Response to questions from the Gateway Antarctica students (January 2018)

What drives the formation, quality and extent of Antarctic Sea Ice?

It's partially trivial, but also fundamental, to state that sea ice formation is primarily driven by the atmosphere. We have to start there, because it is the atmosphere, and its variability over daily, seasonal, and decadal timescales, that has the biggest influence on sea ice formation and evolution. Sea ice formation begins when air temperatures drop sufficiently to allow ice crystals to form in the surface waters. Because of how heat transfer and ice nucleation works (I can give you more detail on these if need be), you won't start to see crystals forming until the air temperature gets down to maybe -10 °C or so. So, this process begins each year in late-February, close to the continent, and later into the winter as you move further north.

Figure 2 Nilas ice in the Ross Sea (Wikimedia)

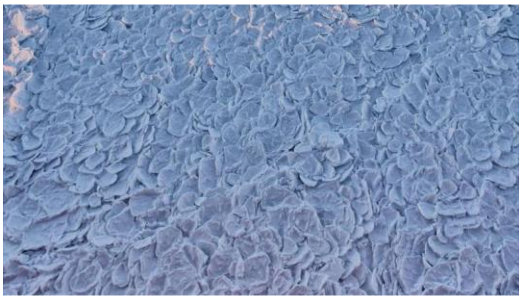

Figure 1 So-called 'Dragon Skin ice', here observed in the Ross Sea, 2017, is a type of Pancake ice. I was told they thought this fantastical term would gain more traction than the possible alternative: 'Scalloped potato ice' (Guy Williams, UTAS, aboard Nathaniel B Palmer).

Once these initial frazil ice 'seeds' exist, however, further ice growth can proceed much quicker. But how that growth proceeds is, again, dictated by what the immediate atmosphere is doing:

- Under calm conditions (almost never the case for the Southern Ocean away from the coast) 'nilas' ice covers the ocean surface with a thin film, which may be similar in appearance and behaviour to an oil slick;
- Rougher conditions (the usual situation in the Southern Ocean) will produce 'pancake ice' – flat discs of ice that have upturned edges from bumping into each other as they're tossed about by waves.

Growth continues, and the pancakes coalesce, until the surface is covered with a continuous layer of ice, known as 'pack ice'. This contiguous ice surface acts like an insulating blanket and it slows the heat loss from the ocean to the atmosphere. Hence, the thicker the ice becomes, the slower it will grow. Over a single winter, Antarctic sea ice typically grows to about 1 m thick, but up to 2 m closer to land.

Away from the coast, the sea ice cover is free to move under the influence of winds. When swells or storms move through it may respond by bending and flexing. Current work being led by colleagues at NIWA is aimed at how far into the pack waves in ice may be translated, but it may be as much as 300 km. Alternatively, it may crack apart where the stress is too great, forming 'leads'. Where leads form, and the sea ice opens, the ocean is suddenly exposed to the cold atmosphere, and new ice generation will occur. In the meantime, however, leads play an important part in the thriving ecology of the Southern Ocean, as it allows sunlight, that would otherwise be blocked by the ice, (plus a covering of snow) directly into the ocean.

The other factor influencing sea ice behaviour is, of course, the ocean. Perhaps somewhat perversely, the ocean's influence on sea ice formation is much less than that of the atmosphere. This is because, apart from the influence of ice shelves (more about this if necessary), the ocean cannot, of itself, get cold enough to allow ice to form. The ocean can, however, hold a 'memory' between sea ice seasons, that will influence how ice formation proceeds in years to come. It is also primarily via the ocean that the long-term global influence of the sea ice cycle is transferred.

In terms of quality, the primary factor is the storminess of the autumn and winter seasons. During a relatively calm growing period, the sea ice has more opportunity to remain as a contiguous mass, and ice growth is primarily 'columnar' – i.e. directly downward into the ocean, and adhering to the crystallographic structure. Conversely, during prolonged stormy periods, the ice is broken up and becomes 'rafted' – i.e. large pieces end up on top of others, creating ridges (and keels) in the ice's upper (and lower) surfaces.

Figure 3 'Rafted ice' from Ernest Shackleton's expedition into the Antarctic aboard 'Endurance' (Scott Polar Research Institute).

Why have model predictions of Antarctic sea ice extent differed so significantly from observations?

I would argue that the model predictions don't differ hugely from observations – the models have come a long way in their three decades of development. Today, they're huge and immensely complex, and use multiple components made up of hundreds of equations to represent the earth as a system of many interactions. The differences arise either where simplifications are made – often necessary in order to move forward – or where new observations reveal something, or some process, that we didn't previously know about, and hence couldn't be represented. But, by and large, the Earth System Models (ESMs) do an amazing job.

In the case of Antarctic sea ice, it remains a hot topic as to why we've seen a gradual expansion of the ice cover, when the models have been predicting a slight decrease. In defence of the models, causing ice to shrink when it's forming in a warming ocean doesn't offend anyone's intuition. After all, it is what we're seeing happening in the Arctic, and the fundamental processes are pretty much the same. However, the difference from observations is 'significant' in the sense that the growth and decay of Antarctic sea ice is the biggest annual change on the planet, so getting it even slightly wrong has a large potential impact. And trending in the wrong direction, even if the absolute difference is small, means there's some critical process that's being overlooked.

