Title Slide

Thank you, Steven for the introduction, and the invitation to present the SCAR Science Lecture at the 40th Antarctic Treaty Consultative Meetin. Grettings delegates. The aim of this presentation is to outline some implications of the UN Paris Climate Agreement for Antarctic science and policy.

I will start off by summarising what the world agreed to in Paris, then briefly examine the relationship between the Antarctic Treaty System SCAR and the United Nations Framework Convention on Climate Change.

I'll then move on to discuss the consequences for Antarctica and the Southern Ocean of 2°C of global warming based on the latest international science, much of which has been conducted under the auspices of SCAR's strategic research programmes.

However, the presentation will primarily focus on one of the biggest uncertainties that is policy-relevant and facing climate science today. This is the question, "how fast and how much will Antarctic ice mass loss contribute to global sea-level rise (SLR) over the coming centuries, and will the Paris Climate Agreement prevent significant melting of Antarctica and global sea-level rise?"

This is one of the key future science challenges presented by Jane Francis in yesterday's special meeting.

I'll consider, potential impacts and hopefully avoided impacts for the Antarctic environment, operations and activities, and look at the consequences of sea-level rise more broadly for the rest of the world. [1'35"]

Slide 2 – The Paris Climate Agreement

The Paris climate Agreement was signed by 196 member nations of the United Nations Framework Convention on Climate Change (UNFCCC) at the 21st meeting of the Conference of Parties (COP 21) in December 2015.

The UNFCCC is an international environmental treaty negotiated at the Earth Summit in Rio de Janeiro in 1992, with the objective to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system".

The Paris Agreement aims to keep global warming below 2°C - "the safe guardrail for dangerous climate change" identified by the Intergovernmental Panel on Climate Change (IPCC)

This will be achieved through nationally determined commitments the so called NDCs, aimed to reduce all anthropogenic greenhouse gas emissions to zero before the end of this century. [1'06"]

Slide 3 - Why the ambition of 1.5°C of global warming?

Following pressure from vulnerable African and low-lying coastal nations, the parties further agreed to "pursue efforts to" limit temperature increase to 1.5°C. This is because the scientific assessments of the IPCC were showing that for the most vulnerable nations, 2C of global warming could be too high and present too much risk. For example Pacific Island nations such as Kiribati would have to be abandoned, and some continental African countries will get too hot and dry out. [20"]

Slide 4 - The challenge of the Paris Agreement

The Paris Climate Agreement was subsequently signed by 194 countries in New York on Earth Day, in April 2016, and the Agreement went into force in November.

Paris was a tremendous diplomatic success, but of course ambition needs to be matched by action. The EU, UK and China have already made significant commitments to reduce emissions that are on track to achieve the 2C target. The Agreement has weight, and parties who reneg on their commitments, or who withdraw from the Agreement will risk serious reputational damage, especially the global leaders. So for Donald Trump this will be a big decision.

However, the Paris Agreement is also challenging, especially given, that at the current rate of global emissions which is 40 billion tonnes of carbon per year, Earth's surface temperature could reach 1.5°C in 5-10 years and 2°C in less than 20 years. Time is short. Action must be taken right now, and national commitments increased significantly this decade for us to have chance [1'05"]

Slide 5 – Geneva IPCC 1.5C Scoping Meeting

So to assess the impacts and consequences of 2 degrees of warming and to determine if there are significant benefits and risk reductions by further restricting global warming to 1.5 degrees, the Paris Agreement requested that the IPCC to undertake a special report.

SCAR nominated Rob DeConto from the USA and myself to attend that meeting. Also in the red circle is Antarctic scientist Valerie Masson Delmotte from France who is the co-chair of WG1 for the next IPCC assessment report.

I have to say that there was a strong feeling of inevitability at the meeting, that at 1.5C of global warming was almost unavoidable and that this report would be more of an academic exercise than useful for policy development. Unless CO2 extraction technology can be developed on a scale to bring us back to 1.5C before the end of the century.

