway. As a result, the entire northern hemisphere cools by as much as 8 °C. On the other hand, parts of the southern hemisphere experience some warming because cold, north Atlantic water is no longer transported south.

The Earth was a very different place during the MSC than it is now, so naturally the results Ivanovic and her colleagues obtained differ from studies looking at present-day climate. Then as now, however, it is clear that R. G. Johnson was not exaggerating when he claimed that the Mediterranean could wreak havoc with global climate. It remains to be hoped that potential far-reaching impacts are considered when planning future mega-projects like the Aswan Dam.

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Local flaring, global impacts: modelling Arctic black carbon

Although most of the Earth's population isn't aware of it, the Arctic is burning. The flames are being fed by natural gas produced as a by-product of crude oil extraction, which is then flared away at the surface. Although practiced worldwide, high-latitude gas flaring has the greatest impact on the fragile Arctic environment. Since the black carbon emissions resulting from flaring know no national boundaries, only a global solution will bring about results to improve conditions in the Arctic.

The flaring of natural gas impacts the Arctic (Credit: Fabien Darrouzet, distributed via imaggeo.egu.eu)

Modelling black carbon

Black carbon (soot) and other combustion emissions from flared natural gas are released into the Earth's atmosphere where they move in patterns that atmospheric scientists try to model. However, standard models have trouble predicting the patterns of black carbon transport into the Arctic. This has been confirmed by Andreas Stohl of the Norwegian Institute for Air Research and his collaborators. According to their research, published in Atmospheric Chemistry and Physics, the atmospheric concentration of black carbon found in the Arctic is underestimated by all existing models.

What makes the Arctic atmosphere so difficult to model? It is a combination of factors, including the complex seasonal changes that occur in higher latitudes (above 40 degrees). The relative inefficiency of aerosol removal in late winter and spring, known as the Arctic Haze phenomenon, also complicates the modelling process.

"It is the removal of black carbon from the atmosphere that is so difficult to model. Black carbon is mainly scavenged by precipitation, which is relatively inefficient in the period between January and March, but the deposition is not very well modelled and the existing models do not show enough black carbon being transported into the Arctic in relation to ground measurements," said Stohl.

The politics of flaring

It is not always clear how much associated natural gas will be produced from an oil well, and it may change in amount, quality and chemical composition over the life of a field. Producers often find

BACK TO CONTENTS

Flaring gases from an oil platform in the North Sea. (Credit: Wikimedia Commons user Varodrig)

that the easiest way to deal with the less economical, and sometimes contaminated, gas is to burn it on site by means of flaring. There are several alternatives, but no cookie cutter solution to the problem, as each area has unique issues in terms of geography, geology and infrastructure.

Russia and Nigeria lead the list of countries with the most flaring activity, with 66 billion cubic metres, or 24% of the overall associated Russian production, flared in 2010. But flaring occurs all over the world. The World Bank estimates that 140 billion cubic metres of associated gas is burned or wasted annually. This is equivalent to about a third of EU gas use and, in terms of CO_2 emissions, it equates to taking 70 million cars off the roads.

The issue is most serious in places where infrastructure development and investment is difficult, especially on brownfield sites and remote locations. It is especially bad for the Arctic, where the combusted black carbon particles settle on the snow and increase the snow-albedo effect, which causes further melting of Arctic ice. Atmospheric warming is also increased by black carbon over the highly reflective surface of the Arctic.

Tracking flaring activities

Historically, it was only possible to track flaring activities through the limited data gathered from companies and governments reporting on local hydrocarbon industries. But this information tends to be incomplete for political reasons. It is now possible to follow black carbon emissions through observation of the black carbon/carbon monoxide emissions ratio, which is specific to certain sources such as diesel vehicles, biomass burning or flaring. Carbon monoxide is another combustion by-product. It remains in the atmosphere over several weeks to months, sometimes longer, and is often used to trace polluted air masses.

It is also possible to track flaring via satellite. A Japanese satellite named IBUKI is able to collect infrared information and detect CO_2 and methane emissions. The collected data can be cross-referenced with additional data points. This is one step closer to a complete picture, but it is not perfect: no completely reliable information on flaring as it occurs is yet available.