There are many potential reasons for the difference that have been offered by the scientific community. And it's likely that there's a component of all of them at play simultaneously:

i. Perhaps there isn't *less* ice… We know that there's been a greater extent of Antarctic sea ice – i.e. the trend has been towards covering a slightly larger area over the last 35 years. But the satellites can't tell us about thickness. In other words, we have no idea how the total volume of sea ice has been changing – it's possible that it's actually a similar volume, just stretched thinner to cover more of the ocean. A team led out of Otago University, and funded through the Deep South National Science Challenge, are working on ways to improve how sea ice thickness is measured remotely, so there's hope for improvement here;

ii. We know that the storm tracks and wind flows over and around Antarctica have been changing in response to human-induced climate change. So that may be pushing sea ice further north, leaving the ocean to the south more exposed to the atmosphere, and able to form ice more readily. Or perhaps the winds are now simply moving the sea ice into places where it's less likely to be melted by the ocean;

iii. The warmer oceans are getting in under the Antarctic ice shelves (the seaward extension of the land-based glaciers), and have been melting some of them at an accelerating rate. This then allows more fresh water to enter the ocean than previously, and since fresh water freezes more easily than salty water, forming ice from it is just that little bit easier;

iv. A corollary to (iii), but which there's very little observational data on, focusses on the fact that the input of glacial meltwater also makes the ocean a little bit colder than it would otherwise be, and therefore it is 'pre-conditioned' to freeze quicker. This is what I'm working on…

Incidentally, it may be that whichever physical process(es) was responsible for allowing the recent expansion of the sea ice has now (finally) been defeated by the incessant push of human-induced climate change. The sea ice extent of 2017 reached a record low, and that immediately followed the record high of 2016. Perhaps we have finally pushed the system to some sort of tipping point. The next few years and decades will tell.

What significance does sea ice variation have from an environmental management perspective?

Nearly all of the Southern Ocean (defined as south of 60 °S) is covered by sea ice in winter, while nearly all of it is ice free in the summer. Hence, the formation and decay of Antarctic sea ice affects multiple aspects of ecosystem functioning enormously, and performs multiple functions in the Southern Ocean. Some of these are:

i. The ice provides a habitat for various life forms (e.g. algae, krill, birds, seals; with flow-on effects for their predators), allowing them to thrive at the ocean surface in an environment that is more secure than the open ocean.

ii. When viewed from space, the sea ice presents a bright white surface, which is in stark contrast to the dark ocean it formed from. Thus, when there is ice at the surface, most of the incident sunlight is reflected back to space, and the ocean is prevented from warming as fast as it otherwise would. In turn, keeping the ocean cool prevents the ice from melting. This effect, known as the 'Albedo effect' is amplified when the sea ice is covered in snow, which is usually the case.

iii. The formation of sea ice can be thought of as salty ocean water being separated into fresh water ice (which remains at the surface) and cold, salty brine, which, being denser than the ambient ocean, has a tendency to sink. In sinking, the brine carries oxygen and nutrients from the ocean surface to the deep ocean, thus helping to sustain life there, too.

iv. The Southern Ocean is connected to all of the major ocean basins. Thus, the continual cycle of formation and release of cold, dense water near Antarctica drives the large-scale overturning of the global ocean. It takes approximately 1,000 years for ocean water to complete one circuit of the 'Great Ocean Conveyor Belt', hence any changes to it that humans are responsible for will be with us for a long time to come.