However, the report will address ONE very important question relevant to the ATS. What is the threshold for major meltdown of the west Antarctic ice sheet. Is it 1.5 C or 2C. I will come back to this key issue in a few minutes. [1'17'']

Slide 6 - The challenge of the Paris Agreement

But first this is why 1.5C or even 2C is so hard. Because we are almost there! This graph shows the trend in global average surface temperature since 1880 - since the start of the industrial revolution. The dramatic rise in temperature in the latter half of the 20th century and the 21^{st} century is clear. 2016 coincided with a big El Nino year during which the global ocean released more heat than usual, so combined with the continued anthropogenic warming trend global temperature for the year almost hit 1.4C above pre-industrial levels. [43"]

Slide 7 - How is the world tracking?

So how is the world tracking in terms of meeting the obligations of the Paris agreement?

- The NDCs tabled in Paris, if delivered on, will restrict global warming to ~2.7°C.
- This is still above the UN safe guardrail, and well-above the more ambitious goal of 1.5°C.
- Current policy settings see global temperatures stabilizing closer to 3.5°C.

- In five years-time nations will be asked to increase their ambition for emissions reduction
- We need to be 40% below 1990 levels by 2030 to be on track [47"]

Slide 8 - The relationship between UNFCCC and IPCC to the ATS

- Although Antarctica is the worlds 5th largest continent it has no status within the UNFCCC, not even observer status.

- Individual ATS nations are of course members of the UNFCCC and are bound by the Paris Agreement in terms of their nationally determined contributions to emissions reductions.

- BUT climate change is going to have major impacts on Antarctica and the activities of the ATS Parties. Yet the ATS does not have a collective policy voice in the UNFCCC. Is this an issue? I'm just putting it out there as an observation.

- SCAR however does have a direct pathway to the IPCC.

- SCAR has observer status within the IPCC, via its membership of the International Council of Scientific Unions (ICSU).

- SCAR/ICSU nominates participants to attend IPCC plenary sessions and meetings, as well as candidates to be considered for authorship of special and assessment reports.

- But most importantly SCAR helps mobilise the international science community to address the impact of climate change on Antarctica, and the role Antarctica plays in the global climate system.

- The SCAR Horizon Scan process held in New Zealand in 2014 identified several scientific priorities that are of direct relevance and interest to the IPCC as it prepares for its 6th integrated assessment report.

- Two of SCAR's strategic research programmes, *Past Antarctic Ice Sheet Dynamics* (PAIS) and *Antarctic Climate in the 21st Century* (AntClim21) made significant contributions to the IPCC's 5th Assessment Report from the legacy of several large IPY research initiatives. These research programmes are also positioning themselves to make even more significant contributions to 6th Assessment Report. [2'30'']

Slide 9 - Sea-level rise is the clearest global consequence of anthropogenic climate change

Sea-level rise is the clearest planet-wide signal of human induced climate change. So far global sea-level has risen 20cm in response to a 1 degree warming.

So what do the Intergovernmental Panel on Climate Change predict future sea-level rise will be by the end of the century? In its 2013 assessment report it said it could be as high as 1m with no policy on emissions reductions and half a metre with aggressive emissions reductions such as this outlined in the Paris Agreement.

No matter what we do we have already committed the planet to 30cm of sea-level rise over the next 40 years from the greenhouse gas warming that has already occurred. This is built into the system and is known as committed climate change.

However, the IPCC left out the contribution from Antarctica in its future sea-level predictions! Even though new evidence suggested Antarctica could respond rapidly, at the time of writing of the report, the scientific evidence was considered not clear enough, not mature enough, so the IPCC left it out of the predictions, but cautioned collapse of marine-based sectors of the Antarctic ice sheets, if initiated, could cause global mean sea level to rise tens of centimetres above the *upper bound of 1m* during the 21st century".[1' 30"]

Slide 10 - Future fate of Antarctica's ice sheets is one of the largest uncertainties in climate science

- So the future fate of Antarctica's ice sheets is one of the largest
- uncertainties in climate science.
- It is arguably the most important policy-relevant climate change impact of concern to decision makers
- This issue has been identified by SCAR in its Horizon Scan and by IPCC.
- The West Antarctic ice sheet has +4m of global sea-level rise if it melted. The East Antarctic ice sheets has 54m of global sea-level rise lock up in it.

- Of major concern is that large parts of the EAIS, and almost all the WAIS sits below sea-level, and are considered highly vulnerable as the Southern Ocean warms.
- If all this highly vulnerable ice melted. Global sea-levels would rise by +20m [1’]

Slide 11 – What has caused the observed sea-level rise,
& where will future sea-level rise come from?