"New satellites can detect temperature signals and have the capacity to not only exactly pinpoint where flaring is happening but to also quantify the gas volumes burned by each flare, which is really needed to estimate the flaring emissions. This technology is also capable of distinguishing between flaring and other sources like forest fires, based on temperature measurements, as flares are extremely hot. Thus, we expect that estimates of flaring emissions will become much more reliable in the near future," Stohl said.

Sources of black carbon

Where is the black carbon most likely coming from? This depends on specific latitude, location and season. Some models show that flaring emissions are dominating at latitudes above 66 degrees (up to 80%) in winter. It can be assumed that flaring is the main producer of black carbon during this time, as biomass burning, one of the other big black carbon contributors, is less frequent in the winter. Residential, transport and industry are the major polluters in the middle latitudes, with aircraft and international shipping contributing to a much lesser extent.

Although flaring occurs globally, the impacts from Russia have a proportionally large impact on the Arctic compared to flaring from lower latitudes. When flaring occurs along the main low-level pathway of air masses directly entering the Arctic from Siberia, black carbon emissions are measured at their highest levels. According to the models, this makes Russia responsible for a large fraction of black carbon loading in the Arctic lower troposphere. Russia also has strong flaring at very high latitudes and Northern Russia has the highest measurements of black carbon concentrations in snow.

Flaring in the Siberian oil fields has been occurring for decades and can generally be attributed to coordination problems and conflicting interests. The Russian presidency has raised this as an issue and has suggested that companies that flare pay large fines, and new laws require companies to use a high percentage of associated gas. The government has also allowed preferred access to the electricity grid for power generated from flare projects and has encouraged use of gas for local power generation, which is often needed in remote regions to supply power to processing plants.

What can be done to reduce flaring?

The problem will only get worse as more and more Arctic areas are opened up for drilling activities and will take on a more international aspect as other areas of the Arctic are exploited.

There are a number of ways to combat natural gas flaring, but since there is no one-size-fits-all solution, a number of organisations need to come together to ensure a balance amongst government, business and private interests. Assumptions that associated gas is not worth gathering need to be challenged. So far, the best efforts to eliminate flaring look at the entire gas value chain and involve a combination of penalties, incentives, investment and inventive uses for the available gas.

For the Arctic, the role of both the scientific and international communities is of vital importance. As the Arctic has no single authority, international institutions and Arctic groups will be vital in supporting commitments to mitigate flaring activities. And as technology advances, there is also the hope that new methods and processes to deal with flared gas will become available. Since there are a number of ways to reduce flaring, this is a realistic and achievable step towards decreasing the presence of black carbon in the Arctic, most possibly in the next ten years. It is another step towards changing local behaviours that have tremendous global impacts.

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Molecules and meteorites: big impacts for life on Earth

You'd be forgiven for thinking that meteorite impacts only spell disaster for life on Earth, and there is plenty of evidence to suggest that an impact was bad news for the dinosaurs. However, a growing body of research suggests that asteroid and comet impacts early in our planet's history may actually hold the key to the origins of life on Earth. In terms of the global impact of a local event, they surely don't come much bigger than this.

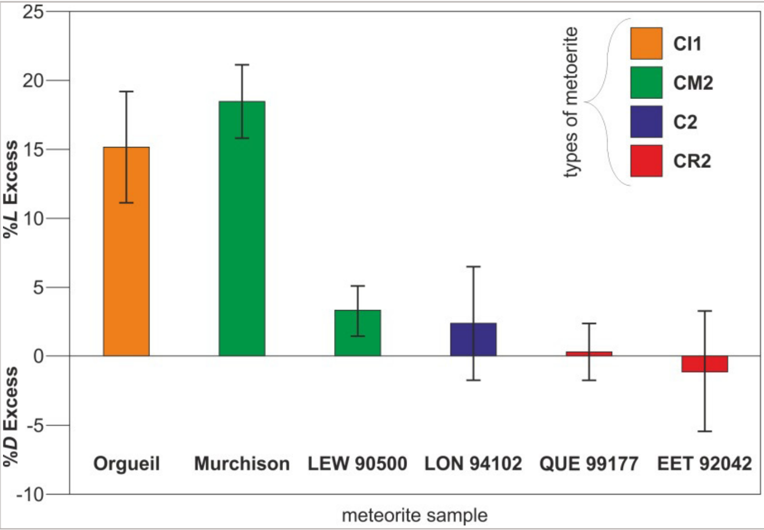
As a geophysicist, I'm well aware of the problems that researchers in my field face in delving back in time to establish the geology of the early Earth. The challenge of doing a similar thing with organic molecules, which I guessed would be rather more ephemeral than the Earth's tectonic plates, seems a daunting prospect! Nonetheless, there are plenty of active researchers in this field, including at NASA and the European Space Agency (ESA). One academic collaborating with these organisations is Zita Martins at the Department of Earth Science and Engineering of Imperial College London. Ahead of her attendance to a symposium on the origins of life, I met with her to get some perspective on the extra-terrestrial influences on the beginnings of life on Earth.