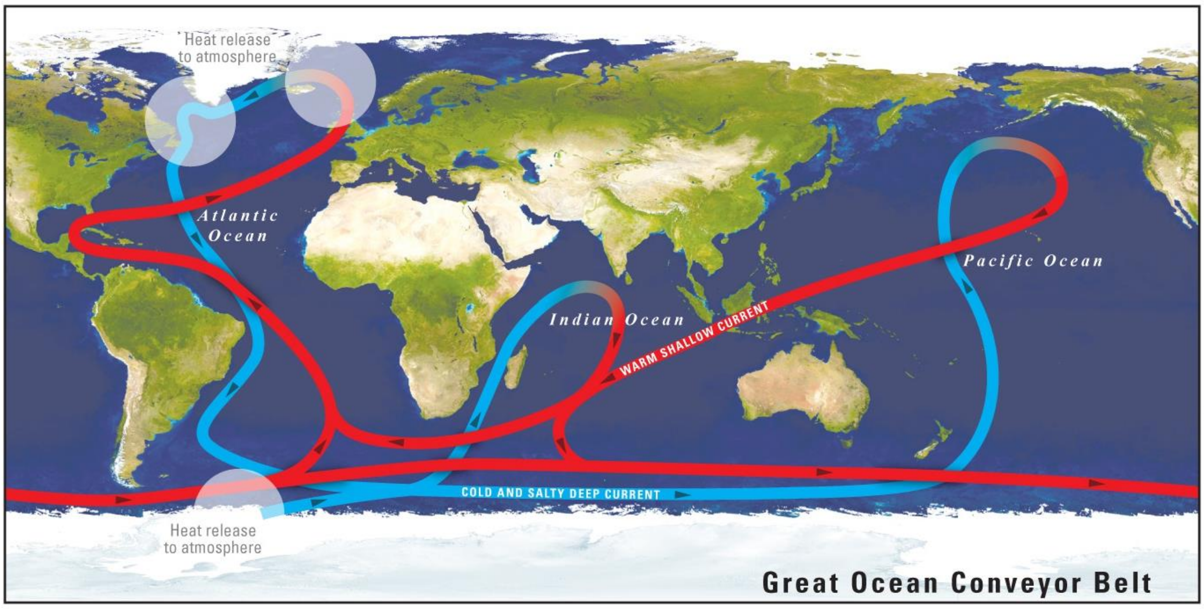

Figure 4 A sketch of the Great Ocean Conveyor Belt (US Geological Survey)

In terms of managing the environment, it is difficult to draw sweeping generalisations, because the many different areas of the Southern Ocean are each subject to different static and dynamic physical components: there are multiple different types of sea ice; different species thrive in different locations; and the sea ice season varies with latitude. However, it is fair to say that throughout the Southern Ocean, sea ice is a defining and critical component of the ecosystem. Hence understanding its natural variability (on timescales from seasons to decades), as well as its likely response to a changing global climate, is fundamental for all areas of the Southern Ocean. And beyond.

What significance does sea ice variation have from an operational perspective?

In terms of operations, sea ice can function either as a platform to work from, or as a hindrance to gaining access to specific areas.

i. Cargo and passenger supply planes routinely land on the sea ice in front of McMurdo Station during the early part of the season when the ice is thick and strong enough. Their alternative is to land on the Ice Shelf – making for a much longer round trip – but many bases do not have the luxury of having an alternative solution;

ii. In contrast, the major resupply to McMurdo Station is made each year via ship with US Icebreaker support. This is a critical lifeline, principally for the fuel that is brought in to allow many stations in the area to continue functioning. During the summer of 2002/03, a massive iceberg blocked part of the entrance to McMurdo Sound, effectively preventing the usual break-up of sea ice, and it was not possible in that year for the supply ship to get in. That was an unusual example of the natural variability of local sea ice cover which serves to demonstrate how it can influence logistical operations.

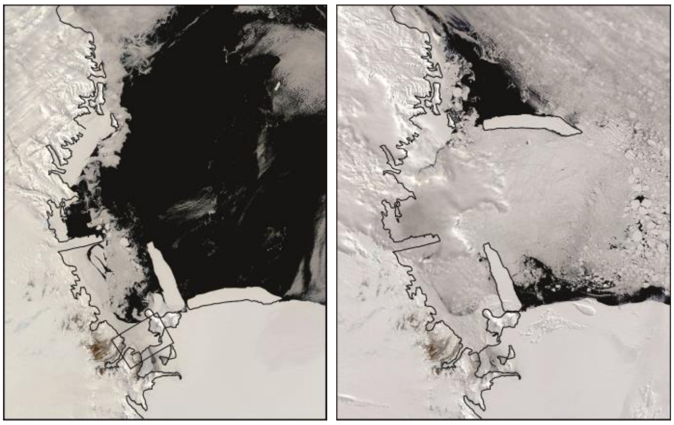

Figure 5 Natural sea ice variability in the Ross Sea as a result of the massive tabular icebergs B-15a and C-19 (NASA).

What reasonable predictions can you make for the sea ice in the Ross Sea region over the next decade?

My job does not involve making predictions – I make observations that help to understand the system as it operates that will hopefully allow those who do run the models to make better predictions. However, the Ross Sea is a highly dynamic region, which means that any long-term signal is likely to be insignificant compared to the year-on-year natural variability, within a 10-year timeframe. For example, the El Nino of 2016-17 was the most-likely culprit for the minimal sea ice extent local to McMurdo Sound, and appears to be a reflection of a similar event related to the large El Nino of 1997. However, looking further back in time, changes have been observed that are able to emerge out of that inter-annual variability. These include:

i. More than half of the Antarctic-wide expansion of sea ice cover over the satellite area is accounted for by changes in the Ross Sea;

ii. The Ross Sea has become measurably fresher – likely due to the input of glacial meltwater from the Amundsen Sea, with an unquantified amount also coming from the Ross Ice Shelf itself.

Therefore, over the next decade or so, I expect the Ross Sea to physically continue to operate within the bounds of what we consider 'normal', with a likely continuation of the two long-term trends mentioned above. With the ratification of the Ross Sea MPA, however, the hope is that the biological system will be more robust than normal. However, it has been given a 35-year window to allow scientists to document effects and justify the MPA's existence. So perhaps identifying any positive (or negative?) effects within only a decade might be a bit much to ask!