Thermal expansion of sea water was the single biggest contributor to 20th century sea level rise. 93% of the heat from global warming has so far gone into the ocean, and as the ocean heats it expands, and sea-level rises.

At present 1/3 of sea-level rise is coming from mountain glaciers, another third is from polar ice sheets melting and 1/3 is from ocean heating.

These relative contributions to sea level rise are changing. The ice sheets will soon be the dominant contributor with the potential to raise global sea-levels many tens of meters. But if all the remaining mountain glaciers on Earth melted global sea-level will only rise half a metre. [1’]

Slide 12 - Polar ice sheet loss is accelerating & sea-level rise is accelerating

The rate of polar ice sheet melting is accelerating. Greenland is contributing more than Antarctica at moment, but that is about to change. [12”]

Slide 13 - Antarctica and Greenland are very different

This is because Antarctica and Greenland are very different. If we remove the ice sheets, you can see from the bedrock topography undernaeath that Greenland sits mostly above sea-level on land and that its margins are mostly on land.

Whereas one third of the Antarctic ice sheet sits below sea-level and is being attacked around its margin by a warming Southern Ocean, especially in the Amundsen Sea sector of West Antarctica. [30”]

Slide 14 – The Southern Ocean is warming. The ice shelves are melting.

This is the evidence. The map on the right-hand side shows areas marked with red circles where the ice sheet is thinning and retreating the fastest and losing the most mass. The map on the left shows where the ocean is warming, and the ocean is warming the fastest along West Antarctica where the ice is melting.

The two block diagrams show how warm ocean water rises up onto the continental shelf and melts the ice shelves. These ice shelves are the floating extensions of the land-based ice where it flows out onto the ocean and floats.

These ice shelves play a very important stabilising role. They essentially hold back the ice sheet from flowing under gravity into the ocean.

When the ice shelves melt and go away as they have around the Antarctic Peninsula the ice sheet slides into the ocean up to 10 x faster. This rapid ice loss contributes to rapid sea-level rise and can result in an unstoppable runaway retreat of the entire ice sheet, especially if the ice sheet sits well below sea-level in a deep subglacial basin.

Two studies published in 2014 said that it may already be too late for the West Antarctic ice sheet.

However, this is still an active area of research and, the debate is very much open.

It all depends on identifying temperature thresholds for Antarctic ice shelf stability. [1’ 45”]

Slide 15 - Atmospheric carbon dioxide concentration through time

One way scientists are trying to understand how Antarctica’s ice sheets might respond in a future warmer world is to look for examples of past warmer climates when atmospheric carbon dioxide and temperatures were higher. Similar to what they are today or will be by the end of the century.

The present level of CO2 in the atmosphere is unprecedented in the last 800,000 years. We know this from the natural variations in carbon dioxide measured from air bubbles in Antarctic ice cores. Its only in the 20th century that concentrations went above 300ppm and they are now at 400ppm.

We know from past geological information that the last time Earth had present day levels of CO_2 was 3 million years ago, and depending on how we intend to reduce greenhouse gas emissions we could be at 900 pppm CO2 by the end of the century - levels not seen in the atmosphere for 35 million years. [1’ 10”]

Slide 16 - Earth’s surface temperature 3 million years ago

So how warm did Earth’s surface get 3 million years ago, with 400ppm of CO2 in the atmosphere? Computer models and paleoclimate data show this pattern of temperature change, with the global average being 3C warmer, and the red colours showing the polar regions 6-7C warmer than now. Polar temperature amplification is a feature of global warming and its of concern because that’s where the ice sheets are. [35”]

Slide 17 - 3 million years ago - the last time Earth had 400ppm carbon dioxide Antarctica melted contributing +13-15m to global sea-level rise

Geological drilling programmes such as ANDRILL and the International Ocean Discovery Program have recovered evidence of ice free highly productive oceans +5C warmer than today off both East and West Antarctica. The geological evidence implied that these warm oceans melted marine based sectors of the West and East and Antarctic ice sheet.

The latest generation of computerized numerical ice sheet models by Rob DeConto and Dave Pollard constrained by the geological data show that up to 15m of global sea-level rise from Antarctic ice melt occurred at sustained levels of 400ppm CO_2, 3 million years ago.