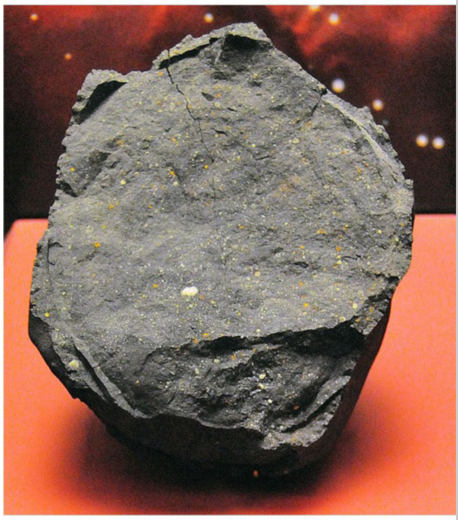
The question of our 'alien origins' is usually taken with a good pinch of salt, as Martins explains. "It's important to appreciate that we're not talking about life being formed somewhere else in space and then being brought to Earth." However, it is entirely possible that the carbon-rich organic molecules contained within asteroids and comets, and delivered to Earth at the point of impact, do have a role to play in the initiation of life on our planet – and unpicking this biological history is a fascinating and multi-disciplinary science. Martins describes herself as an astrobiologist, but she has a background in chemistry and an understanding of physics and geology. "The beauty of astrobiology is that it draws together scientists from different fields, all trying to answer two big questions: how did life

Zita Martins and a sample of space – in the lab at Imperial College London

originate here on Earth, and is there life in other parts of our solar system?"

So, what are the origins of life on Earth? There are a few theories which sit alongside a meteorite impact, including chemical reactions taking place around sea-floor hydrothermal vents. While Martins is happy to accept that there's room for contributions from many processes, she is drawn to a cosmogenic explanation in part because of a set of observations in our geological record. "We know that between 4.6 and 3.8 billion years ago the Earth suffered a heavy bombardment of comets and asteroids." Indeed, our whole neighbourhood was a risky place to be at this time, as there is evidence in craters on its surface that the Moon suffered the same astrophysical assault. "Geological records then show that life originated on Earth around 3.5 billion years ago," give-or-take the uncertainty in the geological dating method. So – cause and effect, or cosmic coincidence? Martins smiles: "As a scientist, I can't believe in coincidences!"





Bias towards *L*-isovaline amino acid in samples of several meteorites, as measured by Glavin and Dworkin (2009): positive percentages on the y-axis suggest that *L*-isovaline is dominant over *D*-isovaline in a sample. The bias is particularly strong in samples of the Murchison meteorite, a fragment of which is shown on the right. (Credit: Glavin and Dworkin, 2009 & Wikimedia user Basilicofresco)

The impact theory says that when a comet or asteroid strikes our planet, the pressure and temperature at the impact site are sufficient to set off a string of reactions among the molecules already on Earth and those within the meteorite. Among the results: amino acids – the components of proteins that are the building blocks of life. For Martins, it's no surprise to see the geological signatures of life taking hold in the period following a heavy bolide bombardment.

However, if the theory is sound, you might expect life on Earth to share some biochemistry with that of the amino acids held within asteroids and comets. Fortunately for astrobiologists, a frequent supply of meteorites rains samples of cosmogenic amino acids onto the Earth's surface. The biggest impact that these usually make is on the media (something that the residents of Chelyabinsk Oblast may dispute, following events of 2013) but even the smallest samples of certain meteorites are packed full of organic molecules, including amino acids, themselves a record of the early chemistry of space.

