***My response to questions from Jamie Morton, who was compiling a piece on the Southern Ocean, and perspectives from various scientists on why we need to understand it better***

****Why is the Southern Ocean so important for understanding the global climate system – and what are the key questions that scientists are trying to answer around it?***

To date, the ocean has taken up 93% of the heat generated by anthropogenic climate change. Without the ocean performing this service, atmospheric temperatures would already be too hot for human survival. So, there's a sense in which the oceans have saved us from ourselves. But ocean processes are very slow compared to the atmosphere – the global ocean conveyor takes an estimated 1,000 years to complete a circuit – so the ocean will slowly release this heat back to the atmosphere until a new equilibrium state of the climate is attained. In other words, even if global carbon emissions were to cease today, we are already committed to a long future of warming due to the heat already taken up by the ocean.

In terms of the role that the Southern Ocean plays, it occupies the only band on Earth in which flow can complete a full longitudinal circuit. In other words, the Southern Ocean connects the ocean basins, and is a major driver of circulation in both the ocean and atmosphere.

The growth and decay of sea ice in the Southern Hemisphere is the largest single change to occur annually on the entire planet. It's a change that's as large (again) as Antarctica itself (50x the size of NZ). And when the surface of the ocean freezes, cold, salty water is also produced, which drops down to the ocean floor – a huge annual signal that keeps the ocean's 'heartbeat' pumping (i.e. the global ocean conveyor). So, although it's largely unseen by humans, its effects are felt across the globe.

Sea ice also acts like a mirror on the surface of the ocean. Whereas dark ocean absorbs heat, the bright white of the sea ice instead reflects that energy back out to space, helping to keep the ocean cool. What we're seen happening in the Arctic is that as less sea ice forms, and more of the dark ocean is left exposed, more heat is absorbed making it less likely that sea ice will form, and the cycle intensifies. We call this a 'positive feedback mechanism', which refers to the fact that it's self-perpetuating, rather than a whether it's a 'positive' or good outcome for the climate.

The Southern Ocean also dominates the global carbon budget. Separate sections of the Southern Ocean act as major sinks and sources of $CO_2$, so a major question is determining how these sinks and sources operate and what might cause them to change, so that we can determine what the net effect is.

https://www.climate.gov/news-features/understanding-climate/climate-change-ocean-heat-content

https://www.nytimes.com/interactive/2016/09/12/science/earth/ocean-warming-climate-change.html

***What has hampered scientists being able to understand big-picture trends surrounding the ocean and its interplay with Antarctica?***

By its very nature, Antarctica is difficult to solicit answers from. It's not easy to get to, it's too cold for independent survival, and both the land and surrounding ocean are covered by thick layers of ice. It's also quite a large continent, which plays a disproportionate role in our climate system, but which has had relatively little human research endeavour. So, it's a place of fundamental discovery – where new processes, or drivers of processes, are still being uncovered.

Hence, we rely on numerical simulations that represent what's happening there, how that affects the rest of the world and how it all might change under future climate scenarios. They've come a long way in the last few decades, and there's now a range of incredibly sophisticated models focused on different aspects of the climate system.

But we need new and ongoing in-situ observational data to both check that the models are representing something close to reality and to identify and characterise new processes that the models don't even know about yet.

We have a continuous 40-year record of satellite observations that has really opened a window into the processes that happen in the Southern Ocean and around Antarctica. However, that record only sees down as far as the surface of the ocean. So, apart from what's happening at the very surface, we cannot directly assess the ocean state or how it changes from satellite data.

There's a new era of autonomous instruments that are filling in our understanding of the global ocean – but these typically cannot operate in ice-covered waters. This leaves us with a conspicuous gap of in-situ data coming from the Southern Ocean, which we know is critical for global climate.

And as we move closer in to the continent, the problem intensifies because the ice gets thicker, longer-lived and increasingly difficult to get through. Eventually, we reach Antarctica's coastline where the land-based ice sheet first contacts the ocean. This is clearly a critical region for one of the biggest unknowns in future climate: how fast will sea levels rise from ice sliding into the ocean? But around 75% Antarctica's coastline (i.e. 13,500 km) the ocean is hidden by hundreds of metres of solid ice, making it so difficult to directly access that it's only been done once in history.

There is a whole raft of remote sensing techniques that have been developed to compensate for the lack of direct access to the ocean in these critical locations. But these are all pointing to the fact that the ocean is driving change (lots of recent references) and that change is accelerating.

*I don't really want to leave the thought hanging there, but I don't know how to finish it. We need actual in-situ observations if we really want to know how the ocean is interacting with the ice – but it's almost an impossible ask, because it's so difficult and expensive…*

***You've been at the forefront of research around sea ice, which, unlike the Arctic, doesn't appear to have followed a straight trend and instead has been a case of swings and roundabouts in terms of changes in extent. Why is understanding the sea ice puzzle so important to understanding the wider picture?***

Antarctic sea ice is huge driver of Earth's climate, and a big component of seasonal stability. It's the pulse of the global ocean – not just for ocean and atmospheric circulation, but also for the ecology of the Southern Ocean, with flow-on effects for the global ecosystem and carbon uptake.

Over the satellite era (i.e. since 1979) there's been a trend towards Antarctic sea ice covering a slightly larger area of the Southern Ocean. However, the models have been predicting change in the other direction – i.e. as you would intuitively expect, they predict less sea ice in a warming ocean. So, getting the underlying direction wrong means there's some fundamental physics missing from our understanding. And this makes forecasting future sea ice conditions under future climate scenarios problematic – and represents a huge area of uncertainty when you consider the role that sea ice plays in the overall climate system.

It may sound like a positive thing that sea ice has been expanding. However, it's possible that the apparent increase *(remembering that we actually can't say anything about sea ice thickness, nor total volume from satellite data)* may be due to increased melting of the Antarctic ice sheet making its way into the ocean – on the one hand contributing to accelerated sea level rise, and on the other generating cold fresh water that forms sea ice more easily. If this is true it implies that we're swapping the permanent ice for seasonal ice which we would not consider a win for the climate system at all. This is a question that I am actively working on with colleagues from Otago, Canterbury and NIWA, and it all comes back to the fundamental role of connection that the ocean plays.

***Lastly, why is the Southern Ocean so crucial for New Zealand and its influence on our climate?***

*A bit beyond my realm of expertise, but I can give you a factual, if not very specific, answer:*
At its peak, Antarctic sea ice stretches to span half of the distance between New Zealand and Antarctica – equivalent to the length of New Zealand itself. The location of the sea ice edge determines where and how the storm tracks that circulate in the Southern Ocean arise, which in term controls the weather patterns we see coming up from the south.

New Zealand's climate is dominated by the ocean and ocean currents. In many ways, this helps to stabilise the temperatures we experience because the ocean doesn't change as rapidly as the atmosphere does. But it also means we are exposed to the variability of the vast tract of frozen ocean for both our day-to-day weather and the longer climate outlook.

*Also, please let me know if you want images to accompany the text. I've got heaps!*