The Greenland ice sheet also melted contributing an additional 5-7m. That’s 20-22m of sea-level rise if we keep the present stock of carbon dioxide in the atmosphere.

Implying that we may be very close right now to crossing the stability threshold for Antarctica’s vulnerable marine based ice sheets. [1’ 30”]

Slide 18 - A new generation of Antarctic ice sheet computer models

But what is that threshold and how fast will sea-level rise if its crossed. These new computer ice sheet models are providing key insights. The model, like the example I just showed you, which have been developed and tested on past climates, are now being applied to the IPCC future climate scenarios.

They now incorporate physical processes that have been observed to lead to rapid ice shelf collapse and disintegration. They also include an important process known as marine ice sheet instability, which occurs when ice sheets retreat into deep basins below sea-level and can melt at an exponential rate.

Sudden break-up of the Larsen B ice shelf on the Antarctic Peninsula in 2002 in the slide. It occurred over several weeks due surface melting and refreezing essentially exploding the ice shelf. Removing the ice shelf is like removing the flying buttresses off a gothic cathedral. The walls fall down. The ice sheet flows into the ocean.

The take home message. Once these processes are incorporated the models predict faster rates of sea-level rise from Antarctica over the next 2 centuries compared to the estimates in the current IPCC report, which underestimates the Antarctic contribution [1'32"].

Slide 19 - Future Antarctic ice sheet projections with paleo-calibrated model physics

This model published in Nature last year by 2016 Martha T Muse Prize winner Rob DeConto is state of the art!. It predicts an additional 1m of sea-level rise from Antarctica for the business as usual emissions IPCC scenario by the end of the century – the red line shows this. It is 1m higher than IPCC's worse case sea-level rise prediction.

Also shown is the black line which limits global warming to below the Paris target of 2C. Resulting in only minimal melting of Antarctica.

The difference between those two lines is the Paris climate target and the role of policy to get the world there [52'59"]

Slide 20 - Revised estimates for year 2100 global sea-level rise

So the SCAR ice sheet modelling community has published several models making predictions of Antarctic ice sheet contribution to the end of the century, and all show that the current IPCC estimate of 1m above present for the high-emissions RCP 8.5 pathway is and UNDERESTIMATE. The study by Nick

Golledge and colleagues produces only half that of DeConto study but it is still 40cm higher. It seems certain that this critical new research once assessed in the next IPCC report will see the upper bound for sea-level rise estimates moved up. [42”]

Slide 21 - Why the Paris Agreement matters
1.5-2°C appears to be a threshold for big loss of Antarctic ice

But more importantly these studies show just how important the Paris Agreement is. And it’s a good news story. It appears that if global warming can be kept below 2C then we may have a chance of saving the Antarctic ice sheet from significant melt down.

Put simply the threshold for loss of Antarctica’s stabilising ice shelves may be the Paris target of 2C of global warming. Go above it and you commit the planet Earth to multi meter sea-level rise that may be irreversible for millennia.

These graphs from the two models show long-term commitment to 4 to 15m of sea-level rise over the coming millennia if the Paris target is not achieved. [48”]

Slide 22 - Why the Paris Agreement matters: The avoided impacts (Shanghai)

This Climate Central website has these interactive maps where you can visualise the impact of different levels of global warming and associated sea-level rise on any coastal city in the world. Climate Central has now teamed up with leading sea-level scientist Bob Kopp and Antarctic scientist Rob DeConto to improve these projections and make them consistent with the latest science.

This is a nice example of how Antarctic climate science will be implemented in a policy context, so that coastal cities and communities are better prepared for anticipating and managing the impacts of sea-level rise.

Here we see the consequences for Shanghai. Now remember that this sea-level rise is not just due to Antarctic melting but also Greenland, ocean thermal expansion, and other glacier melting.

I think the avoided impacts of achieving the Paris target are obvious for Shanghai.

Of concern is that sea-level rise doesn't just stop at the end of the century if the world warms more than 2C. It continues to rise for centuries because the heat in the Southern Ocean and the heat in the Antarctic ice sheet remains their for a long time, centuries.