Certainly, the amino acids involved in our own biology are present within the extra-terrestrial samples. However, the reverse isn't true: while around 80 amino acids have been identified in meteorites (Martins and Septhon, 2009), biological organisms on Earth only use around a quarter of them. Nonetheless, there are subtle links in our own biology to molecular signatures in extra-terrestrial amino acids – and here, we enter the world of 'CSI: Outer Space'.

The clue concerns the chirality of a molecule – essentially, whether it is right- or left-handed. "Put your hands out in front of you," Martins explains (and naturally, I follow the instruction). "Your hands are mirror images of each other, so you cannot superimpose them – your thumbs are on opposite sides." It's the same with amino acids, which exist in left-handed (*L*-) and right-handed (*D*-) forms. On Earth the vast majority of organisms use *L*-amino acids, whereas meteorites contain *D*- and *L*-amino acids. Why is life so selective? It's possible that our biological preference for *L*-amino acids is the result of the chiral distribution of cosmogenic amino acids. Key evidence is given by the amino acid isovaline. *L*-isovaline is non-proteinogenic: it is not involved in any biological process on Earth, therefore any

Artist impression (not to scale) of ESA's Rosetta approaching comet 67P/Churyumov-Gerasimenko. (Credit: spacecraft: ESA/ATG medialab; comet image: ESA/Rosetta/NAVCAM)

L-isovaline detected in meteorites cannot be a terrestrial contaminant. Observations show that the split between *L*- and *D*-isovaline is not fifty-fifty and, as shown in the graph at the top of the page, the samples present in meteorites are somewhat biased towards left-handed chirality. This bias is particularly evident in samples of the Murchison meteorite (pictured) which impacted Australia in September 1969. Martins suggests that "this little bit of excess of the *L*-form could have been enough to expand the use of *L*-amino acids in biological organisms on Earth."

Of course, the reason for the chiral imbalance of amino acids is yet to be explained, and Martins also questions why life on Earth makes use of only a few more than 20 amino acids when there is such diversity available in space. Nonetheless, I find this molecular form of evolution quite elegant, and it's amazing to think that our basic biochemistry has a direct link to a process occurring some 3.6 billion years ago.

If external processes hold the key to life on Earth, then why not life elsewhere? The icy moons of Saturn and Jupiter are prime candidates, since they are likely to contain organic molecules of their own and have certainly faced asteroid impacts at some point in their history. Astrobiology is now sampling further afield. Both NASA and ESA have probes journeying to asteroids and comets, such as

BACK TO CONTENTS

Rosetta (pictured), and ESA's JUICE mission will target Jupiter's icy moons. There is every chance of new insights into deep-space chemistry.

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Chasing ice: studying the stability of the Western Antarctica Ice Sheet

Out of all the world's glaciers, Pine Island Glacier (PIG) is currently making the single biggest contribution to global sea level rise. Scientists are trying to figure out why.

Tractor traverse on Pine Island Glacier. (Credit: Damon Davies)

Clinging onto the edge of western Antarctica, PIG is the fastest shrinking glacier on the planet. With 56 Gt of ice careering into the ocean each year, knowing the future stability of the ice sheet is essential.

"The West Antarctica Ice Sheet (WAIS) is a glaciological hotspot," says Andy Smith who works at the British Antarctic Survey (BAS) in Cambridge, UK. "At the moment, the area is contributing the largest amount to global sea level rise – at around 3 mm per decade. Although this doesn't sound much, the little changes add up over time."

With the return of the sun to the southern continent, scientists from BAS are kicking off the 2014 PIG research season. They will be setting off on the second of a 1000 km trek across the ice to measure snow accumulation at the top of the glacier. As they go, they will record snow density, collect ice cores and gather historical clues from rocks and isotopes to see how fast PIG is changing. "Over the six-year period we have been studying the melting so far, it has been getting worse," says Smith. "However what we don't know is if this is going to carry on or even off."

Living on the ice

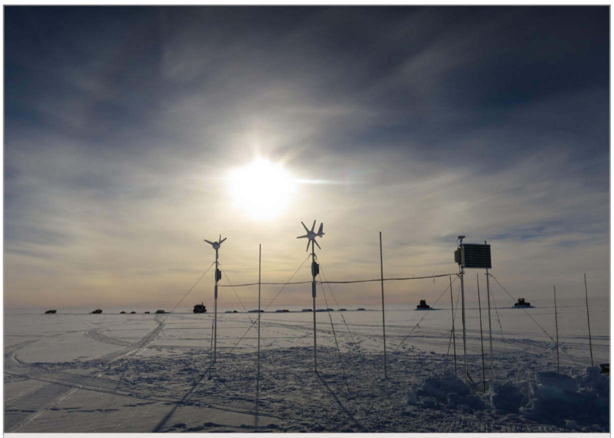
To answer this question, the team will be spending 70 days living on the ice in temperatures barely reaching above -10 °C. Going out into the field involves transporting 80 tonnes of equipment including two tractors, tents, science kits and a shipping container, revamped into a dining room.

"Doing this means the science can happen more efficiently," says Simon Garrod, Field Operations Manager at BAS. "When you're living in the snow, a significant amount of time must be spent just living – pitching tents and melting snow for water. Being able to pull your dining room along with you means you have more time for science."

By pitching their tents at such chilly latitudes, they hope to figure out what's going on at PIG. "The reason why we think its changing so fast is because it's being forced by what's happening in the ocean," says Smith.

As warm water currents in the Amundsen Bay meet the underside of glacier's ice shelf, they speed up the melt. The amount of ice loss more than doubled in the past couple of decades. Ice discharge between 1992 and 2011 was reported at an average of 20 Gt per year but is now reaching 56 Gt per annum, which is equivalent to removing a block of ice 100 metres deep and about 1000 square kilometres wide from the ice shelf each year.

The WAIS is more vulnerable to oceanographic changes than the eastern side because the sheet sits on ground below sea level. The grounding line, the point where the ice lifts off the bed rock and starts



GPS stations on the glacier with the base camp in the background. (Credit: Jan De Rydt)

to float, has retreated by tens of kilometres. For example, between the same period of 1992 to 2011, Rignot et al. (2014) suggest PIG retreated 31 km at its centre. This means it was 400 metres deeper below sea level in 2011 than in 1992. As the ice recedes, the ocean drains into the grooves at the bottom of the glacier, which reduces the friction on the glacier bed. The ice starts to fast-track downhill into the sea. "It's like removing the brakes," says Smith.

The PIG team setting out in October are part of a larger project called the Ice Sheet Stability Research Programme, or iSTAR, of which Smith is the Science Programme Manager. As part of this project, data from nunataks – exposed areas of rock peaking out of the ice – will be combined with information collected by atmospheric balloons, by airplanes dropping sensors in crevasses and by ships, which will create the most integrated picture of a glacier ever attempted. "BAS is doing what no one has done before by studying the ice and the ocean in an integrated method of the whole system," says Smith.

Curious assistants

Hungry elephant seals are also playing their part to fill in the missing data gaps. Last year, scientists tagged female elephant seals with ocean profile collectors. As the seals dive down to hunt for food, the tags collect data on conductivity, temperature and depth. When they resurface, the data are beamed back via satellites to the University of St Andrews, UK.

"The seals give us a mass of data in places we just can't get to observe," says Michael Fedak, a biologist from the University of St Andrews. "They have been working their tails off since we tagged them."

The seals have so far collected almost 9000 ocean profiles around the edge of the ice shelf. In comparison, the ship in the same location managed to gather 120 profiles.

Being able to tag the females gave the researchers an unexpectedly complete record. Only male elephant seals had previously been seen on Edwards Island near the mouth of the glacier as they complete their annual moult. But males have one downside: they have the habit of going on a mid-winter break from feeding to take a rest onshore.

The females are different. They are out hunting at sea for long periods of time and do not require a break, diving intensively for up to 300 days to put on weight for breeding. So for the data record, this means a more comprehensive and uninterrupted profile.

"We were really surprised to find the females in [Amundsen] Bay. They are doing something not seen anywhere else so far south in the world – benthically feeding at the front of the glacier," says Fedak. "This was an odd place, as usually at this time of year the females are far out at sea intensively feeding and putting on body fat ready for producing pups – which use up to 35 per cent of their body mass."

Close-up of juvenile southern elephant seal. (Credit: Serge Ouachée)

The observations are combined with a wide range of oceanographic sampling methods from ship transects, sea gliders and underwater submarines. The information gathered from the water bordering the glacier will help the scientists build models to predict how much of WAIS could be heading seaward.

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