Remember this is the climate change commitment we talked about earlier. China unlike many countries, takes a long term strategic view on climate change. It has been around for millennia and so the year 2300 where global sea-level could be 9m higher is not far into the future [2"]

Slide 23 - Impacts on Antarctic operations: sea-level

OK so lets look at some impacts specific to Antarctica. Some of these impacts I'm going to show you were already identified by SCAR and COMNAP to the ATCM meeting in Hobart in 2012.

Now this first one might surprise you. If Antarctic melting contributed 1m to global sea-level rise as the latest ice sheet latest models predict, then sea-level would fall around the coast of West Antarctica by as much as 2.5m. That's right fall not rise. This is because of regional changes in the gravitational field when water is transferred from an ice sheet to the global ocean.

Lower sea-level could make coastal station access by ship or over sea-ice or ice shelf difficult. Air fields on the ice shelf or sea-ice might be impacted, and ship access to piers and wharves could be compromised. Certainly new over snow and land routes would need to be develop and infrastructure such as water pipes would be affected. [1' 22"]

Slide 24 - Impacts on Antarctic operations: ice shelf collapse

As ice shelves disintegrate and collapse they can produce impenetrable ice berg melange over large areas restricting ship access to large parts of Antarctica and stations. The Ross and Weddell Sea sectors would be particularly impacted. Antarctic ice bergs then travel large distances around the Southern Ocean and north out of the Southern Ocean for example around New Zealand and South America. The impacts on fishing, merchant shipping, tourism and operations would be significant. [30"]

Slide 25 - Impacts on Antarctic operations: sea-ice

Antarctic summer sea-ice extent has slowly increased in area as a whole around Antarctica for the last 40 years, but in 2016-2017 decreased dramatically as you can see in the graph above. Perhaps this represents the influence of anthropogenic climate change and the beginning of a longer term trend, or perhaps the sea-ice will come back.

The science is still out on this, but what the climate models do show is that Antarctic sea-ice will decrease in the coming decades as the ozone hole repairs and atmospheric CO_2 increases. When this happens new areas will be widely accessible for both operations and research.

Until then the pattern of sea-ice is complicated. Red shaded areas on the map in the Weddell and Ross Seas show increasing sea-ice. Blue shaded areas show where sea-ice is being lost. For example the Amundsen Sea. So some areas will be accessible and some more difficult to access. Understanding the future trends and patterns in Antarctic sea-ice has important implications for the design and level of strengthening of new ice breakers, access to stations and tourism, and may provide opportunities for Antarctic science [1' 36"].

Slide 26 - Future research focus: Climate change on Antarctica a high priority

Less than one third of the 194 member states of the UNFCCC belong to Antarctic Treaty System and have direct access to Antarctica for research. So SCAR supported by COMNAP has an important role to play.

SCAR strategic research programmes will make major contributions to the IPCCs next assessment report especially on Antarctica's contribution to global sea-level rise.

The impacts of climate change on Antarctic activities and operations will be significant, yet the ATS does not have a coherent voice in the UNFCCC. Part of the issue is Antarctic is not a nation state and does not have permanent population, but it could have observer status.

A number of critical knowledge gaps have been identified in the IPCC's 5th Assessment Report, through strategic assessments carried out by national Antarctic programmes, funding agencies' and the SCAR Horizon Scan process.

The Protocol on Environmental Protection and the Convention on the Conservation of Antarctic Marine Living Resources also require evidence-based policy and decision-making, that includes knowledge of the impacts of climate change.

Understanding the impacts and avoided impacts on Antarctica of Paris Climate Agreement, is a key *Future Science Challenge* identified by SCAR and being addressed in ACTM XL Working Group 2 agenda item 15a (see Background Paper 20).

To meet these challenges the Council of Managers of National Antarctic Programmes (COMNAP) have undertaken the Antarctic Road Map Challenge (ARC), which identifies the resources, infrastructure, logistics and supporting technologies needed to enable priority science objectives to be achieved over the coming decades. [2’43’].

My parting comment is that the clock is ticking and time is short. Many knowledge gaps still exist on how Antarctica will respond to global warming, that will have wide reaching impact and will be critical to anticipating and managing the impacts of climate change. They ATS and its Agreements are key stakeholders whose functions will be impacted by climate change, but the Parties also have a collective responsibility to address these knowledge gaps as quickly as possible.